Spontaneous Ignition of Hydrogen Jets in the Presence of Reflected Shock Waves

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1 Introduction

The current study addresses spontaneous ignition of hydrogen jets that are released into a confined oxidizer environment. Previously, several experiments [1–6] have shown that when pressurized hydrogen is suddenly released directly into the atmosphere, spontaneous ignition of the resulting jet can occur through shock induced diffusion-ignition; whereby the expanding jet drives a strong shock wave into the oxidizer ahead of the jet. It is the resulting diffusive mixing between the shocked oxidizer and fuel that leads to ignition [1, 7]. Several numerical investigations [7–10] have been able to identify the limiting criteria in order for ignition of this type to occur. Specifically, Maxwell [7] was able to show that this type of spontaneous ignition, for unconfined hydrogen releases into air, was strongly dependent on the storage pressure of the fuel and the size of the hole through which it escapes. The experiments [2–5], however, have only been only to identify such trends providing there exists some confined downstream geometry (i.e. tube extensions) from the release point. Such experiments, and also numerical investigations [11–14] have shown that such releases are more likely to ignite when extension tubes are used. The main question we attempt to answer, experimentally, is why releases into confined environments, such as tubes, are more likely to ignite than releases directly into atmosphere. Currently, it is believed that reflected shock waves, in the presence of downstream geometry or tube walls, play a major role influencing jet ignition in confined releases [2, 11]. Thus, in this study, reflected shock wave interactions with the transient jet upon release and the associated ignition limits are under investigation. Furthermore, we propose an experimental method to study shock induced diffusion-ignition of hydrogen jets in the absence of tube extensions and without the need to pressurize the hydrogen to potentially dangerous levels. Furthermore, to address the small scale limitations of previous experiments of H2 jet releases in confining tubes, we decided to scale up the experiment and consider larger hole releases (67mm) through a 20 cm confinement. Although clearly not realistic of hydrogen releases, the scaling up of these experiments permits us to implement several visualisation diagnostics and pressure measurements in order to monitor, with adequate space and time resolution, the evolution of the hydrodynamic flow field obtained when hydrogen is released into an oxidizer through a hole in partly confined spaces. The motivation of these experiments is to develop a set of controlled experimental data which can be used to validate numerical models.

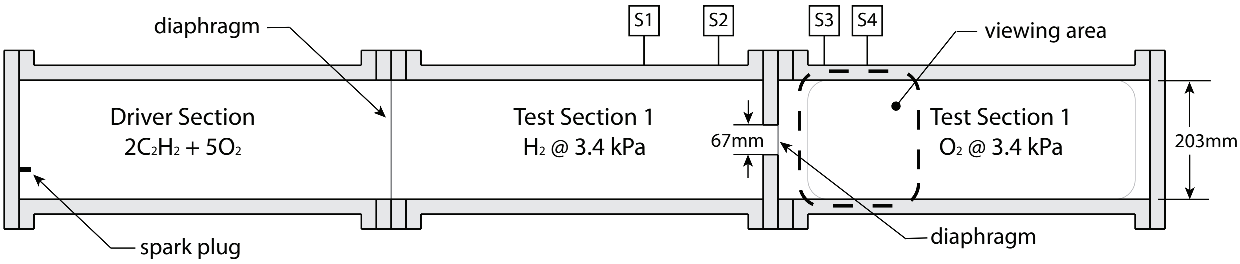

Figure 1: Shock tube setup for hydrogen release experiment. Each section of the shock tube is separated by diaphragms, shown, and filled with the respective gas. The shock tube is fitted with pressure sensors, labeled S1 through S4. Also shown in the Figure is the viewing area of the camera. The cross section of the shock tube is 203mm high by 19mm wide.

2 Experimental Setup

In order to study the spontaneous ignition of hydrogen jets in the presence of reflected shock waves, a 3m long shock tube is used that has a rectangular cross section area of 203mm high by 19mm wide; essentially used to study two dimensional flow. The experimental setup, inspired by Wolanski and Wojcicki's experiment [1], consists of a test section where hydrogen gas is initially separated from oxygen by a diaphragm and a plate that contains a single pore (67mm $\times$ 19mm). An acetylene-oxygen driver is used to drive a strong shock wave through the test section, causing hydrogen to flow into oxygen. A sketch showing the setup is shown in Figure 1. Prior to conducting the experiment, each chamber is vacuumed below 50 Pa before it is filled with the respective gas. The test sections are then filled with pure oxygen and hydrogen to 3.5$\pm$0.1 kPa and 3.4$\pm$0.1 kPa, respectively. The oxygen section is pressurized slightly more to ensure that the diaphragm rests against the pore in the constrictor plate. The driver section contains stoichiometric acetylene-oxygen mixture, whose initial pressure is varied. The driver section is detonated from a spark plug located at the end wall as shown in the Figure. Once the resulting detonation wave reaches the first diaphragm, a shock wave transmits into the hydrogen, whose strength is controlled by the initial pressure of the driver. When the incident shock wave breaks the second diaphragm, the compressed hydrogen expands into the oxygen section, driving a strong shock wave ahead of the jet. To capture any resulting combustion, a photo-sensitive PIV camera is used to take direct photos of the jet. The viewing area of the camera is illustrated in Figure 1. When the camera is triggered, the shutter is opened only for 5µs. In an alternate configuration, the camera is used to capture Schlieren photographs [15]; an imaging technique which uses refraction of light in a fluid to capture density gradients. Finally, the shock tube is equipped with 4 pressure sensors, as shown in Figure 1. Sensors S1 and S2 are used to estimate the strength of the incident shock which travels through the hydrogen and also to estimate the time at which the hydrogen jet begins to burst into the oxygen section. Sensors S3 and S4 are used to calculate the trigger timings for the camera.

3 Experimental Results

A series of experiments have been conducted, where the pressure of the driver gas was varied between 8.7 kPa to 14.8 kPa to drive different strength shocks into the test sections. In all experiments, the pressures of the test sections, hydrogen and oxygen, are kept constant. A summary of the various experiments, including their parameters and principle observations, is shown in Table 1. Also shown in the table are the estimated strengths of the incident and transmitted shocks, in the hydrogen and oxygen sections, respectively. In Figure 2a, a Schlieren image is shown for an expanding hydrogen jet into oxygen for a case where ignition was detected (experiment 1 from Table 1). The particular image in this figure was taken approximately 290µs into the release process. Clearly, a shock wave is observed traveling through the oxygen ahead of the jet. Also, the interface of the jet with the shocked oxygen is very turbulent; which is ideal for increased mixing of the gases, and also for promoting complete ignition of the transient jet. Typical images showing the combustion of jets under similar conditions, experiments 2 and 3, are shown in Figures 2b and c, respectively. These two figures were taken approximately 310µs and 400µs after the jet was released into oxygen. Of particular interest in Figure 2b are the two evident hotspots on the top and bottom walls of the shock tube. The increased luminosity in these regions suggests that the combustion resulting from reflected shock waves interacting with the expanding jet is much more intense then elsewhere along the jet surface. It is believed that this locally intense combustion is a result of increased local mixing due the RichtmyerMeshkov instability [16, 17]. Finally, Figure 2c shows complete ignition of the entire jet at a later time. To confirm that the images in Figures 2b and c are showing combustion, the experiment is repeated by substituting the oxygen with nitrogen. In this case, experiment 4, only darkness is captured, thus confirming the observed combustion in the previous experiments. In the remainder of the experiments, the pressure of the driver was varied find conditions for which the jet did not ignite upon release into oxygen. Specifically, two experiments, 8 and 9, were cases where no ignition was captured. Interestingly, a third regime was observed, in experiments 7 and 10, where local ignition hot spots appear near the top wall of the shock tube but do not lead to complete ignition of the jet. These hotspots are shown in Figures 3a and 3b, respectively.

Table 1: Experiment Results

Experiment number	Driver pressure (kPa)	Incident shock in H_2 (Mach number)	Transmitted shock in O_2 (Mach number)	Observation
1	14.8	3.4	5.6	Full jet ignition detected
2	14.8	3.5	5.8	Full jet ignition detected
3	14.8	3.4	5.6	Full jet ignition detected
4	14.8	3.4	5.6	H_2 into N_2 (no ignition)
5	13.8	3.7	6.2	Full jet ignition detected
6	12.4	3.3	5.4	Full jet ignition detected
7	8.8	2.3	3.4	Hotspot found on top wall
8	10.3	2.5	3.8	No ignition detected
9	10.3	2.6	4.0	No ignition detected
10	10.3	2.5	3.8	Hotspot found on top wall
11	12.4	3.1	5.0	Full jet ignition detected
12	14.8	2.9	4.6	Full jet ignition detected
13	11.7	2.9	4.6	No ignition detected
14	12.1	2.7	4.2	No ignition detected

4 Discussion

In order to quantify the conditions for when ignition occurred during a release, we first determined the state of the contact surface immediately after the incident shock breaks out across the perforated plate. At the perforated plate, this problem is a one-dimensional gasdynamic problem, solved by determining the wave interactions at the hole. These are illustrated in Figure 4. Since the incident shock is transmited into a medium with a higher acoustic impedance (ρc), there will be a reflected shock wave. The state of the interface after the interaction and Mach numbers of the transmitted shock can be simply obtained by matching the pressures and particle speed at the interface. Given the strength of the incident shock, as

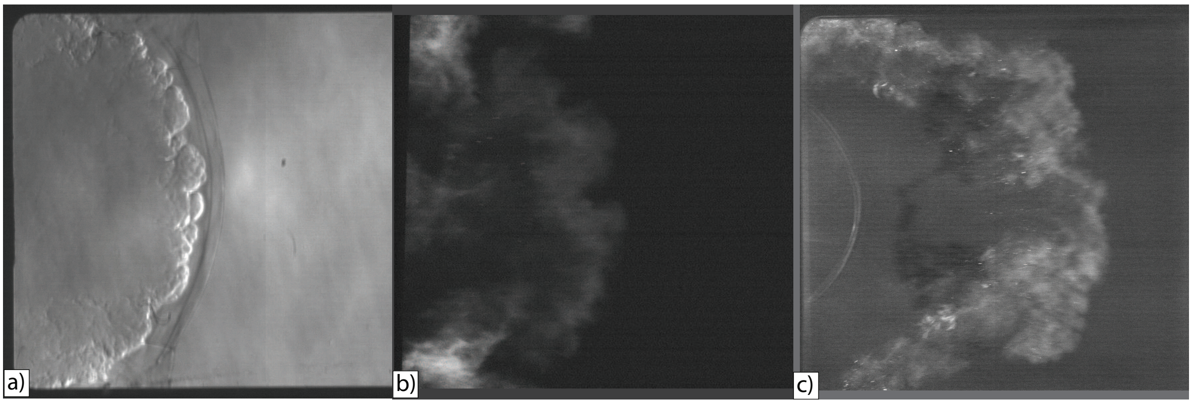

Figure 2: Typical cases where full jet ignition is observed. Frame a) is a Schlieren image showing density gradients of the expanding hydrogen jet into oxygen at approximately 290µs into the release process. Frames b) and c) show the combustion occurring at approximately 310µs and 400µs into the release process, respectively.

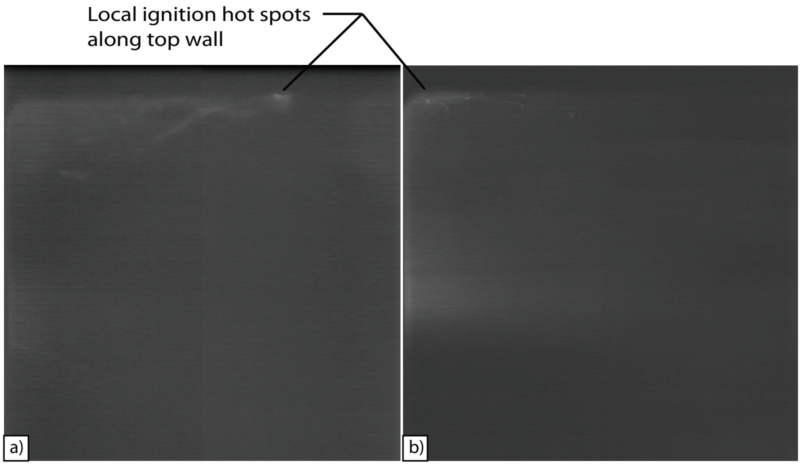

Figure 3: Images showing localized ignition hot spots for cases where complete jet ignition does not occur, corresponding to experiments 7 (a) and 10 (b), respectively.

measured by the pressure sensors 1 and 2, the state of the interface and the transmitted shock are readily determined. Table 1 lists this information.

With the knowledge of the initial shock heating of the diffusion layer, we can estimate the potential of the mixing layer to ignite using the model formulated by Maxwell and Radulescu [7]. The model takes into account the rapid expansion of the mixing layer as a quenching mechanism, but not any further shock reflections, nor any subsequent turbulent mixing. It thus only provides the prediction if the gases ignite, but not how much of the gas ignites.

The model is a localized one-dimensional description of the thin diffusion layer at the head of the jet, in Lagrangian coordinates. Realistic thermodynamic properties, reaction rates, and transport properties are taken into account. The rate at which the pressure decays in the diffusion layer is prescribed as a source term. Specific details of the model are found in [7]. To adapt the model to the experiment described in this paper, known information about states 3 and 4 from Figure 4 are applied as the initial conditions of the diffusion layer. Also, the pressure decay rate source term is adapted to the two dimensional slit jet geometry of this experiment.

Results of the numerical experiment indicate that in order for ignition to occur as a result of the shock induced diffusion ignition, in the absence of reflected shocks, the strength of the incident shock (in

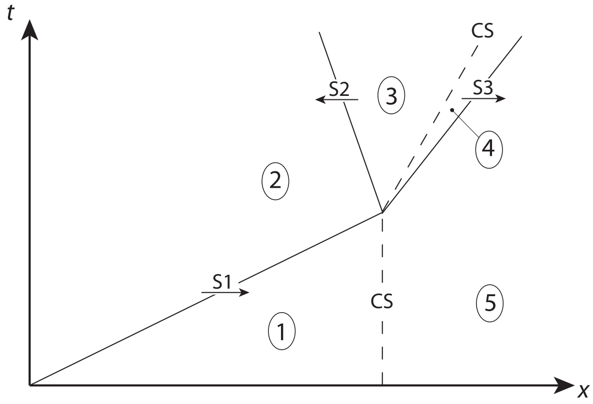

Figure 4: An $x - t$ diagram illustrating the interaction of a shock wave (S1) propagating through the undisturbed hydrogen (zone 1) with a contact surface (cs) separating undisturbed oxygen (zone 5) from the hydrogen. Also shown in the figure are the reflected shock wave (S2), the transmitted shock wave (S3). Also labelled are the shocked states of hydrogen (zone 2 and 3) and also the shocked state of oxygen (zone 4).

H_2) must be greater than $M = 3.0$. This value corresponds to a transmitted shock strength (in O_2) of $M = 4.8$. Comparing this value to the ignition limit found in the experiments ($M = 4.6 \pm 0.4$) in Table 1 reveals that the numerical model is consistent with the shock tube experiments for predicting jet ignition. It should be noted, however, that although ignition hotspots were observed for weaker shocks (shock tube experiments 7 and 10), the localized combustion was resulting from reflected shocks near the shock tube walls. Thus, these special cases are considered consistent with the numerical model as jet ignition, due of the initial shock compression of the gases, was not detected.

5 Conclusions

In this study, shock induced diffusion ignition of pressurized hydrogen jets flowing into a confined oxidizer environment has been studied. In the experiment, it was found that ignition of a hydrogen jet flowing into hydrogen can be induced by controlling the strength of the shock wave that is driven into the oxygen, ahead of the jet. Furthermore, it was found that localized ignition is possible as a result of reflected shock waves from the walls of the shock tube. Interestingly, however, it was found that in some cases the appearance of such ignition hot spots did not cause full ignition of the jet. Instead these hot spots remained localized near the shock tube walls. Finally, a one-dimensional numerical model [7] was used to find the ignition limit of the releases in the absence of reflected shock waves. The model was found to be in excellent agreement with the shock tube experiments for predicting complete ignition of the jet. The resulting implication is that controlled shock tube experiments, as presented here, can be used to validate numerical models for simulating pressurized hydrogen releases into air. As such, it is the authors aim to develop a multidimensional numerical model, in order to gain further insight into the role of the reflected shock waves, and how they may influence or contribute to ignition of the hydrogen jet ignition.

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