Sub Topic: Detonation

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Supersonic Deflagration of Hydrogen-Air Mixture

Jacob Klein[1], Tusharr Goyal[1], Omid Samimi-Abianeh[1,]*

[1]Department of Mechanical Engineering, Wayne State University, 5050 Anthony Wayne Dr, Detroit, Michigan, 48202, USA
[*]Corresponding Author Email: o.samimi@wayne.edu

1. Introduction

Deflagration to detonation transition (DDT) of gaseous mixtures represents a phenomenon of paramount importance and potential across various fields, including combustion science, aerospace engineering, and mining. Despite decades of intensive research, there remains a mystic surrounding the failure of certain mixtures to undergo this critical transition. Understanding the intricate mechanisms underlying the failure of gaseous mixtures to transition to detonation is not only pivotal for enhancing our comprehension of combustion dynamics but also holds promise for the design and optimization of propulsion systems, detonation engines, and explosion mitigation strategies. In this work, an analysis of the complexities surrounding the failure of gaseous mixtures to transition to detonation, through experimental observations and theoretical frameworks, is undertaken.

A significant number of mixtures, initial conditions, critical energies for initiation, and DDT promotion methods have been explored in the literature to date. For example, Meyer et al. [1] analyzed the effectiveness of several DDT promotion or enhancement devices such as Shchelkin spirals, extended cavities/spirals, and a co-annulus tube for hydrogen-air. Ultimately, they found that explosions localized within the Shchelkin spiral configuration exhibit distinct behavior along the spirals compared to those generated by axisymmetric obstacles. Additionally, the co-annular geometry with inner tube diameters less than half of the main tube diameter revealed a lack of strong detonations. Lee and Matsui [2] investigated the critical energy required for direct initiation of detonations in acetylene-oxygen mixtures using electrical sparks. Their work demonstrated a lack of dependency of critical energy on mixture composition. However, critical energy does depend on the initial mixture pressure with the required energy decreasing with increase in initial pressure. Frolov [3] reviewed the phenomenon of fast deflagration to detonation transition in which a turbulent flame is sped up to a much lower velocity than that required for the classic DDT. Fast DDT occurs when self-ignition zones form synchronously with a relatively weak shock wave. These zones arise due to wave reflections from profiled obstacles. Experimental evidence and calculations have demonstrated that the critical velocity for such transitions can be quite low compared to CJ detonation velocities. The required DDT run up length for hydrogen-air was investigated by Kuznetsov et al. [4]. It was suggested that the run-up distance to DDT is depended on the initial pressure. Empirically, this dependence is proposed to be inversely proportional. The flow preceding the flame leads to the development of the turbulent boundary layer, which regulates the size of turbulent movements within the flow. Furthermore, it was hypothesized that the onset of detonation occurs when flame acceleration causes the maximum turbulent fluctuations to reach a magnitude around ten times the detonation cell widths.

Overall, the phenomenon of DDT represents one of the last unconquered frontiers of combustion research and as such merits more research. Herein, DDT is studied once more with the aim of addressing a portion of its enigmatic nature.

2. Methodology

Experiments were performed in the newly realized, optically accessible detonation tube at Wayne State University's Supersonic Combustion Research and Measurements (SCRAM) Laboratory. The tube measures 3.43 meters in length, has a 69.85 mm primary inner diameter, a 203.20 mm secondary inner diameter, and is equipped with four 95.25 mm diameter sapphire optical accesses. The tubes' ignition chambers house Shchelkin spirals with blockage ratios (area based) of 32.8%. The geometry of the detonation tube is graphically depicted in Figure 1.

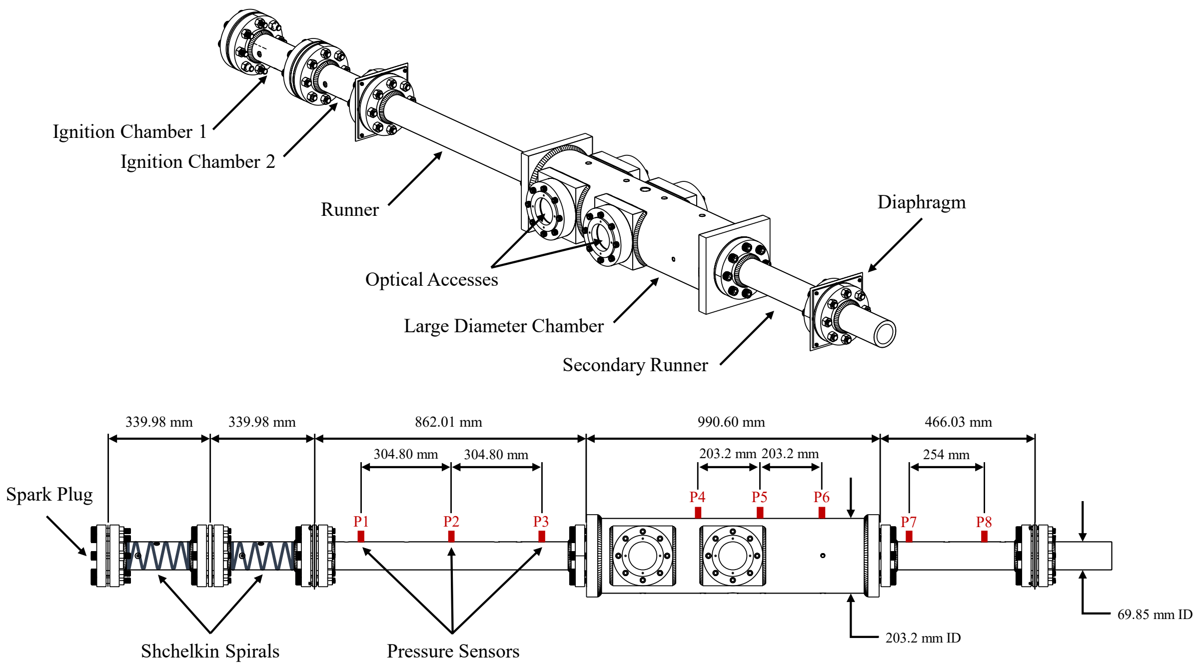

Figure 1. Schematic of detonation tube: (top) isometric view and (bottom) horizontal view.

Eight PCB 113B22 piezoelectric pressure transducers, located along the length of the tube, recorded dynamic pressure inside the detonation chamber. Pressure signals were recorded at a rate of 0.2 MHz. A Z-type schlieren system was used to visualize the flow inside the tube's larger chamber. The schematic of this system is shown in Figure 2. The Schlieren system used an LED (Visual Instrumentation 900415) and two f/8 spherical mirrors. Images were recorded using a Phantom V12.1 high-speed Camera. The V12.1 recorded 256 by 256-pixel images at a frame rate of 67,000 fps with an exposure time set to 1 microsecond for all experiments.

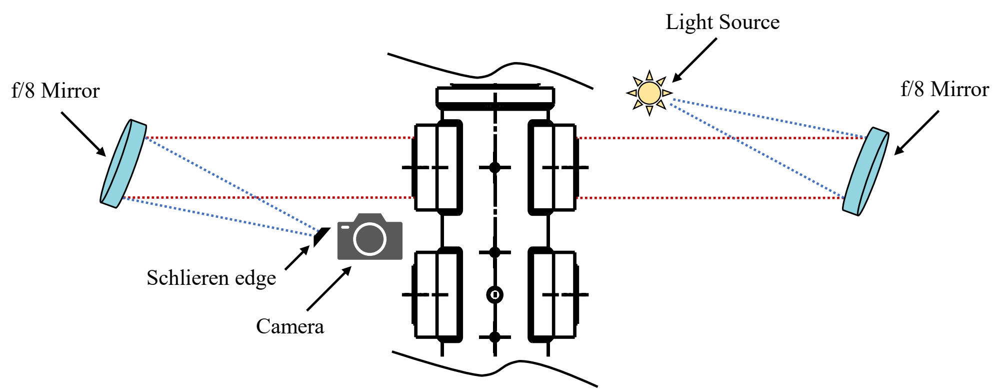

Figure 2. Schlieren setup for experiments using led light, f/8 spherical mirrors, and high-speed camera.

Before each experiment, the detonation tube was evacuated and filled to the desired initial pressure and composition via the method of partial pressures. Static pressures for mixture introduction were measured by a high accuracy static pressure transducer (Kistler 4260A). Airgas supplied all gases for mixtures, including air (ultra-zero grade), hydrogen (research grade), and acetylene (99.6% purity). After allotting sufficient time for the gas inside the chamber to reach a homogenous state, spark ignition was initiated by way of discharging a variable voltage capacitor through an ignition coil (MSD Ballast 2) resulting in a spark across the in-situ sparkplug's (NGK Iridium IX) electrodes inside the first ignition chamber. A PE0630 solid-state relay by VB Controls and a DG646 Stanford Research Systems delay generator governed the timing of spark ignition. NI LabVIEW software recorded all pressure data during experimentation. The mixtures used were hydrogen-air and acetylene-air at equivalence ratios of 1.0 and 1.2.

3. Results and Discussion

The supersonic deflagration behavior of hydrogen-air mixture was investigated in this work. Pressure histories from two experiments with hydrogen-air (Φ = 1.0 and 1.2) at initial pressure and temperature of 100 kPa and 300 K are shown in Figure 3 below.

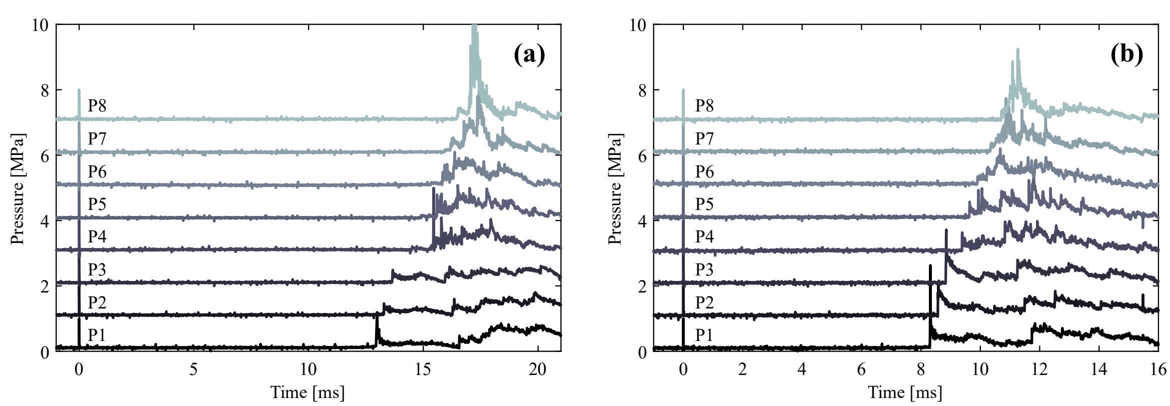

Figure 3. Pressure traces for hydrogen-air at equivalence ratios of (a) 1.0 and (b) 1.2 at initial pressure and temperature of 100 kPa and 300 K.

The pressure traces in Figure 3 have been temporally zeroed to the time of spark ignition and the pressure traces have been offset vertically by 1 MPa from each other to maintain clarity. Normalizing the distance between sensors by the duration (Δt) between initial dominant peaks on the corresponding pressure traces, the average velocities of the flow were computed. These velocities are reported in Table 1.

Table 1: Average Flow Velocities for hydrogen-air at equivalence ratios of 1.0 and 1.2

Sensors:	Location:	($\Phi_{1.0}$) Velocity [m/s]:	($\Phi_{1.2}$) Velocity [m/s]:
P1-P2	Runner	1063.34	1355.54
P2-P3	Runner	934.34	1259.01
P4-P5	Larger Diameter Chamber	592.32	920.88
P5-P6	Larger Diameter Chamber	548.75	854.17
P7-P8	Secondary Runner	559.54	799.35

Recorded frames of the flows from the two mixtures discussed above are shown in Figure 4. As seen for the mixture at unity equivalence ratio, the shockwave is decoupled from the combustion front. This greatly contrasts the behavior of the richer mixture, where the combustion and wave remain coupled.

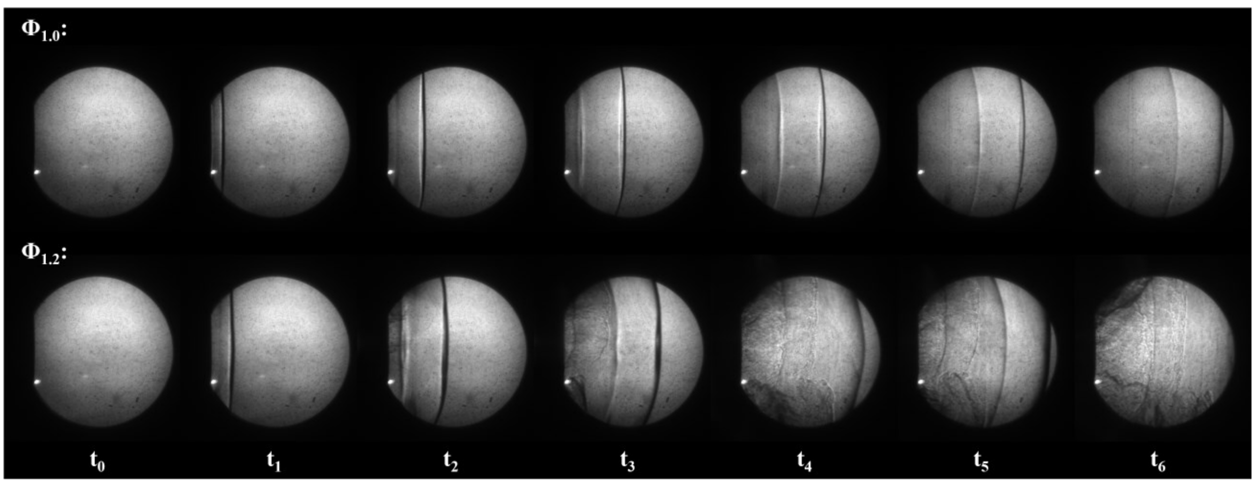

Figure 3. Schlieren images of flow for hydrogen-air at equivalence ratios of (top) 1.0 and (bottom) 1.2 at initial pressure and temperature of 100 kPa and 300 K.

It is known that prior to DDT, a supersonic deflagration will obtain a velocity of the order of about half the CJ detonation speed (the CJ deflagration speed) at which point the spontaneous onset of detonation can take place. [5] Based on the measured flow speeds; the richer hydrogen-air mixture reached the CJ deflagration speed (~1200 m/s) which is 58% of the CJ detonation speed. [6] The hydrogen-air mixture at an equivalence ratio of unity never reached this theoretical velocity which is attributed the detachment of the shockwave from the combustion front. Neither of the two mixtures detonated under the studied conditions, however the richer mixture reached conditions in which DDT was primed to occur.

4. Conclusions

This study examined detonation, supersonic deflagration, and DDT characteristics. The newly implemented Wayne State SCRAM detonation tube was used to analyze hydrogen-air and acetylene-air mixtures at a variety of initial conditions. Preliminary results indicate detonation limits for hydrogen-air. Moreover, coupling of shock wave and combustion fronts was observed for certain conditions whereas decoupling was observed for others. Overall, further analysis is required for qualitative and quantitative understanding of why certain mixtures detonate and others do not. Deflagration to detonation transition is a phenomenon with inherent importance to various fields and industries and thus warrants further efforts to understand its fundamental mechanisms.

5. Acknowledgements

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