Sub Topic: Detonations, Explosions, and Supersonic Combustion

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Flame Acceleration and DDT in Ethylene/Nitrous Oxide at Elevated Pressures

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Abstract: Nitrous oxide and ethylene appear extremely promising as a bipropellant mixture for rocket propulsion systems. Earlier work with this bi-propellant mixture suggested that at high initial pressures, a deflagration will undergo extremely rapid acceleration and achieve transition to detonation in very short distances. To study the flame acceleration and DDT behavior as a function of initial pressure, tests were carried out in a closed, large L/d combustion/detonation tube and detonation pressures and velocities were measured. These mixtures were ignited using a high voltage spark ignition system and the results were compared to those which used a nichrome wire igniter. In addition, similar tests with ethylene-oxygen were performed in the same combustion tube for comparison. The detonation run-up distances from the nitrous oxide and oxygen tests, and the dependence of run-up distance on initial pressure were determined and compared with those values from the nichrome wire igniter tests.

Keywords: Detonation, DDT, Nitrous oxide

1. Introduction

The decomposition and combustion properties of nitrous oxide (N_2O) have been studied for nearly a century and research intensified in the 1960s because of the compound's positive heat of formation. Also, upon complete dissociation the products were pure nitrogen (N_2) and oxygen (O_2). Well before the 1960s, a nitrous oxide and coal hybrid rocket was developed and tested at I.G. Farben in Germany which produced 10-kN thrust for 120 s [1]. This was followed by its usage for supercharging aircraft engines, investigated by both the Germans and NACA during World War II [2].

In the 1960s, the Air Force conducted a great amount of research to study the detonability of pure nitrous oxide [3] and the detonation of hydrazine with nitrous oxide to assess the viability of nitrous oxide as an oxidizer for rocket propulsion [4]. They measured detonation speeds of hydrazine-nitrous oxide mixtures at low initial pressures (on the order of 0.1 atm) and found the speeds to be near the ideal Chapman-Jouguet (CJ) detonation velocity.

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In the late 20th century, nitrous oxide re-emerged as a “safe”, clean oxidizer for rocket propulsion systems that is useable as both a monopropellant or as a bipropellant [5]. Numerous rocket systems were tested with nitrous oxide and notable ones include the hybrid engine by Grubelich et al. [6] with hydroxyl terminated polybutadiene (HTPB) as the fuel, a bipropellant rocket engine by Tyll et al. [7] where nitrous oxide was catalytically decomposed and the exothermic reaction ignited propane to produce sustained combustion in the engine, and a constant volume rocket motor by DiSalvo et al. [8] using propane in pulsed motor mode generating brief chamber pressure pulses on the order of 500-700 psia. In 2011, Boeing was contracted to develop the launch vehicle for DARPA’s Airborne Launch Assist Space Access (ALASA) program and they intended to lower the complexity and thus costs by powering the rocket with a monopropellant comprised of a pre-mixed combination of nitrous oxide and acetylene [9].

In the present work, the flame acceleration of nitrous oxide and ethylene at elevated pressures was investigated with a scope of applying this bi-propellant mixture to detonative propulsion systems. Earlier work with these bi-propellant mixtures at higher initial pressures using nichrome wire igniters showed extremely fast transition to detonation in a small [10] and large [11] L/d combustion tube, with detonations traveling at steady velocities in the large L/d combustion tube. In order to use this bi-propellant mixture in a pulsed detonation engine, rapid flame acceleration is essential to achieve transition to detonation in a short period of time. To further study the flame acceleration and DDT behavior, ethylene-nitrous oxide mixtures were tested in a large L/d, closed tube for a range of initial pressures using a high voltage spark ignition system.

2. Experimental Setup

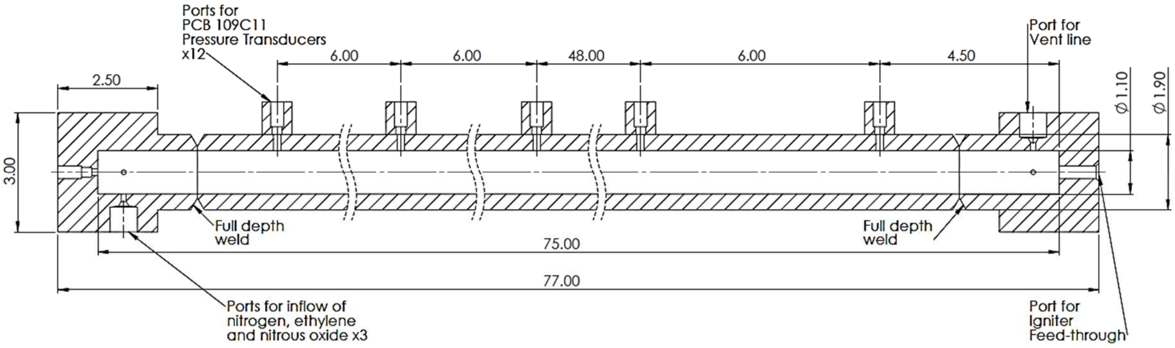

Figure 1: Diagram of the large L/d combustion tube used in the present work.

A schematic of the 75 inch long closed combustion tube with an inner diameter of 1.1 inches (L/d = 68) used in this work is shown in Figure 1. The combustion tube was designed to accommodate eleven PCB 109C11 transducers on the side wall, 6 inches apart, to measure pressure peaks at each location along the length of the tube during the propagation of the combustion wave. One pressure transducer was installed in the end wall to measure the reflected pressure. Pressure from these transducers was recorded at 600,000 samples/s/channel.

Ethylene and nitrous oxide (or oxygen) were supplied from respective bottles and separate sonic venturis were used to set mass flow rates of the propellants resulting in the appropriate final pressure and equivalence ratio for each test. The tube was heated to 100°F using a tape heater to prevent condensation of the propellant gases at high pressures. The ethylene and nitrous oxide (or oxygen) gases flowed into the tube from opposing ports to facilitate mixing of the gases. The combustion tube was purged with nitrous oxide (or oxygen) before pressurization with the bi-propellant mixture to ensure an atmosphere of nitrous oxide (or oxygen) at ambient pressure thereby eliminating any air or residual combustion gases in the tube. Further details of the test setup and operations were described in our previous work [11].

The bi-propellant mixture was ignited with an automotive spark plug using a high voltage spark ignition circuit fabricated in-house [12]. The circuit has the capability to produce high-energy (up to 0.5 J) pulses at voltages up to 45 kV. The details of the design are available in the cited reference. The discharge triggering, or "firing" circuit, used an external TTL signal to trigger the capacitor to discharge through a high voltage pulse transformer, which initiated electrical breakdown across the electrodes of the spark plug [12].

3. Experimental Results

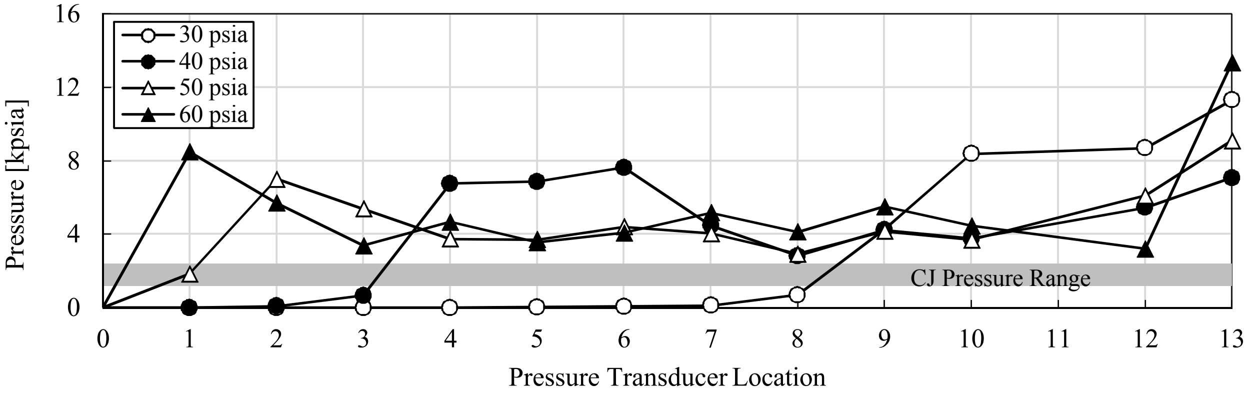

Figure 2: Peak pressures vs. transducer locations for stoichiometric ethylene-nitrous oxide tests at initial pressures of 30 to 60 psia. The theoretical CJ detonation pressure range is indicated in gray.

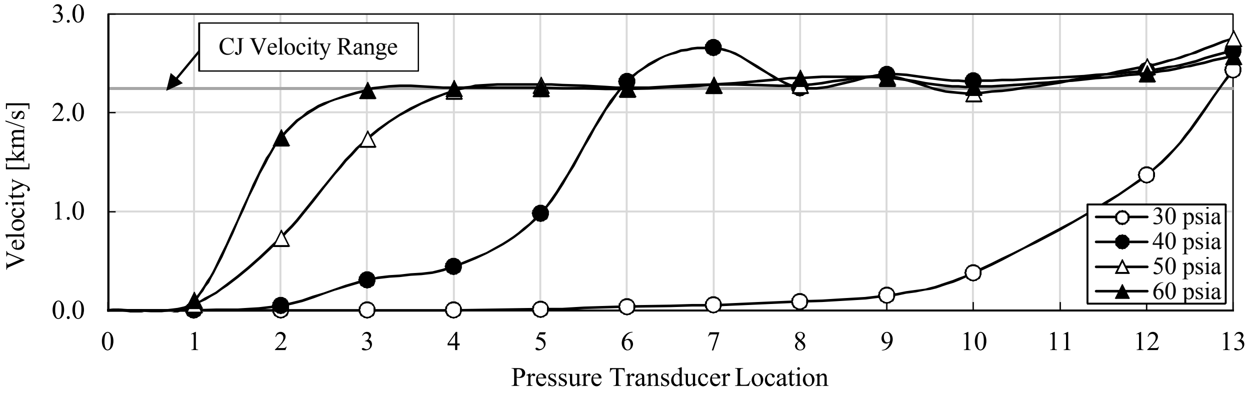

Figure 3: Velocity vs. transducer locations for stoichiometric ethylene-nitrous oxide tests at initial pressures of 30 to 60 psia. The theoretical CJ detonation velocity range is indicated in gray.

First, experimental runs were conducted with stoichiometric ethylene-nitrous oxide mixtures at initial pressures of 30 to 60 psia, with at least 5 runs at each initial pressure. The explosion pressures were recorded at all 12 locations in the combustion tube and the average explosion pressures at each location were plotted against pressure transducer location in Figure 2. These explosion pressures were compared to the theoretical CJ detonation pressures calculated using the Shock and Detonation Toolbox [13] in Cantera [14]. The range of theoretical values were plotted in gray on the same figure for comparison. In each test, the explosion pressures post-DDT were higher than the theoretical CJ detonation pressures and this was a consequence of pre-compression or pressure piling of the combustible mixture by the deflagration. The deflagration compressed the combustible mixture to a new "starting pressure" which led to higher detonation pressures.

The time instance of each pressure peak from these tests and the distance between pressure transducers (PTs) were used to calculate the propagation velocities of the combustion wave. These velocities were averaged at each location and plotted against PT location in Figure 3, along with the theoretical velocities in gray for comparison. As the initial pressure was increased the combustion wave accelerated faster, transitioning to a detonation in shorter distances.

Next, experimental runs were conducted with oxygen as the oxidizer at initial pressures of 55 to 95 psia, and average explosion pressures and velocities were plotted against PT location in Figure 4 & Figure 5.

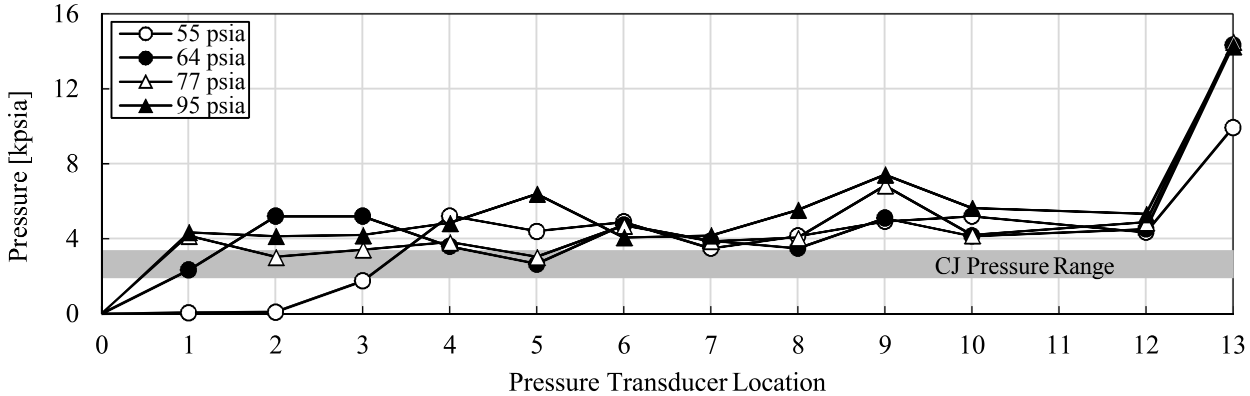

Figure 4: Peak pressures vs. transducer locations for stoichiometric ethylene-oxygen tests at initial pressures of 55 to 95 psia. The theoretical CJ detonation pressure range is indicated in gray.

These plots showed trends similar to those exhibited in the nitrous oxide tests, but the recorded explosion pressures were lower and velocities were higher than those from the nitrous oxide tests. This was concurrent with the theoretical values calculated using the Shock and Detonation Toolbox [13].

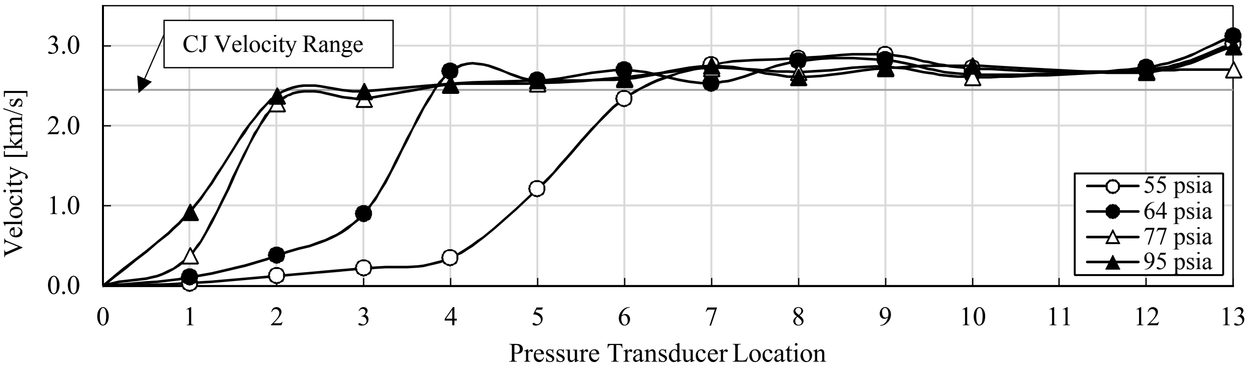

Figure 5: Velocity vs. transducer locations for stoichiometric ethylene-oxygen tests at initial pressures of 55 to 95 psia. The theoretical CJ detonation velocity range is indicated in gray.

4. Run-up Distance Comparison

Run-up distance is defined to be the distance between the source of ignition and that point in the tube where the combustion wave first travels at the velocity of the stable detonation wave (CJ velocity) and is non-dimensionalized using the tube inner diameter (X_d). The dimensionless run up distance for each nitrous oxide and oxygen test was determined based on this definition and the average value at each initial pressure was plotted against initial pressure, p_o, on a log-log scale shown in Figure 6. The run-up distances determined from the nichrome wire igniter tests were plotted on the same figure in black for comparison. These distances also followed a power law with respect to initial pressure as suggested by Nettleton [13]:

$$X_d = \frac{k}{(p_o)^m} \tag{1}$$

where k is a constant. Trend lines fit to the nitrous oxide tests with both ignition systems produced exponents of 2.333 and 2.312, and thus followed the same trend with initial pressure. However, the tests with oxygen using the high voltage spark system produced a lower exponent of 1.762 and larger run-up distances compared to nitrous oxide for similar initial pressures. These nitrous oxide tests produced run-up distances shorter than those with the nichrome wire igniter and this was expected due to the high energy spark ignition system used for these tests. Trend lines fit to the oxygen tests and the nitrous oxide tests with the nichrome wire igniter predict a dimensionless run-up distance larger than the L/d of the tube, and coincidentally no detonations were observed for these conditions.

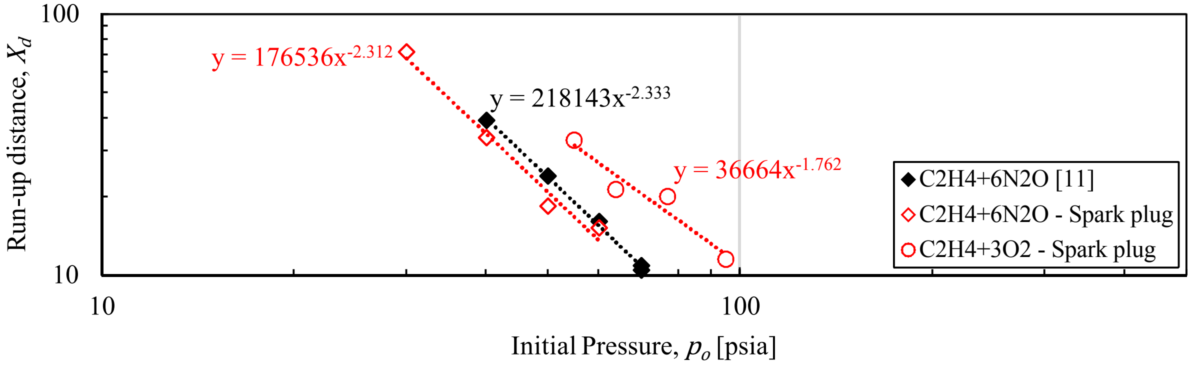

Figure 6: Dimensionless run-up distances for ethylene-nitrous oxide and ethylene-oxygen mixtures.

5. Conclusion

This series of tests was conducted to investigate the effect of different ignition systems on the flame acceleration of ethylene-nitrous oxide and ethylene-oxygen mixtures. The average explosion pressures for all these tests followed trends similar to those with the nichrome wire igniter, but the velocity plots indicated that the combustion wave accelerated faster when ignited with the high voltage ignition system. This was also concluded by determining the run-up distances, which followed the same increment rate with initial pressure as compared to the previous tests, but were shorter. In addition, previous tests with ethylene-oxygen mixtures using nichrome wire igniters did not provide a run-up distance trend, but a run-up distance trend was determined from the tests in this series and it was observed that ethylene-oxygen mixtures had longer run-up distances in comparison to those of ethylene-nitrous oxide mixtures with both ignition systems. This was due to the exothermic decomposition of nitrous oxide, which initiated sustained combustion in ethylene-nitrous oxide mixtures at pressures as low as 30 psia. Future work will involve the development of a computational model to support these tests and investigate the trends observed on the basis of chemical kinetics.

Acknowledgement

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