

Prechamber Hot Jet Ignition of Ultra-Lean H_2 /Air Mixtures: Effect of Supersonic Jets and Combustion Instability

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ABSTRACT

An experiment has been developed to investigate the ignition characteristics of ultra-lean premixed H_2 /air mixtures by a supersonic hot jet. The hot jet is generated by combustion of a stoichiometric mixture in a small prechamber. The apparatus adopted a dual-chamber design in which a small-volume (1% of the main chamber by volume) prechamber was installed within a large-volume main chamber. A small orifice (nozzle) connects the two chambers. Spark initiated combustion inside the prechamber causes a pressure rise and pushes the gases through the nozzle, resulting in a hot jet that would ignite the lean mixture in the main chamber. Simultaneous high-speed Schlieren photography and OH^* Chemiluminescence were applied to visualize the jet penetration and the ignition processes inside the main chamber. Hot Wire Pyrometry (HWP) was used to measure temperature distribution of the transient hot jet. A novel velocity measurement technique based on Schlieren PIV (SPIV) has also been developed to characterize the local flow field. Three nozzle geometries (straight, convergent and converging-diverging) have been studied to understand their effect on ignition probability and characteristics. The results show that a supersonic jet by using a converging-diverging nozzle can ignite leaner mixtures than the jet produced by a straight nozzle of the same throat area (e.g., the ignition limit is reduced to $\phi = 0.22$, from 0.35). Additionally, infrared imaging and OH^* Chemiluminescence indicated diamond shock structures in the supersonic jets and a high-temperature zone downstream the shocks. This high-temperature zone is likely the reason why the main-chamber flammability limit can be further reduced. Lastly, combustion instability becomes noticeable near the lean-limit conditions for all three types of nozzles, which affect the structural integrity of the combustion chamber. Two unstable frequency modes, natural frequency of the combustor at 180 Hz and a higher mode at 2400 Hz were observed.

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INTRODUCTION

One demand manufacturers of gas engines are facing is to meet ever-stringent legislation on emissions including oxides of nitrogen [1,2,3,4]. Ultra-lean operation of internal combustion engines can reduce NO_x emissions and also improve their thermal efficiency [5]. However, ignition of ultra-lean fuel/air mixtures has many challenges. For example, misfires can occur in the engine as a result of poor ignition. Such misfires and difficulties in ignition can lead to cycle-to-cycle variability, rough operation, reduction in efficiency, and increase in unburned hydrocarbon emissions - none of which are desirable [6-7].

An approach that can potentially solve this problem is to use a hot turbulent jet to ignite the lean mixture instead of a conventional electric spark [8-9]. The hot turbulent jet is generated by burning a small quantity of stoichiometric or near-stoichiometric fuel/air mixture in a separate small volume called the prechamber. The higher pressure resulting from prechamber combustion pushes the combustion products into the main chamber in the form of a hot turbulent jet, which then ignites the mixture in the main chamber. Compared to a conventional spark plug, the hot jet has a much larger

surface area over which ignition can occur. Hot jet ignition has the potential to enable the combustion system to operate near the fuel's lean flammability limit, leading to ultra-low emissions.

Turbulent hot jet ignition, however, is a complicated phenomenon. There are very few computational and experimental studies on the fundamental mechanisms involving the complex coupling between turbulent mixing and chemical reactions. Several interrelated chemical and physical processes are involved. For example, the jet containing hot combustion products penetrates into the lean mixture, providing a high-temperature environment for mixing and ignition. It may also contain active radicals such as H , O and OH , which initiate chain-branching reactions. We can expect that the radicals which are important for ignition chemistry, the mixing process between the hot exhaust and the fresh lean mixtures, turbulence, and strain rate all affect the ignition process.

Among the very limited studies we could find in the literature [10,11,12,13,14,15,16], Chen *et al.* [11] is among the first to study turbulent hot jet ignition. It was found that the formation of the large-scale eddy structure of turbulent jets is influenced first by vortex pairs; these eddy structures dominate the external features of the jet.

Yamaguchi *et al.* [12] investigated the effect of nozzle diameter in a divided chamber bomb. Their results show that a smaller nozzle diameter resulted in “well-dispersed burning”, the larger nozzle diameter resulted in “flame kernel torch ignition”, and the largest nozzle diameter enabled laminar flame to pass through the nozzle. Sadanandan *et al.* [15] studied ignition of hydrogen/air mixtures by a hot jet using a high-speed laser Schlieren and OH-Planar Laser Induced Fluorescence (PLIF) techniques. They observed no OH radicals at the nozzle exit and speculated that possible heat loss through the nozzle walls had a strong influence.

Attard *et al.* [17] performed single cylinder experiment using turbulent jet for wide range of dilution while still maintaining adequate combustion stability. Toulson *et al.* [18] tested spark ignition combustion with natural gas and propane fuels across varying speed and load points at several air to fuel ratios varying from stoichiometric to lean in a single cylinder optical engine. Flame propagation of different fuels were studied at varying engine load conditions. These studies were limited mainly to measuring performance parameters in engine. They do not provide much insight about the physics of jet ignition. Gentz *et al.* [19] studied the effect of nozzle diameter and number of nozzles for combustion of a premixed propane/air mixture initiated by a turbulent jet ignition system using a Rapid Compression Machine. They studied the jet spread and jet Reynolds number effect on ignition. Shah *et al.* [22, 23] carried out CFD simulations to characterize hot jet in inert environment.

These limited studies have shown the great potential of the concept of hot jet ignition for extra-lean combustion. Our knowledge, however, is far from complete. Contradictory results exist. For example, there is disagreement on where ignition most likely occurs: Sadanandan *et al.* [16] observed ignition occurring near the tip of the jet, whereas Elhsnawi *et al.* [14] observed ignition occurring on the lateral sides of the jet. More importantly, no studies have examined the effect of nozzle geometry and the effect of supersonic jets on ignition characteristics. Furthermore, combustion instability in gas engines under ultra-lean operation conditions has not been extensively discussed.

Motivated by these, we developed an experiment that uses a dual chamber design (a small prechamber resided within the big main chamber) to understand the fundamental mechanisms of turbulent hot jet ignition. The primary focus was to find out the physics of jet ignition and governing time scales and length scales affecting ignition behavior. Both high-speed Schlieren photography and OH Chemiluminescence were applied to visualize the jet penetration and ignition processes in the main chamber. Infrared imaging and Schlieren PIV (SPIV) were used to characterize the thermal and velocity fields of the hot jet. The present paper focuses on the ignition mechanisms, the effect of supersonic jets on lean ignition limits, as well as combustion instability. The results show substantial decrease in the lean limit using supersonic jets. Moreover supersonic jets result

in smaller ignition delay time. Supersonic jets create a high temperature zone at the downstream of shock structures. This region initiates ignition in main combustion chamber. Lastly, combustion instability becomes severe at the lean limit conditions. Instability modes are mainly focused at two frequencies, 180 Hz which is the natural frequency of the combustor and 2400Hz, longitudinal mode of flame propagation.

EXPERIMENTAL SETUP

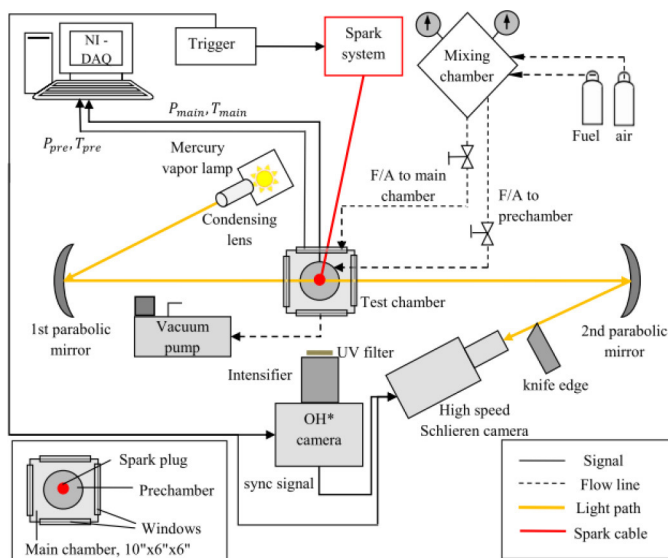
The experimental setup is schematically shown in Figure 1 (a) and (b). A small volume, 100cc cylindrical stainless steel (SS316) prechamber was attached to the rectangular (10" x 6" x 6") carbon steel (C-1144) main chamber. The main chamber to prechamber volume ratio was 100:1.

Table 1. Dimensions of nozzles used in turbulent hot jet ignition experiment.

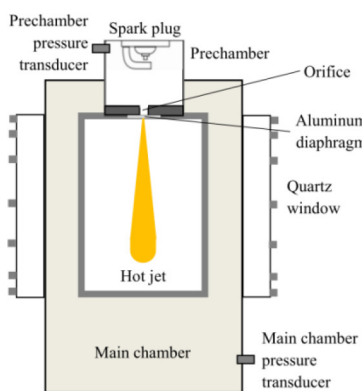
Nozzle #	Type	d_{inlet} (mm)	d_{throat} (mm)	d_{exit} (mm)	A_g/A_t
1	Straight	1.5	1.5	1.5	—
2	Straight	3	3	3	—
3	Convergent	3	—	1.5	—
4	C-D	3	1.5	3	1
5	C-D	3	1.5	4.5	9
6	C-D	3	1.5	7.5	16

A stainless steel orifice plate with various nozzle designs (as shown in Figure 1 (c)) separated both chambers. Jet ignition characteristics of H_2 /air for six different nozzle designs (straight, convergent and convergent-divergent (C-D)) were studied. Nozzle dimensions are tabulated in Table 1 and schematically shown in Figure 1(c).

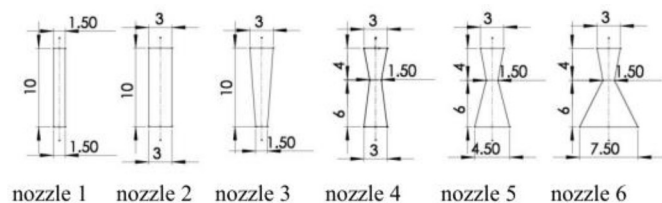
A thin, 0.001" thick aluminum diaphragm isolated both chambers with dissimilar equivalence ratios from mixing. A provision was made to heat up the fuel/air mixture in both chambers up to 600 K using built-in heating cartridges (Thermal Devices, FR-E4A30TD) inserted into the main chamber side and bottom walls. For the present paper, all tests were done at room temperature 300 K. The mixture in the prechamber was ignited by an electric spark created by a 0-40kV capacitor discharge ignition (CDI) system. An industrial grade double Iridium Bosch spark plug was attached at the top of the prechamber. The transient pressure histories of both chambers were recorded using high resolution ~ 5kHz Kulite (XTEL-190) pressure transducers combined with NI-9237 signal conditioning and pressure acquisition module via by LabVIEW software. Two K-type thermocouples were positioned at the top and bottom of the main chamber to ensure uniform temperature lengthwise thus avoiding natural convection or buoyancy effect. A 1" thick polymer insulation jacket was wrapped around the prechamber and main chamber to minimize heat loss. Fuel (industrial grade H_2) and air were introduced separately to the main chamber using the partial pressure method. Unlike the main chamber where fuel and air mixed in the chamber itself, fuel/air in the prechamber was premixed in a small stainless steel mixing chamber (2.5 cm diameter, 10 cm long) prior going into prechamber.



(a).



(b).



(c).

Figure 1. Schematic of (a) experimental setup for ultra-lean ignition of premixed H_2 /air mixtures using a hot turbulent jet generated by prechamber combustion, (b) prechamber and main chamber assembly, (c) different types of orifice/nozzle design, all dimensions are in millimeter.

Diaphragm Assessment

After an electric spark ignites the fuel/air mixture in the prechamber, prechamber pressure starts to rise. Because the volume of the prechamber is very small and the initial flow field is quiescent, combustion in it is very likely to occur through the propagation of a laminar flame. Once prechamber pressure reaches the rupture pressure of aluminum diaphragm, the diaphragm bursts and the pressure difference between pre and main chamber results in a

transient compressible jet with large density ratio with respect to the relatively cold fuel/air mixture in the main chamber. The jet further penetrates into the main chamber and could possibly ignite the mixture in the main chamber under favorable conditions. The jet properties, such as temperature, mean and fluctuating velocities are largely influenced by the prechamber combustion process, orifice geometry.

An accurate assessment of diaphragm rupture time is required in order to calculate precise ignition delay. Ignition delay is defined as the time required from the time of diaphragm rupture to the instant of main chamber ignition. A series of tests were conducted to find out when and at what conditions the thin aluminum diaphragm will rupture. A potential difference of 5V was applied using National Instrument DAQ module (NI-9263) to the aluminum diaphragm via two thin copper wires touching the diaphragm. As the diaphragm ruptured, copper wires lost contact with aluminum. As a result, voltage dropped sharply marking the event of rupture. The rupture time is defined as the time interval between the completion of the electric spark in the prechamber and the rupture of the diaphragm. It was found the rupture time for H_2 /air mixtures to be 2.6 ± 0.1 milliseconds, consistent for all test conditions.

High-Speed Schlieren and OH^* Chemiluminescence Imaging

A customized trigger box synchronized with the CDI spark ignition system sent a master trigger to two high-speed cameras for simultaneous Schlieren and OH^* chemiluminescence imaging. The main chamber was installed with four rectangular (5.5" x 3.5" x 0.75") quartz windows (type GE124) on its sides for optical access. High quality UV transparent (85% UV transmission at 240 nm) quartz windows were used. One pair of the windows was used for ztype Schlieren system. Z-type Schlieren system positions light source, mirrors, test section and camera in a "Z" shape as shown in Figure 1. Another pair was selected for simultaneous OH^* chemiluminescence measurement. The high-speed Schlieren technique was used to visualize the evolution of the hot jet as well as the ignition process in the main chamber. The system consisted of a 100W (ARC HAS-150 HP) mercury lamp light source with a condensing lens, two concave parabolic mirrors (6" diameter, focal length 1.2 m), and a high-speed digital camera (Vision Research Phantom v7). Schlieren images were captured with a resolution of 800 x 720 pixels with a framing rate up to 12000 fps.

The simultaneous high-speed OH^* chemiluminescence measurement provided a better view of the ignition and flame propagation processes. A high-speed camera (Vision Research Phantom v640) camera, along with video-scope gated image intensifier (VS4-1845HS) with 105 mm UV lens, were utilized to detect OH^* signals at very narrow band 386 ± 10 nm detection limit. The intensifier was externally synced with the camera via high-speed relay and acquired images at the same frame rate (up to 12,000 fps) with the Phantom camera. A fixed intensifier setting (gain 65,000 and gate width 20 microseconds, aperture f8) was used all through.