

Experimental Studies of a Liquid Propane Auxiliary Fueled Turbulent Jet Igniter in a Rapid Compression Machine

Gerald R. Gentz and Elisa Toulson
Michigan State University

ABSTRACT

Lean combustion is a promising combustion technology that has the potential to improve engine efficiency while decreasing emissions. One reason why lean combustion has not been more widely implemented is that as the air-fuel ratio increases, the resulting flame propagation speed becomes slower and combustion becomes unstable. Turbulent jet ignition is a pre-chamber ignition enhancement concept that facilitates ultra-lean combustion by using a hot combusting jet as a distributed ignition source. The jet penetration allows for shorter flame travel distances, which decreases the overall burn duration and improves stability. By using a rich mixture in the pre-chamber, the pre-chamber mixture is easily ignitable and the transport of chemically active radical species and unburned fuel into the main-chamber charge improves ignition quality. In this paper a series of experiments are performed in an optically accessible rapid compression machine to demonstrate the extension of the lean limit due to the jet ignition process with auxiliary injection of liquid propane into the pre-chamber. Combustion is characterized by analyzing the pressure traces and optical data generated in each test. Using a pre-chamber pressure sensor, the flow interaction between the main-chamber and prechamber is also explored for different conditions. Combustion visualization using a high speed color camera gives further insight into the turbulent jet ignition process, and allows for comparison between different testing configurations.

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INTRODUCTION

The dependence on foreign oil and new stringent fuel economy standards [1] make the design of an efficient engine a top priority for engine developers. In addition to concerns about fuel consumption, regulations governing acceptable levels of emissions, including particulate matter, unburned hydrocarbons, carbon monoxide, Oxides of Nitrogen (NO_x), and greenhouse gasses such as carbon dioxide make the design of an engine even more challenging [2]. Diluting the initial charge of fuel and air with excess air (lean burn technologies), or recirculated exhaust gas, commonly referred to as Exhaust Gas Recirculation (EGR), is one strategy that concomitantly increases the efficiency of an engine and decreases the formation of NO_x due to the lower combustion temperatures [2]. However, the combustion of highly dilute mixtures and lean burn technology is challenging to implement since as the mixture reactants becomes increasing dilute, the burning speed becomes much slower and combustion starts to become unstable [3]. In this case, ignition enhancement allows for faster burning rates and increased stability either by increasing the ignition energy supplied, and/or distributing the ignition source over many ignition sites [4, 5, 6]. One promising ignition enhancement technology is Turbulent Jet Ignition (TJI) which is a pre-chamber ignition enhancement concept for use in internal combustion engines that uses a distributed ignition source through the use of a chemically active turbulent jet [6]. This reacting jet acts as the ignition source, with a TJI igniter replacing the spark plug in a conventional spark ignition engine. This technology is promising due to its fast burn

rates and the ability to ignite mixtures with increased levels of dilution (lean combustion and/or EGR) when compared to conventional spark ignition [6, 7, 8]. A few of the challenges associated with TJI include the incompatibility of using a three-way catalyst with lean combustion to clean up the exhaust emissions, and the heat transfer losses associated with the extra prechamber volume and surface area [6]. Despite these challenges, the advanced ignition concepts continue to find increasing momentum and renewed interest as the automotive industry attempts to increase dilution levels in order to meet future fuel economy targets. Furthermore, TJI is not fully understood due to the complicated and coupled physics that occur during the ignition process. One fundamental question that arises is how far TJI can extend the lean limit due to the ignition enhancement of the hot, turbulent, reacting jet as it is discharging. Of course, the overall chemistry and stoichiometry is one limiting factor, but other less obvious influences include the nozzle diameter and flow properties of the discharging jet since this will determine the distribution of heat and level of mixing. Also, details of the flow between the pre-chamber and main chamber are often not characterized and the interaction of the discharging jet on the combustion process and resulting pressure trace is not always taken into consideration. Although jet ignition visualization studies have been performed by various authors, including Schlieren imaging [9, 10, 11], direct combustion visualization [12, 13, 14, 15] and laser diagnostics [16, 17, 10], the majority of jet ignition analysis is

derived from the experimental pressure trace. Further visualization studies are needed to help interpret and support the data analysis made from the pressure trace.

The concept of jet ignition was first introduced by Nikolai Semenov in the late 1950's [18, 19]. This led to the pioneering work done by Gussak et al. on the LAG ignition process, which is an acronym for "Avalanche Activated Combustion" [6, 20, 21]. More recent research on jet ignition includes work done by Oppenheim et al. on Jet Plume Injection Combustion (JPIC) [22, 11, 19, 9, 18, 23, 5], and Watson et al. on the Hydrogen Assisted Jet Ignition concept [24, 25].

Turbulent Jet ignition (TJI) is a further refinement of the jet ignition concept for direct application to standard spark ignition engines. Attard et al. has performed extensive engine studies of TJI [26, 7, 8, 27, 28, 29, 30], including a visualization study of TJI in a single cylinder optical engine using natural gas at several air to fuel ratios and engine speeds [13], as well as demonstrating successfully that vaporized gasoline is a viable pre-chamber fuel [29].

The purpose of this paper is to study some of the fundamental aspects of turbulent jet ignition and build upon the authors' previously published work on the subject [14, 15, 31]. This is accomplished by performing a series of experiments in an optically accessible rapid compression machine (RCM) using gaseous propane as the main chamber fuel and liquid propane as the auxiliary fuel. The experimental lean limit without any auxiliary injection is first presented, and then when using auxiliary injection the lean limit extension is demonstrated. Combustion characterization is then performed by analyzing the pressure traces for each test. Using a pre-chamber pressure sensor, the flow interaction between the main-chamber and pre-chamber is explored for different conditions. Combustion visualization using a high speed color camera gives additional insight into the turbulent jet ignition process, and allows for comparison between different testing configurations and further interpretation of pressure trace features.

EXPERIMENTAL METHODS

The experiments presented in this paper were performed in an optically accessible rapid compression machine, shown in Figure 1.

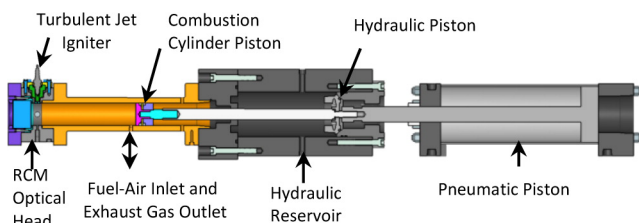


Figure 1. RCM schematic with the combustion chamber highlighted

A RCM uses a single mechanical stroke of a piston in order to rapidly compress and heat a charge of fuel and air to engine relevant temperatures and pressures. The RCM used consists of three separate

pistons that are mechanically coupled together on the same rod, which allows the high pressure hydraulic fluid in the hydraulic reservoir to act as a holding pressure while also allowing the driving force from the pneumatic piston to be transferred to the combustion cylinder piston. Band heaters are used to pre-heat the combustion chamber walls to simulate the temperature of an engine cylinder head, nominally 80°C. In order to maintain a uniform temperature and to prevent heat transfer to the surroundings a high temperature insulating jacket is used. A 50.75 mm diameter fused silica optical window is installed onto the combustion chamber to give an unobstructed view of the entire cylinder bore for combustion visualization. To acquire main chamber pressure data, a type 6125C Kistler piezoelectric pressure transducer is installed into the bottom of the combustion chamber. A Kistler type 6117BFD17 spark plug and pressure sensor combination is used to acquire the pre-chamber pressure data. LabVIEW software is used for high speed data acquisition of the pressure trace, generation and acquisition of the control signals, and control of the band heaters. A Photron SA4 high speed color camera coupled with a Nikon 50 mm f/1.2 objective lens was used to directly visualize the combustion process with the camera frame rate set to 10,000 frames per second.

Figure 2 gives a cross sectional view of the TJI igniter assembly installed onto the RCM optical head with the components labeled. The pre-chamber adapter body is a two-piece design that clamps together. The top piece of the adapter body is the mounting location for the fuel injector and spark plug, while the bottom piece contains the pre-chamber cavity and an interchangeable nozzle that threads into the bottom. For the experiments performed in this paper, a single orifice nozzle with a diameter of 1.5 mm was used.

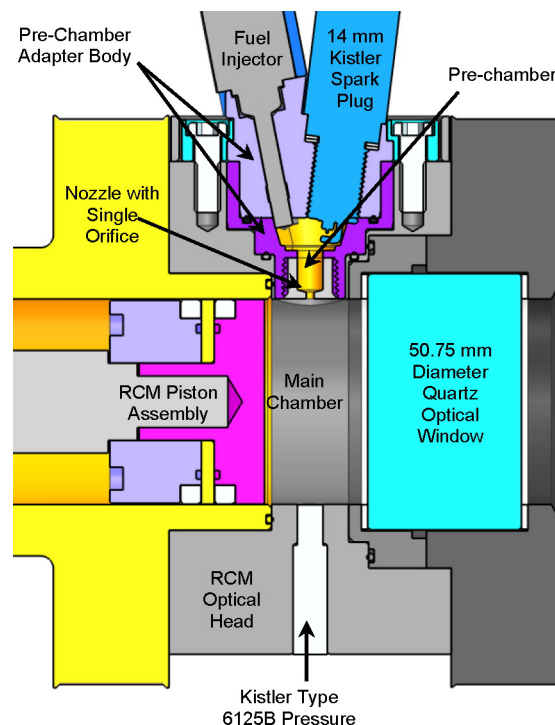


Figure 2. Cross-section showing TJI Igniter geometry installed in the RCM optical head.

The fuel injector clamps onto the pre-chamber using a mounting block. The spark plug with the integrated pressure sensor threads onto the pre-chamber adapter body and seals using a crush washer. The pre-chamber volume has an elliptical shape near where the spark plug, pressure sensor, and fuel injector are located, while the geometry is cylindrical in the portion of the pre-chamber near where the nozzle is installed. 3D renderings of the pre-chamber assembly are given in Figure 3 to give the reader a better visualization of the pre-chamber geometry.

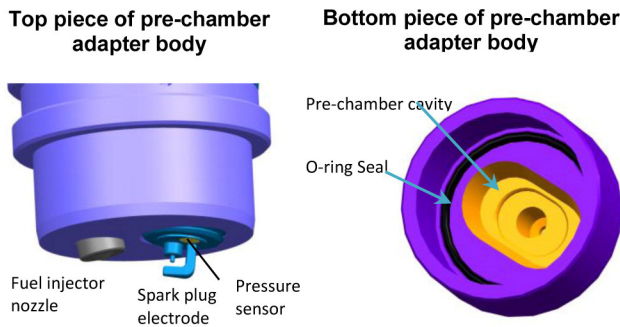


Figure 3. 3D rendering of pre-chamber assembly components showing pre-chamber geometry, fuel injector nozzle, spark plug electrode, and pressure sensor location.

Liquid propane is used for the auxiliary fuel. Propane is naturally in the gaseous phase at room temperature, and has a relatively low saturation pressure compared to other fuels (951 kPa at 298K). Thus, in order to change the state from a gas to a liquid, an expandable bladder system was used to pressurize the gaseous propane past the saturation pressure to 965 kPa. To determine the injected mass, a calibration of the fuel injector was performed with the cylinder heated up to the operating condition of 80°C by pulsing the injector into the RCM at atmospheric pressure and using a pressure sensor to measure the incremental pressure increase due to the injection event. Pulse widths from 2 ms to 15 ms were used, and three data points at each pulse width were obtained in order to show linearity and repeatability. Since the liquid propane will evaporate as it is injected into the RCM cylinder, the injected mass can then be calculated from the ideal gas law. The calibration curve for the fuel injector is shown in Figure 4. The details of the RCM and TJI set-up are summarized and given in Table 1.

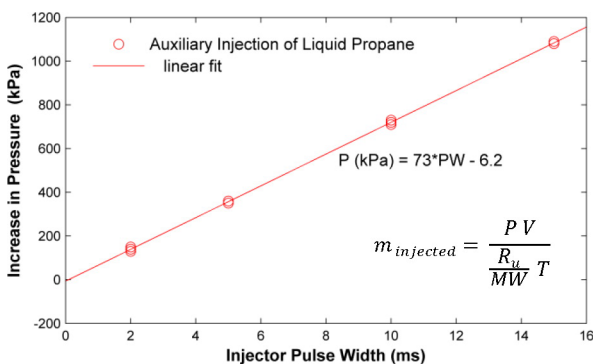


Figure 4. Auxiliary fuel injector calibration.

Table 1. Overview of RCM set-up and experimental details

Cylinder Wall Temperature	80° C
Compression Ratio	8.51
Cylinder Capacity	459.33 cm ³
Clearance Volume	53.91 cm ³
Piston Stroke Length	203.2 mm
Cylinder Bore	50.5 mm
Compressed pressure at TDC	1500 kPa
Fuel used	Instrument Grade Propane (99.5% Purity)
Auxiliary fuel	Liquid propane
Auxiliary fuel injector	Audi Direct Injector, OEM pin: 079906036C
TJI pre-chamber volume	2.35 cm ³
Nozzle Orifice Diameter	1.5 mm
Orifice length	3.0 mm
Electrical Ignition System	Conventional inductive discharge
Power Supply Voltage	13.5 V
Ignition Coil Dwell Time	5 ms
Spark Plug and Pre-Chamber Pressure Sensor	Kistler Type: 6117BFD17 (14 mm spark plug with pressure sensor mounted next to spark plug electrode)
Main chamber pressure sensor	Kistler Type: 6125C

In general, the following procedure was followed to perform the experiments. Before testing, the RCM cylinder walls were set to preheat to 80° C to simulate the temperature of an engine block. Prior to each test the cylinder was evacuated of all residual gases using a vacuum pump. The partial pressures for fuel and air for the desired RCM main chamber λ were calculated, and the RCM cylinder was then filled to the correct partial pressure of propane, followed by the partial pressure of air. Since there is initially a vacuum, and the TJI pre-chamber is connected to the main chamber via the nozzle/orifice, the propane molecules are distributed throughout both chambers. The partial pressure of propane is small relative to the amount of air that is added, thus when filling the cylinder with air to near atmospheric pressures, the fluid motion mixes the reactants so that they can be considered pre-mixed. After the charge preparation is complete, a valve connecting the RCM cylinder to the vacuum manifold and supply gasses is then closed. The next steps in the testing process involve preparing the RCM to fire, and this preparation time gives the fuel-air charge in the RCM cylinder and TJI pre-chamber further time to pre-mix thoroughly. The hydraulic chamber is pressurized by manually pumping the reservoir with hydraulic fluid. This acts as the