

Combustion Visualization, Performance, and CFD Modeling of a Pre-Chamber Turbulent Jet Ignition System in a Rapid Compression Machine

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ABSTRACT

Turbulent jet ignition is a pre-chamber ignition enhancement method that produces a distributed ignition source through the use of a chemically active turbulent jet which can replace the spark plug in a conventional spark ignition engine. In this paper combustion visualization and characterization was performed for the combustion of a premixed propane/air mixture initiated by a pre-chamber turbulent jet ignition system with no auxiliary fuel injection, in a rapid compression machine. Three different single orifice nozzles with orifice diameters of 1.5 mm, 2 mm, and 3 mm were tested for the turbulent jet igniter pre-chamber over a range of air to fuel ratios. The performance of the turbulent jet ignition system based on nozzle orifice diameter was characterized by considering both the 0-10 % and the 10-90 % burn durations of the pressure rise due to combustion. It was found that the 1.5 mm orifice exhibited the shortest 0-10 % burn duration, which corresponded to the fastest flame initiation. The orifice diameter did not significantly affect the 10-90 % burn duration near stoichiometric air to fuel ratios. In addition to the experimental results, further insight into the combustion process was obtained by performing computational fluid dynamic modeling, which showed similar flame propagation and jet structure.

CITATION: Gentz, G., Thelen, B., Litke, P., Hoke, J. et al., "Combustion Visualization, Performance, and CFD Modeling of a Pre-Chamber Turbulent Jet Ignition System in a Rapid Compression Machine," *SAE Int. J. Engines* 8(2):2015, doi:10.4271/2015-01-0779.

INTRODUCTION

Turbulent Jet Ignition (TJI) is a pre-chamber ignition enhancement method that produces a distributed ignition source through the use of a chemically active turbulent jet which can replace the spark plug in a conventional spark ignition engine. In TJI a hot, chemically active, combusting jet is discharged through one or more small orifices and initiates combustion through a complex coupling of fluid mechanics, thermal effects, and chemical kinetics [1,2,3,4,5,6]. An advantage of TJI is that the ignition process is distributed over the area of the jet, which allows for short flame travel distances and very fast burn rates [1]. TJI is also promising for improving the efficiency of SI engines due to the potential for knock mitigation, since the end gas that typically causes engine knock can be burnt first by the impinging jet before it has a chance to auto ignite. This also allows the fuel octane requirement of an engine to be lowered [5]. Some potential challenges with using this technology include purging the pre-chamber cavity of residual gasses as well as optimizing the combustion process to offset losses associated with the additional pre-chamber volume and surface area [1, 5].

Due to the complicated physics and chemistry involved, the TJI process is not fully understood and further effort is needed to characterize the combustion processes that occur. Visualization of combustion can lead to insight into the fundamental processes of TJI such as flame speed, flame structure, and ignition zones. These images can then be used to help interpret the experimental data. Furthermore, Computational Fluid Dynamic (CFD) modeling can also be used to simulate the combustion initiation due to TJI and provide further insight into the TJI process.

Previous studies have investigated TJI by employing various means of observation, experimental testing, and numerical modeling; however few visualization studies have been published. Lumsden and Watson [7] obtained optical images of jet ignition in an optically accessible engine using hydrogen as a pre-chamber fuel. Attard, Toulson et al. [8, 9] provided further combustion visualization comparing Spark Ignition (SI) and TJI in another optically accessible single cylinder engine showing the lean limit extension provided by TJI. Hensinger et al. [10] used Schlieren imaging of hot combustion

products discharging through an orifice into a combustion vessel filled with air, thus observing the mixing of the jets without combustion. Sadanandan et al. [11] also used Schlieren imaging along with laser induced fluorescence to study the mixing of a hot gas jet impinging into an unburned hydrogen/air mixture. In this case the Schlieren images show the ignition zones, but the entire flame structure is not entirely clear. Chinathambi et al. [12] obtained gray scale images of a traversing jet of reacting gas in a constant volume combustor. Ignition was identified based on intensity thresholding, and an edge finding algorithm was used to extract information on the flame structure and flame velocity from the captured images. Additionally, Murase et al. [13, 14] used high speed imaging, Schlieren Imaging, and planar-laser induced fluorescence to visualize the combustion initiation of a methane/air mixture due to a jet of reacting combustion products discharging through an orifice. The effects of different orifice diameters and cavity volumes on the combustion performance were also investigated.

The purpose of this paper is to gain a better understanding of the TJI process by studying how the orifice diameter in a turbulent jet igniter affects the combustion performance of a TJI system. This is accomplished by visualizing the transient ignition process by using a high speed camera, obtaining quantitative pressure data, and using CFD modeling to simulate TJI in a Rapid Compression Machine (RCM).

EXPERIMENTAL METHODS

Experimental testing of the TJI system was performed in an optically accessible RCM. The RCM uses the mechanical stroke of a piston to rapidly compress a charge consisting of fuel and air to an elevated temperature and pressure necessary for ignition. A thorough description of the operating principles and design features of the MSU RCM is provided by Allen et al [15, 16]. Figure 1 shows a schematic of the main components of the RCM including the optical head, combustion chamber, piston assembly, hydraulic chamber, and pneumatic chamber and Table 1 gives an overview of the important experimental parameters. Before each test, the entire combustion chamber is evacuated using a vacuum pump. Following this, the desired amount of gaseous fuel and air is added to the main combustion chamber and also flows into the pre-chamber of the igniter through the orifice connecting both chambers. Propane from a compressed gas cylinder was used as the fuel for the entire set of experiments. Absent from the schematic are several thermocouples that are used to continuously monitor the chamber wall temperature as well as the electronically controlled band heaters that maintain the temperature. In order to simulate the typical operating conditions of a combustion device, the temperature of the chamber walls was set to be 80 °C. A high temperature thermal insulation jacket was also used to prevent heat losses.

Figure 2 shows an enlarged section view of the RCM optical cylinder head. The turbulent jet igniter, a Kistler 6125C piezoelectric pressure transducer, and a 50.8 cm diameter fused silica optical window are all installed onto this component. When the piston has reached the end of its stroke length, the combustion chamber is defined by the disk shaped volume created by the flat face of the piston, the optical window, and the RCM cylinder head. The turbulent jet igniter itself is

composed of a steel adapter body, a spark plug, and a nozzle (with single orifice) that threads into the bottom of the adapter. The internal volume in the turbulent jet igniter when these components are assembled is termed the pre-chamber, which is 1 cm³ and approximately 2 % of the RCM compressed volume.

The ignition system also includes an inductive ignition coil, power supply, and an ignition triggering circuit. The power supply delivers a constant 13.5 V to the triggering circuit. When a 5 V triggering signal with a dwell of 5 ms is sent to the triggering circuit, the primary voltage is turned on/off in the ignition coil inducing a high voltage in the coil which produces a spark across the spark plug electrode. The triggering signal is programmed to be sent 6 ms after the piston has reached top dead center to ensure constant volume combustion. The spark creates a flame kernel that propagates throughout the pre-chamber until it reaches the nozzle, where the flame is mostly extinguished as it passes through the small orifice, creating a high velocity, turbulent jet of radical species that initiates combustion in the main chamber of the RCM.

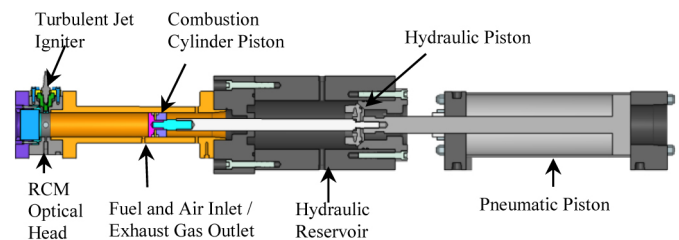


Figure 1. RCM schematic showing the optical head, combustion chamber, hydraulic chamber and pneumatic piston

Table 1. Overview of Experimental Set-Up

Cylinder Wall Temperature	80 °C
Compression Ratio	8.51
Cylinder Capacity	459.33 cm ³
Clearance Volume	53.91 cm ³
Piston Stroke Length	20.32 cm
Cylinder Bore	5.05 cm
Fuel used	Propane
TJI pre-chamber volume	1 cm ³
TJI Nozzle Orifice Length	3 mm
TJI Nozzle Diameters	1.5, 2.0, 3.0 mm
Electrical Ignition System	Conventional inductive discharge
Power Supply Voltage	13.5 V
Ignition Coil Dwell Time	5 ms
Spark Plug	NKG CR6F

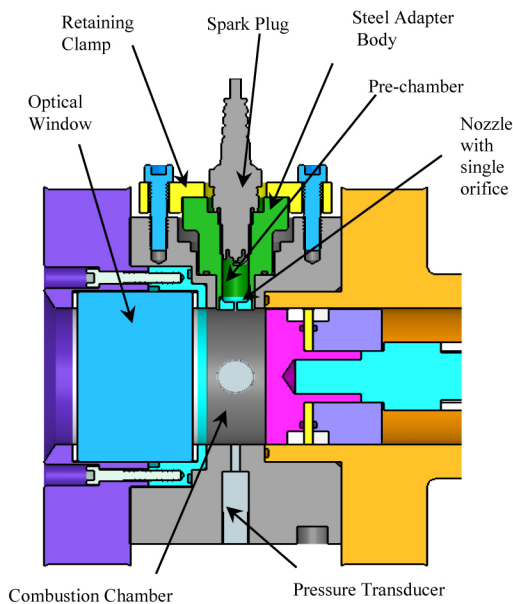


Figure 2. Enlarged sectional view of the RCM optical head with turbulent jet adapter installed

A Photron SA4 high speed color camera with a Nikon AF-S VR Micro-Nikkor 105 mm objective lens was used to image the combustion in the main chamber of the RCM through the 50.8 cm diameter end window, giving a complete two-dimensional view of the combustion chamber. The frame rate (FR) of the camera was operated at 10,000 frames per second and the shutter speed was operated at the minimum speed of $1/\text{FR}$ in order to capture the maximum amount of light. The images were captured at a resolution of 512×512 pixels, where the physical size of each pixel is approximately 0.019 cm^2 . The brightness and contrast of the images were enhanced for visualization purposes in order to clearly see the initial flame development.

The turbulent jet igniter was used to initiate combustion in the constant volume combustion chamber of the RCM for a range air to fuel ratios (AFR) given by the variable λ , where λ is defined as the actual AFR of the mixture divided by the stoichiometric AFR. In order to study the effect of the nozzle geometry, three different single orifice nozzles were tested with orifice diameters of 1.5 mm, 2 mm, and 3 mm. The orifice length was held constant for all diameters, with the length being 3 mm.

EXPERIMENTAL RESULTS AND DISCUSSION

High Speed Visualization of Turbulent Jet Ignition and Conventional Spark Initiated Combustion

High speed images of the TJI and SI combustion processes were obtained in order to study the temporal and spatial development of the jet for different nozzle configurations and AFR conditions. Figure 3 shows combustion visualization for SI at $\lambda=1$. Figures 4 and 5 show combustion initiated by TJI at $\lambda=1$ and $\lambda=1.25$, respectively. The time scale of TJI is nearly an order of magnitude faster than for the baseline SI case. For TJI, the turbulent jet ignites the main charge near the center of the combustion chamber and then propagates downward and outward prior to consuming the charge that is closest

to the orifice. This characteristic may contribute to the reduction in knock propensity that is seen in spark ignition engines with TJI, as the end gas is burned rapidly before having time to autoignite [5]. The jet speed was found to be inversely proportional to the orifice diameter as the nozzle with the smallest diameter had the fastest jet velocity and penetrated furthest into the chamber before igniting the main charge.

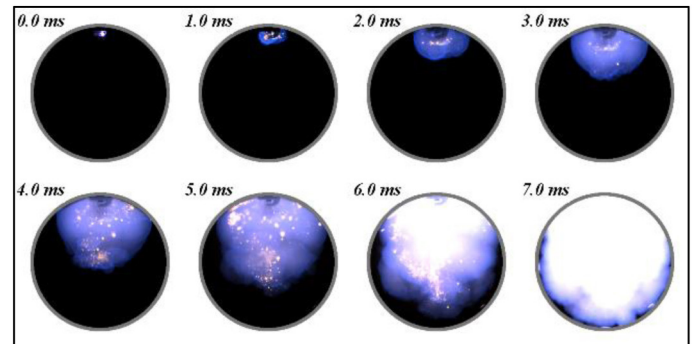


Figure 3. Combustion visualization of spark ignition in the main chamber of the RCM for a stoichiometric air to fuel ratio $\lambda=1$

Combustion Performance Based on Pressure Trace Data

One of the fundamental measurements of combustion that can be obtained in a RCM is a pressure trace. Quantitative parameters can then be defined as a function of the pressure rise to characterize the combustion. Figure 6 shows a typical pressure trace of TJI obtained in the MSU RCM. The initial pressure rise is due to the piston compressing the charge. 6 ms after reaching the end of the compression stroke, the spark plug fires inside the igniter leading to combustion initiation and a pressure rise due to the combustion event. Thus, the total pressure rise is equal to the pressure rise due to compression and the pressure rise due to constant volume combustion in the main chamber. In all cases the time datum was zeroed to correspond to the spark timing. Two combustion parameters, based on a similar analysis performed by Shiga et al. [17], were defined to be the 0-10 % burn duration of the pressure rise due to combustion, which gives an indication of flame initiation, and the 10-90 % burn duration of the pressure rise due to combustion, which characterizes the flame propagation speed.

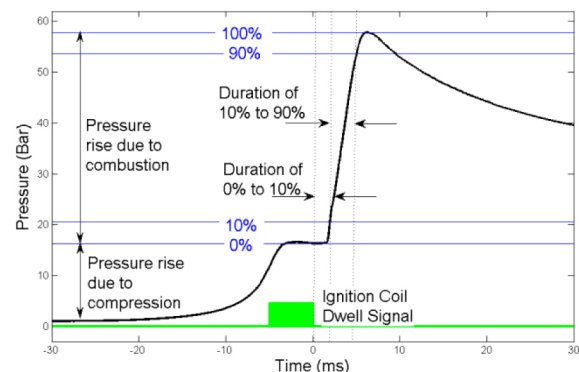


Figure 6. Typical pressure trace with annotations showing the derived combustion performance parameters and spark timing