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Research paper

A study of the influence of orifice diameter on a turbulent jet ignition system through combustion visualization and performance characterization in a rapid compression machine

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HIGHLIGHTS

- The influence of orifice diameter on a pre-chamber turbulent jet ignition system was studied.
- High speed imaging of the turbulent jet ignition process was performed.
- Pressure data was collected to compare the combustion performance of different nozzles.
- Small nozzle orifice diameter was found to be advantageous to combustion initiation.

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ABSTRACT

Turbulent Jet Ignition is a prechamber initiated combustion system that can replace the spark plug in a standard spark ignition engine. The nozzle orifice is critical in a turbulent jet ignition system as it determines the shape and structure of the jet which acts as a distributed ignition source. In this paper, the effect of nozzle diameter and number was studied by performing combustion visualization and characterization for combustion of a premixed propane/air mixture initiated by a turbulent jet ignition system in a Rapid Compression Machine. Color images of the jet ignition process and visualization of the emission of the chemiluminesence of OH^* and CH^* radicals were performed. Several nozzle configurations were tested which expanded on the limited experimental results that were available in the literature. The performance of the turbulent jet ignition system based on the nozzle orifice diameter was characterized by considering the 0–10% and 10–90% burn durations of the pressure rise due to combustion. In general it was found that for near stoichiometric air to fuel ratios, a nozzle that produced more spatially distributed jets would result in faster combustion progression. However, at leaner conditions a smaller diameter nozzle that produced a faster and more vigorous jet was required to initiate combustion. The Reynolds number of the discharging jet for the single orifice cases was calculated and it was found that increasing the nozzle diameter increased the Reynolds number, and thus the turbulence for $\lambda = 1$. The Reynolds number was not found to be sensitive to orifice diameter at the leaner condition of $\lambda = 1.25$. Further characterization of the jet development leads to the conclusion that the jet was considered to be in the intermediate flow field, where the transient jet does not have enough time to become fully developed before it reaches the combustion chamber wall.

1. Introduction

Turbulent Jet Ignition (TJI) is a prechamber initiated combustion system that can replace the spark plug in a standard spark ignition engine. Most TJI systems consist of a prechamber and main chamber connected with one or more small orifices. Generally,

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combustion is initiated in the prechamber using conventional Spark Ignition (SI), which causes a high pressure increase and forces the hot products of combustion to discharge through one or more small orifices into the main chamber, which is ignited through a complex coupling of turbulence generation, chemical kinetics, and thermal effects [1]. Turbulent jet ignition enables very fast burn rates due to the ignition system producing multiple, distributed ignition sites, which consume the main charge rapidly and with minimal combustion variability. The fast burn rates allow for increased levels of dilution (lean burn and/or EGR) when compared to conventional spark ignition combustion [2,3].

Some TJI systems supply a fuel-rich mixture to the prechamber in order to easily ignite the prechamber charge, which has been shown to extend the overall lean limit of the entire combustion system [2,4]. Other TJI systems have unfueled prechambers and use the same air/fuel mixture in the main chamber and prechamber, which reduces complexity [5]. Due to the complicated physics and chemistry involved, TJI is not yet fully understood and further effort is needed to fully characterize the fundamental processes that occur when initiating combustion. In particular, the orifice number and diameter are extremely important to any TJI system and their influence on the transient jet development is worthy of further study.

Previous studies have investigated TJI and the influence of nozzle geometry by employing various means of experimental testing [6–8], numerical modeling [9,10], and Schlieren imaging [7,9,11]; however few other visualization studies have been published, and there is no comprehensive overview in the literature of how the nozzle geometry affects the TJI process.

Roethlisberger and Favrat [12,13] tested a TJI igniter in a diesel engine that had been converted to operate using natural gas. The nozzle configuration for their experiments consisted of 6 orifices, oriented at approximately 62° from the prechamber axis and was unevenly distributed. Using this arrangement of orifices, four different orifice diameters were tested: 1.41 mm, 1.73 mm, 2.00 mm, and 2.24 mm. By examining pressure data, it was generally found that a small total nozzle cross-sectional area was advantageous for jet penetration and combustion initiation. However, there was a limit to how small the orifice could be reduced before the occurrence of ignition failure, which was theorized to be due to an increase in turbulence intensity at the ignition point.

Murase and Hanada [11] obtained Schlieren images and images of OH fluorescence of their Pulsed Flame Jet (PFJ) system in a constant volume combustion chamber using single orifice nozzles with diameters of 1.25 mm and 4.00 mm. They showed that the OH fluorescence area was observed inside the jet as well as at the periphery, which supports the idea that combustion occurs volumetrically due to the active radicals that initiate combustion. They also found that the smaller 2.5 mm diameter orifice produced a faster pressure rise than the larger 4.0 mm orifice. The same system was also tested in a rapid compression machine in order to demonstrate that PFJ could be used to initiate auto ignition of a lean air/fuel mixture [14]. A high speed camera was used to capture images of the combustion initiated by the turbulent jet as it discharged through the orifices. The images illustrated that jet shape was quite different for the two nozzle diameters, with the smaller 2.5 mm orifice producing a profile that was more sharp and thin relative to the larger 4.0 mm orifice.

Oppenheim et al. [6–8] experimentally tested a Jet Plume Injection and Combustion (JPIC) system that operates using essentially the same principles as TJI. The JPIC system operates by first injecting fuel into the prechamber which displaces some prechamber air and fuel into the main chamber creating a jet plume. Next, the fuel-rich mixture in the prechamber is ignited using a spark plug and the hot products of combustion exit through a small orifice to initiate combustion in the jet plume structure that is present in the main chamber. Single orifice nozzles having diameters of 2.5 mm, 4.0 mm and 6.0 mm were tested. In addition, a triple orifice nozzle was tested (3 × 1.44 mm), having equivalent cross sectional area to the single 2.5 mm diameter orifice. The minimum orifice diameter that operated satisfactorily was determined to be 2.5 mm. Using an orifice diameter of 2.0 mm, the system performed unreliably which was thought to be a result of excessive quenching of the jet at the nozzle exit. The triple orifice nozzle (3 × 1.44 mm) had the best combustion performance as evaluated from the pressure rise rate and pressure amplitude. From the Schlieren images, it was determined that the 2.5 mm orifice created a jet that impinged onto the combustion chamber wall very quickly which was detrimental to the combustion performance due to the heat transfer losses to the cold walls as well as creating a stagnation zone which prevented the jet from entraining unburned mixture into the jet structure. The Schlieren images also showed that the triple orifice nozzle produced jets that distributed the ignition source throughout most of the volume of the combustion chamber with less of the detrimental wall effects as shown in the single orifice case.

Sadanandan et al. [9,10] studied the TJI process in an optically accessible constant–volume combustion chamber. Their experimental setup allowed them to vary the pressure ratio across the nozzle by mounting the spark plug in the prechamber different distances from its orifice. Several different orifice diameters ranging from 0.7 to 1.3 mm were tested. Optical diagnostics included laser Schlieren imaging and OH Laser Induced Florescence (LIF) measurements. Sadanandan et al. emphasized that different orifice diameters and electrode ignition distances lead to different jet velocities and rates of cooling. An important result was that for a 100% ignition probability, the nozzle orifice diameter must increase with an increasing pressure difference in order to decrease the outflow velocity and increase the temperature of the hot jet. A secondary result was that a low OH-LIF signal near the nozzle exit implied quenching of the jet.

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. To accomplish this, a TJI system was tested with several different orifice nozzle diameters and configurations in an optically accessible Rapid Compression Machine (RCM). Quantitative pressure data was gathered in order to compare the relative combustion performance of each orifice diameter. In order to help interpret the pressure data, combustion visualization of the transient ignition process was also obtained by using a high speed color camera. A second high speed camera coupled to an image intensifier was configured to capture the chemiluminesence of OH^* and CH^* radicals. A novel aspect of this paper is the color optical images and radical imaging, which allow for additional observations about the flame structure and ignition zones due to the jet ignition process. The experiments presented in this paper also test a greater range of nozzle diameters and expand on efforts and results of other authors as presented in the literature.

2. Experimental methods

2.1. Rapid compression machine

All experimental testing was performed in an optically accessible RCM at Michigan State University. An 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. For the experiments presented here, the RCM was configured to have a compression ratio of 8.5. Band heaters are used to heat the combustion chamber walls to 80 °C and a high temperature insulating jacket is used to maintain a uniform temperature and to