THE IMPACT OF CYLINDER PRESSURE ON FUEL JET PENETRATION AND MIXING

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ABSTRACT

Investigations of fuel jet penetration and fuel and air mixing are performed in a static piston, pressurized optical engine. The pressure in the cylinder that the gas is injected into is varied to study the effect of the compression process. The engine has the same piston and cylinder geometry as a Cooper-Bessemer GMV-4TF two-stroke cycle natural gas engine. A 14" quartz cylinder section allows the cylinder gases to be radiated with an Nd:YAG UV laser, and imaged with an ICCD camera. Nitrogen gas that is seeded with acetone, which fluoresces in the visible range when irradiated with UV light, is injected through the fuel valves. Two types of fuel injectors are studied, a low pressure (45 psi) and a high pressure (500 psi) gas injection valve. Both fuel injection valves are manufactured by Woodward Governor. Planar laser induced fluorescence is implemented to image fuel concentration within the cylinder at various times during the injection and mixing processes. Spatial standard deviations of the variations of fuel concentration ("unmixedness") and the volume fraction of gas in the flammable range ("mixedness") across the image plane are computed.

INTRODUCTION

Poor in-cylinder mixing processes due to ineffective fuel delivery are believed to be problematic in large-bore, slow-speed, natural gas two-stroke cycle engines. High levels of combustion variability and documented engine performance improvements due to mixing enhancements, such as high pressure fuel injection, support this belief[1]. The natural gas industry operates over 8000 stationary large bore (bore > 35 cm) natural gas engines for natural gas compression on pipelines and power generation. Much of the research in the past 10-20 years on large bore natural gas engines has been aimed at enhancing the mixing process. This includes hardware modifications as well as CFD work. The focus of this project is to advance the current understanding of the fuel injection process and provide data for computational fluid dynamics (CFD) code validation.

Planar laser induced fluorescence (PLIF) is the technique implemented in this work to study fuel injection. Characterization of mixing with PLIF is prevalent in internal combustion engine research[2,3,4,5,6,7,8,9]. In this method the fuel is seeded with a tracer that fluoresces when radiated with laser light. Some tracers that have been used to study air-fuel mixing are acetone, NO, NO_2, and biacetyl. For studying mixing in natural gas fueled engines acetone has emerged as the tracer of choice[7,10,11]. Particles have also been used as tracers to study mixing. When a gas rather than a particle is used as the tracer, the concern over traceability goes away even though the tracer is likely to be of a different molecular weight than the fuel. When two gases are mixed together, the intermolecular forces are much greater than forces from buoyancy or differences in angular momentum. Hiltner and Samimy[7] investigated this issue thoroughly and found that once acetone and natural gas were mixed it was very difficult to "unmix" them.

When acetone is radiated with UV light it fluoresces in the visible spectrum, from about 350-550 nm, with peaks at 445 (violet) and 480 (blue) nm. The maximum absorption occurs between 270 and 280 nm. Lasers which have been used for this application to fluoresce acetone are pulsed Nd:YAGs operated in the fourth harmonic (266 nm) and pulsed excimer lasers (308 nm). Nd:YAG stands for Neodymium Yttrium Aluminum Garnet, the lasing material. The fourth harmonic of the Nd:YAG because of its closer proximity to the maximum absorption band is preferred. The Nd:YAG laser is implemented to produce a very thin, coherent, high energy, small pulse-width sheet of UV light to fluoresce the acetone. The short pulse-width is important so that, effectively, a "snapshot" of the fuel distribution can be taken at select times during the injection process. Generally an intensified charge coupled device (ICCD) camera that is synchronized with the laser pulse captures an image at 90 degrees to the laser sheet.

EXPERIMENTAL APPARATUS AND METHOD

The experimental investigation is targeted for a Cooper-Bessemer GMV-4TF large bore natural gas test engine, housed in the Colorado State University (CSU) Engines and Energy Conversion Laboratory (EECL). The GMV-4TF engine is a 4 cylinder two-stroke cycle, 36 cm (14 in.) bore, 36 cm (14 in) stroke, natural gas engine. The GMV-4TF has a sea level brake power rating of 330 kW (440 hp) at 300 rpm. The engine is nominally operated with spark ignition and cam driven mechanical gas admission valves for fuel injection. Two fuel valves are examined here, which have both been run on the test engine. The two fuel valves investigated are both electro-hydraulically actuated. One is a low pressure valve that operates with a nominal injection pressure of 0.39 MPa (57 psia), and the other is a high pressure valve that operates with an injection pressure of 3.5 MPa (512 psia). Mechanical drawings for the lower portions of both valves are shown in Figure 1. The high pressure valve contains a nozzle to help direct flow in the axial direction. The radial gap between the nozzle inner diameter and the poppet outer diameter is the same as the lift, 0.64 mm. The Woodward Governor Company manufactures both valves. The electro-hydraulic fuel valves described above are after market retrofit technologies. They are designed to facilitate improved engine control and enhance fuel and air mixing.

In this work the fuel injection process is examined using PLIF. A general description of the technique is provided in the introduction. The specific test schematic for the fuel injector investigations is shown in Figure 2. The pulsed Nd:YAG laser is a Spectra-Physics Model LAB-150-10. Operating in the 4th harmonic (266 nm), it produces over 70 mJ/pulse at 10 Hz and a 5 ns pulse width. A Galilean telescope arrangement is used to create a light sheet, which passes through the fuel jet axis of symmetry. A Berkeley Nucleonics Model 555-8 pulse generator orchestrates experiment timing. The pulse generator controls the fuel valve, camera trigger, and both the flash lamp and Q-switch in the laser. The fuel injector driver requires three signals, simulated TDC, simulated speed (encoder), and a trigger/relay. The laser and camera are synchronized. The camera gate opens just before the 5 ns laser pulse is emitted, and closes 20-30 ns after the end of the laser pulse. Fluorescence lifetimes are typically 10-15 ns; therefore, the camera gatewidth encompasses the entire fluorescence event. The camera is a DiCAM-PRO ICCD camera, manufactured by The COOKE Corporation. The camera has 12 bit dynamic range, 1280x1024 resolution, and gate widths down to 3 ns.

A picture of the optical engine is shown in Figure 3. A three dimensional cut-away drawing is presented in Figure 4. The only difference between the GMV-4TF and the optical engine is the flat head. The length of the cylinder was adjusted to maintain the same compression ratio of the GMV-4TF, 8.5.

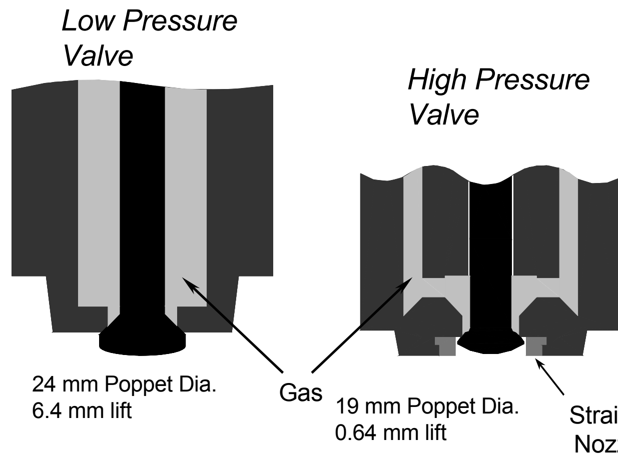

Figure 1 Drawings of low and high pressure fuel valves.

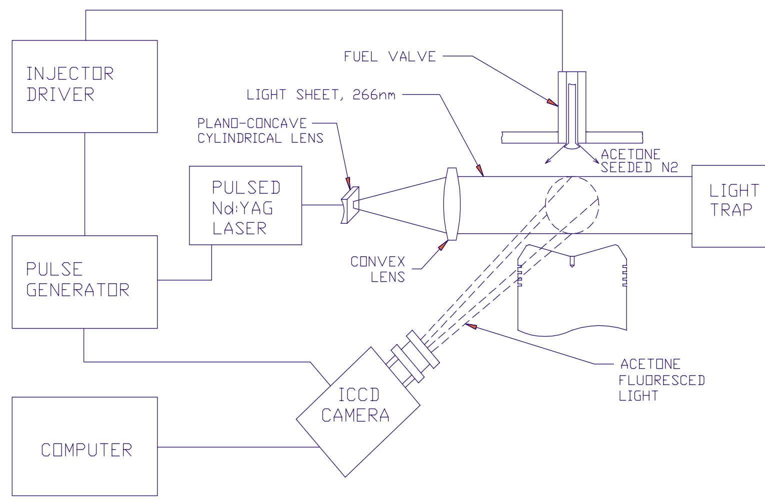

Figure 2 Test schematic for PLIF imaging of injection process.

Figure 3 Picture of 36 cm bore optical engine.

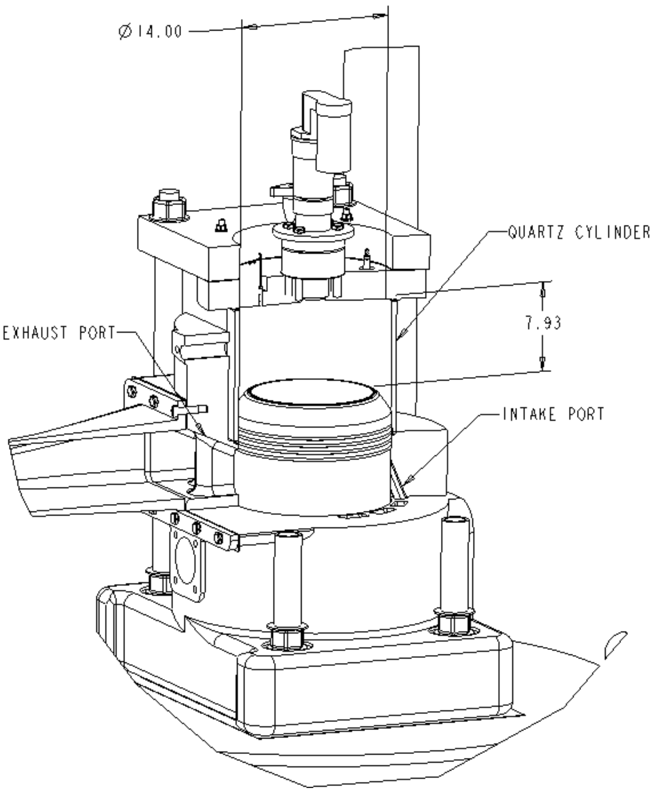

Figure 4 Three dimensional cut-away drawing of optical engine (dimensions in inches).

The flat head (when quartz is used) allows for imaging through the head for future combustion studies. The imaged area is approximately 8x8", or 20x20 cm. This is limited vertically by the presence of the head and the piston. The field of view is limited horizontally by optical effects on the imaged light, excessive refractive error and Brewster's angle of total internal reflection.

For all of the tests performed the gas being injected is nitrogen rather than natural gas. Nitrogen is used to eliminate the possibility of an explosion. Nitrogen is seeded with acetone by bubbling it through a large 25 cm diameter x 150 cm tall tank that is approximately 2/3 full of liquid acetone. The temperature of the liquid acetone and the nitrogen pressure are controlled throughout testing. A higher liquid acetone temperature results in a larger mole fraction of acetone because of an increase in acetone vapor pressure. Larger nitrogen pressures produce smaller mole fractions of acetone in the seeded gas because the acetone vapor pressure is a smaller fraction of the overall pressure. Thus, by varying acetone liquid temperature and nitrogen pressure a wide range of acetone mole fractions can be created. The tubing between the acetone seeding system and the fuel valve as well as the fuel valve are heated to, approximately, 40°C higher than the seeding temperature. This prevents acetone condensation in the lines and fuel valve.

RESULTS AND DISCUSSION

Testing is performed using the optical engine with the piston stationary and 7.0 cm above the top of the exhaust ports. The purpose of the testing is to examine the effect of compression pressure on fuel injection and mixing. Depending on the fuel injection pressure, the injection event can take place at any time during the compression process. In general the fuel is delivered in an operating engine just after port closure to prevent fuel from short-circuiting out the exhaust and to allow for adequate time for mixing to occur prior to ignition. Depending on valve lift, injection durations from 20 to 40 crank angle degrees are utilized for the GMV-4TF engine with the valves being studied in this work. The cylinder pressure at nominal operating conditions varies from 17 to 310 kPag between port closure to 40° after port closure. Based on this, cylinder pressures chosen for this testing are 0, 207, and 310 kPag. These represent possible pressures in the cylinder during fuel injection. A fuel injection duration of 20° is utilized for both valves. This gives a fuel mass delivered per injection event for each valve that is equivalent for nominal injection pressures of 0.31 and 3.4 MPag for the low pressure and high pressure fuel valves, respectively.

The fastest frequency at which PLIF images can be captured is nominally 10 Hz (100 ms period). The fuel injection event takes place in 20°, which corresponds to about 11 ms at an engine speed of 300 rpm. Thus, there is no way to capture successive images, say 0.5 ms apart, from the same fuel injection event. Alternatively, images are captured from different injection events at different times during the injection and mixing processes. The issue of repeatability becomes apparent. This is discussed in detail in other work[12] where fuel injection into ambient air with no cylinder is investigated. It is observed that small scale flow structure, roughly 2 cm or less, varies between injection events. The general shape of the plume and flow structure of scale greater than about 2 cm is consistent between injection events.

Impact of Injecting Nitrogen Rather than Natural Gas

As discussed earlier the gas injected through the fuel valve is acetone seeded nitrogen as opposed to natural gas for safety reasons. Natural gas would normally be injected through the fuel valve in an operating engine. The properties of acetone seeded nitrogen are significantly different than natural gas. To investigate this issue further a "pseudo gas" mixture of nitrogen, helium, and acetone is used. The composition of the pseudo gas can be varied to match various natural gas properties. Images of pseudo gas injection are compared to the injection of acetone seeded nitrogen. Table 1 compares properties of acetone seeded nitrogen, pseudo gas, and natural gas. Acetone seeding of 1% is used for this example. The actual

Gas Mixture→	N2/Acetone	Pseudo Gas	Natural Gas
Composition	99% N2, 1% C3H6O	28% He, 71% N2, 1% C3H6O	Gas Analysis
MW (g/mole)	28.3	21.5	19.1
Ratio Specific Heats	1.38	1.43	1.27
Speed of Sound (m/s)	349	407	407
Mass per injection (g)	1.9	1.7	1.5
Moles per injection (μmole)	67	77	79
Momentum per injection (kg-m/s)	0.66	0.68	0.61

Table 1 Comparison of injected gas properties for three different gas mixtures.

percentage of acetone seeding varies between 0.5 and 4%, depending on the temperature and pressure in the seeding apparatus. The table contains mass, moles, and momentum of injected gas that corresponds to a constant valve open duration and lift. The flow parameters are computed assuming an isentropic flow relation with a flow coefficient of 0.6. The pseudo gas mixture is composed such that it has the same speed of sound as natural gas.

The impact of gas properties on fuel injection is examined by imaging the initial jet development for the first two cases in Table 1 for the high pressure fuel valve. In this case the gas is injected into open air; there is no cylinder surrounding the jet. Qualitatively there is very little difference between the jets. Plume penetration speed is approximately the same, and there is no significant difference in the shape of the jet envelope. Thus, it is unlikely that significant errors will result from using the acetone seeded nitrogen mixture for subsequent studies, particularly those that involve relative comparisons of different fuel valves and cylinder pressures.

A series of images at various times during injection and mixing for the five cases considered is presented in Figures 5 and 6. The cases for the low pressure injector (0.31 MPag) are shown in Figure 5. The cases for the high pressure injector (3.4 MPag) are displayed in Figure 6. For all cases the images near the top of the figures are early in the injection process, while the images at the bottom are toward the end of injection and during post injection mixing. The images are intended to be used for qualitative purposes. In general, intensity is proportional to the mole fraction of the gas injected through the fuel valve. However, the intensity levels in the images are rescaled using different factor for different times during injection to ensure that the injected gas is visible. For quantitative analysis, such as evaluating mole fractions or equivalence ratio, the images would need to be scaled in a consistent manner. The only post processing performed on the images is the subtraction of the background. This process primarily removes reflections. Although still visible, the reflections are much brighter in the raw images. The reflections are probably due to the fact that the cylinder is a full cylinder (as opposed to windows) and very large. They are minimized

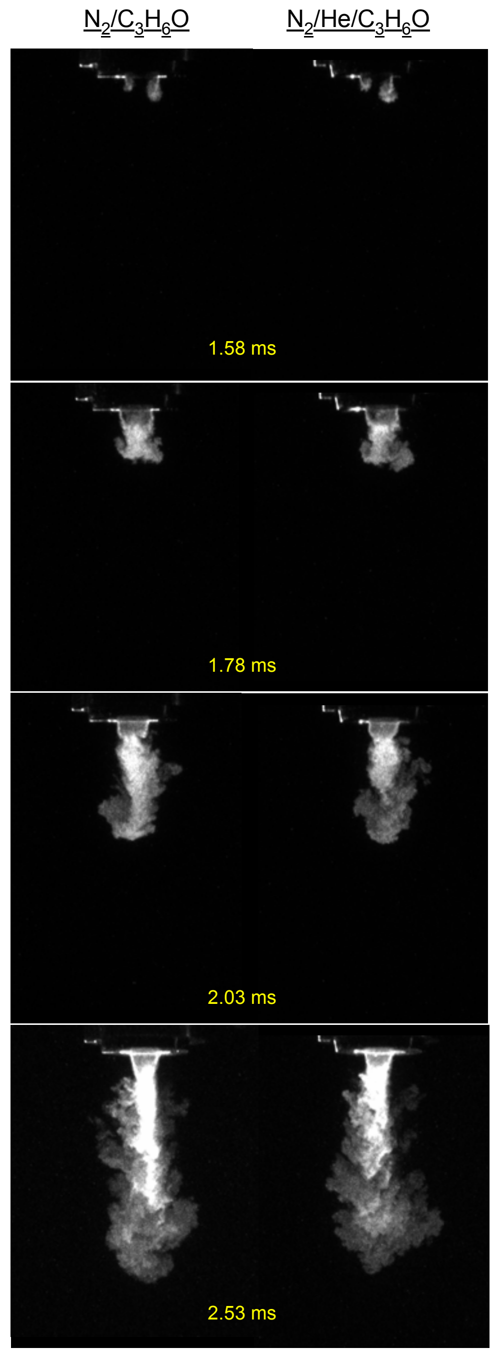

Figure 5 Comparison of high pressure gas jet for two different injected gas mixtures.

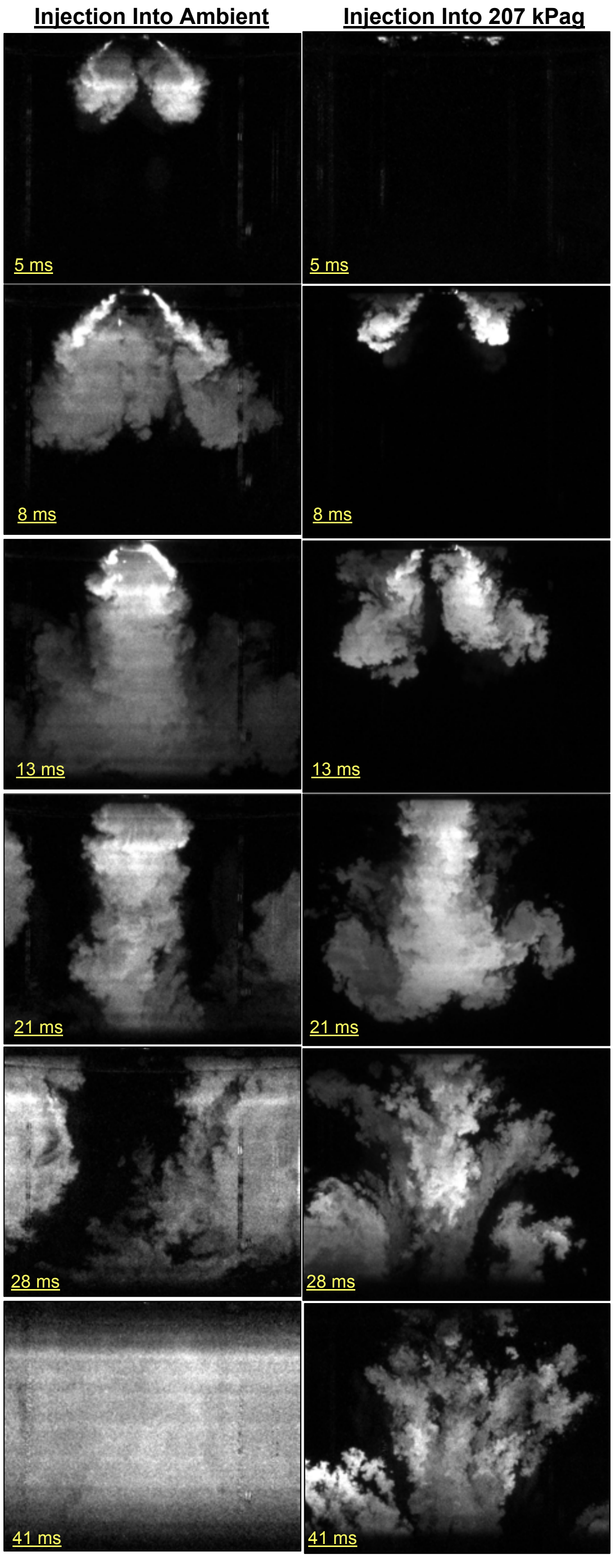

Figure 5 Fuel jet penetration and mixing for low pressure injection.

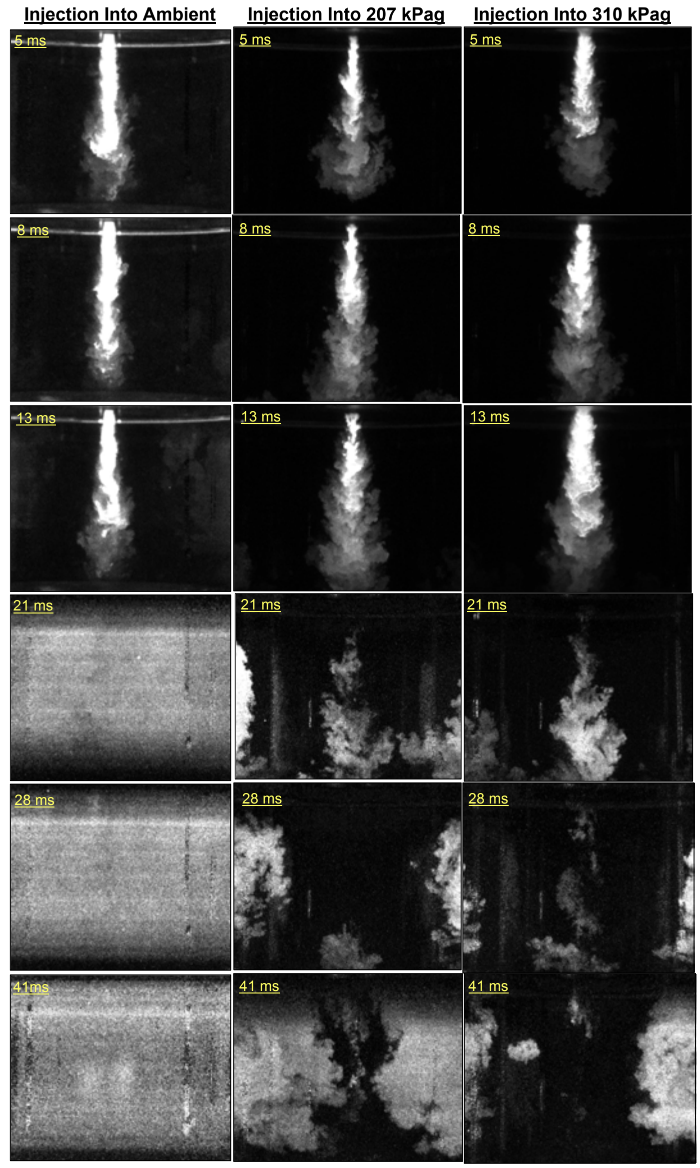

Figure 6 Fuel jet penetration and mixing for high pressure injection.

by eliminating reflective objects near the optical path. The reflections seem to be related to fluorescence of impurities in the quartz and reflections inside the cylinder. They are relatively consistent between injection events and do not affect the interpretation of the data in this work.

Low Pressure (0.31 MPag) Injection

The low pressure injection is affected significantly by cylinder pressure. Images are presented at ambient and 207 kPag (30 psig). Note that a case where the cylinder pressure is 310 kPag (45 psig) could not have been tested, since there would not have been a differential pressure to force gas into the cylinder. Throughout the injection events the plume penetration into the pressurized cylinder is significantly slower. For the ambient pressure case at 25 ms the jet has fully penetrated the cylinder, impinged onto the piston crown, and circulated up the cylinder wall to the head/cylinder interface. At the same time for the 207 kPag cylinder pressure case the plume has impinged on the piston crown but has not circulated up the cylinder wall. This is a dramatic effect and provides insight into what the process might look like during compression. The compression process is likely to significantly reduce plume penetration, dissipate plume kinetic energy more rapidly, and generally inhibit mixing of fuel and air.

High Pressure (3.4 MPag) Injection

Cylinder pressure has a significant effect on high pressure fuel injection as well. Comparing the ambient and 207 kPag cases the plume penetration is seen to be significantly slowed by the higher cylinder pressure. In fact, at 25 ms the ambient pressure case appears qualitatively to be well mixed. In contrast the injected gas in the 207 kPag case appears to be just reaching the head, along the wall, much of it out of the field of view. The jet angle appears, at least initially, to be larger in the 207 kPag case than the ambient case. The differences between the 207 and 310 kPag cases are more subtle and initially appear to be insignificant. It is apparent, however, that jet penetration and mixing are more advanced at 25 ms for the 207 kPag case.

Evaluation of In-Cylinder Mixing

One of the primary focuses of this research is to investigate the in-cylinder mixing process of fuel and air. To do this it is important to perform quantitative as well as qualitative analysis. The spatial standard deviation of image intensity, which is referred to as the degree of heterogeneity or "unmixedness", can be used to quantify the mixing process. It is defined as

$$\alpha = \sqrt{\frac{1}{XY}\sum_{x,y}\left[I(x,y) - I_{mean}\right]^2}$$

where

α = degree of heterogeneity
XY = number of measuring points, or pixels, in the measuring plane
$I(x,y)$ = light intensity at location x,y
I_{mean} = mean intensity over measuring plane

Intensity values in the unprocessed images are 8 bit integers, 0-255.

Mixture heterogeneity vs. time is plotted in Figure 7. Data are plotted from the time when the jet initially develops to the time corresponding to ignition in the engine, about 57 ms. The data are discussed by referring to three distinct regions on the plot, referred to as (1) initial jet development, (2) rapid entrainment, (3) and moderate mixing. During the initial jet development the mixture heterogeneity rises rapidly. Initially there is no fuel in the cylinder and the heterogeneity is low. As the jet develops and more fuel flows into the cylinder the heterogeneity rises because the jet structure is highly ordered and has not had time to entrain the surrounding air. There appears to be a lot of variability in the data in this region, probably resulting from variability in the injection events. Rapid entrainment occurs after most of the fuel is delivered. At this time the fuel has a high level of kinetic energy, impinging on the piston and circulating throughout the cylinder. The heterogeneity falls sharply. Note that there is a clear difference between the two cylinder pressure cases for low pressure injection during this region. However, there is not a clear difference in the rapid mixing During the moderate mixing period most of the mixing has taken place and the general trends are nearly level. The high pressure cases enter this region between 20 and 30 ms. The low pressure data does not display this behavior until between 35 and 45 ms. In the moderate mixing region it is difficult to draw any conclusions from the data. The heterogeneity is very low, and the data seems to be influenced by regions outside the field of view. This is evidence by, in some cases, the heterogeneity increasing as time increases.

Another important aspect of the analysis is the obvious advantage of the high pressure fuel valve. There are two important advantages. First, mixing occurs at a much faster rate in the case of high pressure fuel injection. In the high pressure case the heterogeneity is reduced to less than 10 in less than half the time when compared to low pressure fuel injection. This is expected to be particularly important in a operating engine when compression is occurring during this part of the cycle. In this study it is observed that increasing the cylinder pressure inhibits mixing. By extension it is likely that mixing will be significantly impeded during compression, where the pressure reaches about 2 MPa at spark. Therefore, it is advantageous to establish a uniform mixture early in the compression process while the cylinder pressure is relatively low. The second advantage is the lower mixture heterogeneity seen at spark (57 ms) in the high pressure cases.

SUMMARY AND CONCLUSIONS

An experimental evaluation of the effect of cylinder pressure on gaseous fuel injection has been performed. Images were taken using PLIF at two different cylinder pressures for a low pressure fuel injector and three different cylinder pressures for a high pressure fuel injector. Images were analyzed qualitatively by examining them at different times during the injection process and quantitatively by evaluating a mixture heterogeneity parameter.

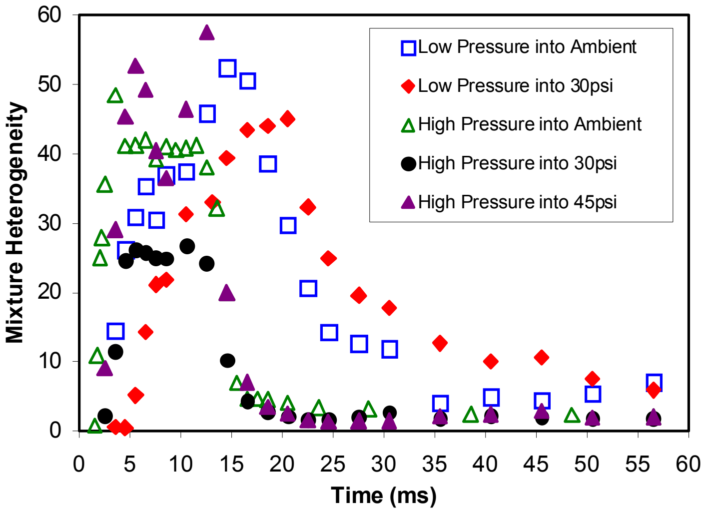

Figure 7 Mixture heterogeneity ("unmixedness") vs. Time from start-of-injection.

Conclusions drawn from this work are as follows:

- In-cylinder pressure, and by extension the compression process, has a significant effect on fuel injection and mixing.
- Low pressure fuel injection is affected much more than high pressure fuel injection by in-cylinder pressure; significantly reduced penetration and entrainment rates are observed for at higher cylinder pressure.
- The resulting mixture heterogeneity at spark is lower for the high pressure injector than for the low pressure injector; on average the high pressure heterogeneity is about 30% of the low pressure heterogeneity.

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