PLIF TECHNIQUE FOR FUEL VISUALIZATION IN ENGINES AND ITS ROLE IN RETROFIT TECHNOLOGY

Evelyn Roberts Levine

Problem

A problem in large-bore, slow-speed, natural gas two-stoke cycle engines is poor in-cylinder mixing processes caused by ineffective fuel delivery. Engines in this class are used primarily for power generation and gas compression on natural gas pipelines. Poor in-cylinder mixing can cause elevated oxides of nitrogen emissions due to thermal stratification, high carbon monoxide and unburned hydrocarbon emissions due to partial combustion, and low engine efficiency.

Experimental Technique

To address the mixing problem, a visualization technique is needed to image the fuel in the cylinder, or combustion chamber. Fuel visualization in the combustion chamber enables the advancement of current understanding of fuel injection and mixing in combustion chambers. A well-suited technique for this is Planar Laser Induced Fluorescence (PLIF). PLIF allows the user to visualize injected fuel flow and the ensuing fuel and air mixing process. A seeded gas (acetone tracer) is used such that, when irradiated with laser light, it fluoresces, enabling the gas mixture to be visible for high-speed photography within an optically accessible combustion chamber.

Facility

The experiments were conducted by Dr. Daniel Olsen and his staff at the Colorado State University (CSU) Engines and Energy Conversion Laboratory (EECL). The EECL was established in 1992 by Dr. Bryan Willson, Director of Research. The Laboratory, originally the Fort Collins Municipal Power Plant built in 1936, is driven by the need to reduce pollutant emissions and increase efficiency from internal combustion engines. The mission of the EECL is to *"facilitate, through research and educational programs, the development of new technologies for reducing the emissions and fuel consumption from engines and energy conversion processes."* The focus of much of the EECL research is on large bore (>35 cm) natural gas engines used for natural gas compression. The EECL houses the new Laser Diagnostics Laboratory (LDL). This state-of-the-art facility is used to visualize in-cylinder phenomena involving air-fuel mixing and combustion processes in large bore engines.

Equipment Used

High and low pressure injection valves (.39 MPa and 3.5 MPa) were used to investigate the effects of injection pressure on charge mixing. The fuel injection and mixing processes are examined utilizing PLIF. The DiCAM-PRO ICCD camera, manufactured by The COOKE Corporation, was used along with a Spectra-Physics Model LAB-150-10 Nd:YAG laser as the basis for the PLIF data collection. The camera offers a 12-bit dynamic range, 1280 x 1024 resolution and gate widths down to 3 ns. The laser operates at 266 nm and produces over 70 mJ/pulse at 10 Hz with a 5 ns pulse width.

DiCam-PRO ICCD Camera

Nimesh Juthani, High Speed Imaging Product Manager at The Cooke Corporation characterizes the DiCam-PRO, “Typically for experiments that require a submicrosecond exposure time in low light conditions, you need an intensified camera that can provide variable gating, accurate synchronization with other equipment, single photon detection sensitivity, and high resolution. The DiCam-PRO meets this criteria with a custom designed gating power supply and high resolution CCD.”

Dr. Olsen characterizes the DiCam-PRO’s suitability for this experiment as follows: “The DiCam-PRO is well suited for this experiment because of its capability to vary gate width and gain, trigger externally, and achieve high resolution. It also provides us with high sensitivity, necessary for planned future experiments to examine combustion intermediates and emissions formation during the combustion process.”

Use of Nitrogen vs. Natural Gas

Nitrogen, rather than Natural Gas, is used as the injected gas for safety purposes, as nitrogen is non-combustible. While the actual properties of acetone-seeded nitrogen are significantly different than natural gas, investigations utilizing fuel injection into open air with various gas mixtures indicate that little variation (due to gas properties) is exhibited via the injection on plume penetration speed, jet shape and dispersion.

Results

Fuel injection investigations were performed in a two stroke cycle optical engine with a 36 cm bore quartz cylinder and a static piston positioned just above the exhaust ports. Testing was carried out with the cylinder at various pressures characteristic of those experienced during compression.

Plume Penetration:
Low-pressure injection is significantly effected by cylinder pressure. The effects are more pronounced on charge circulation than on plume penetration, but are evident on both. Higher cylinder pressure inhibits charge circulation and penetration, as evidenced by less circulation up the cylinder walls. One can conclude that during the compression process, plume penetration and charge circulation will be significantly reduced due to elevated cylinder pressure. Therefore, fuel-air mixing in the chamber will be less complete and less efficient.

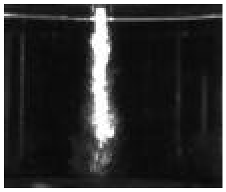
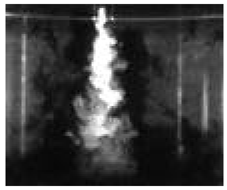
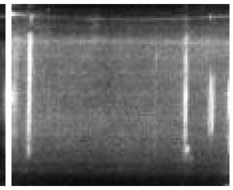
Similar results are observed for the high-pressure injection investigations. Indeed, even the jet angle appears, at least initially, to be larger in the high cylinder pressure investigation than in the low cylinder pressure case. This indicates that higher cylinder pressures cause dispersion of the jet spray, reducing penetration of the jet and potentially inhibiting mixing and combustion efficiency.

In-Cylinder Mixing:
In the initial jet development phase, test data showed high variability in this region (where jet structure is highly ordered and is not sufficiently intermingling with the surrounding air in the chamber). The most likely cause of this variability is from variations in valve actuation.

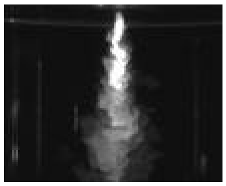
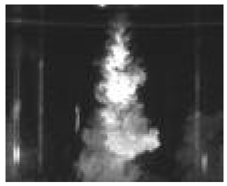
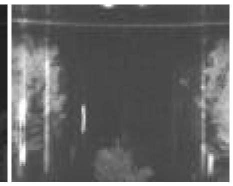
Rapid entrainment occurs after most of the fuel is injected into the combustion chamber. This is a point at which the injection charge has a high level of kinetic energy. It is at this stage that the plume impinges on the piston and cylinder circulation of the charge occurs. Mixing occurs rapidly at this stage and cylinder content homogeneity rises sharply. It should be noted that for the low-pressure injection case, cylinder pressure effects are clearly differentiable via the irradiated seeded gas.

In the moderate mixing phase, most of the fuel-air mixing has taken place. The high-pressure case enters this region significantly ahead of the time that the low-pressure case does. Since the heterogeneity of the cylinder contents is very low at this stage, it is hard to draw any conclusion from this region.

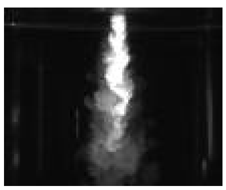
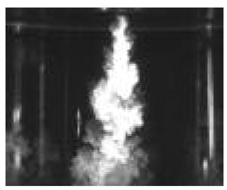
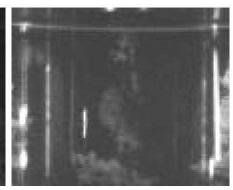
High pressure injection into various in-cylinder pressures

Ambient @ 7ms Ambient @ 15 ms Ambient @ 29 ms

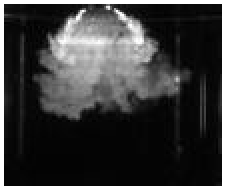
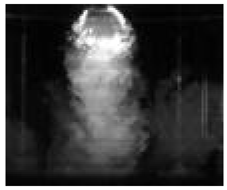
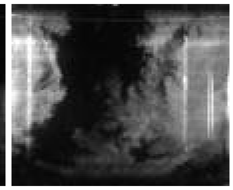




207kPag @ 7ms 207kPag @ 15 ms 207kPag @ 28 ms

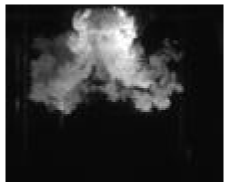
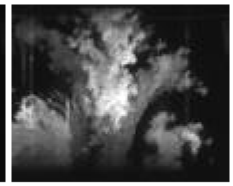




310kPag @ 7ms 310kPag @ 15 ms 310kPag @ 28 ms

Low pressure injection into various in-cylinder pressures

Ambient @ 7ms Ambient @ 15 ms Ambient @ 28 ms

207kPag @ 7ms 207kPag @ 15 ms 207kPag @ 28 ms

Low Pressure vs. High Pressure Fuel Valves
High Pressure fuel valves have two significant advantages over low-pressure valves. Fundamentally, there is more energy available when higher pressures are implemented. Mixing occurs at a much faster rate and lower mixture heterogeneity is seen at the time of spark (ignition.)

Cylinder Pressure
Cylinder pressure has significant effects on fuel injection and mixing in the cylinder. Low-pressure fuel injection is affected more than high-pressure fuel injection by in-cylinder pressure; higher cylinder pressure inhibits and/or reduces injection charge penetration and entrainment rates.

Retrofit technology
Increasing natural gas demand and rigid emission regulations are challenges that the natural gas industry is facing. In 1998 22.0 trillion cubic feet (tcf) of natural gas was consumed in the United States. Forecasted consumption for 2020 ranges from 29.5 tcf in a low economic growth case to 34.8 tcf in a high-growth case. This forecast of a 50% increase in gas consumption coupled with increasingly stringent emissions regulations poses some difficult challenges. One way that these challenges are being addressed is through improvements to existing infrastructure, referred to as retrofit technologies. In large bore engine testing at the EECL, high-pressure fuel injection has been demonstrated to reduce both fuel consumption and pollutant emissions through improvements to in-

cylinder mixing and combustion. The implementation of these types of retrofit technologies can allow more natural gas to be delivered to the end-user while aiding in meeting emissions regulations.

References:

Olsen, Daniel B., Mastbergen, Dan B., and Willson, Bryan D., "Planar Laser Induced Fluorescence Imaging of Gas Injection from Fuel Valves for Large Bore Natural Gas Engines", Proceedings ASME-ICE Fall Technical Conference, Vol. 37-2, Paper No. 2001-ICE-409, 2001.

Olsen, Daniel B. and Willson, Bryan D., "The Impact of Cylinder Pressure on Fuel Jet Penetration and Mixing", Proceedings ASME-ICE Fall Technical Conference, Vol. 39, Paper No. ICEF2002-502, 2002.

The Cooke Corporation
IMAGING

1091 Centre Road, Suite 100,
Auburn Hills, MI 48326-2670
Tel (248) 276-8820
Fax (248) 276-8825
Email info@cookecorp.com
Website www.cookecorp.com