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Development of Innovative Combustion Processes for a Direct-Injection Diesel Engine

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Abstract

In support of the Partnership for a New Generation Vehicle (PNGV) emissions and fuel economy goals, a small-bore, high-speed, direct-injection (HSDI) diesel facility in which to conduct research into the physics of the combustion process relevant to these engines has been developed. The characteristics of this facility are described, and the motivation for selecting these characteristics and their relation to high efficiency, low-emission HSDI engine technology is discussed.

Two candidate technologies for improving the emissions of HSDI diesel engines are evaluated: injection-rate modulation and water injection. The injection rate modulation studies have been conducted in both a diesel combustion simulation vessel and in the new HSDI diesel engine facility, while the water injection studies were conducted in an existing heavy-duty diesel engine facility. Injection rate modulation studies in the diesel combustion simulation vessel provide direct evidence of the increased flame surface area which can be achieved using split injection techniques, with associated potential for increased mixing rates and soot oxidation. Pilot fuel-injection strategies investigated in the HSDI diesel engine demonstrate the effectiveness of these strategies in reducing combustion noise, as deduced from the apparent rate of heat release. Imaging of early flame chemiluminescence has, to date, been only partially successful in elucidating the mechanisms by which these pilot injection strategies affect the ignition and main-combustion processes. The water injection studies have shown that injecting water with the fuel (as an emulsion) can significantly reduce soot formation rates in diesel engines in addition to the well known effect of reducing NO_x by lowering combustion temperatures. Even a modest 10% water emulsion was found to reduce soot volume fraction during the main combustion event by approximately a factor of two. Higher water concentrations (20 and 30%) that would be advantageous for even greater reductions in NO_x were found to produce a further reduction in soot formation, although at a decreasing rate. These results strongly suggest that both split injection and appropriate water injection are viable strategies for breaking the soot- NO_x tradeoff that currently limits HSDI diesel engine design strategies.

Introduction

The engine for the Partnership for a New Generation Vehicle (PNGV) is one of the most critical components for meeting the fuel economy goal of 80 miles per gallon. In FY96, PNGV selected a small-bore, high-speed, direct-injection (HSDI) diesel as the best engine candidate. These engines offer high thermal efficiency, reliability, and compatibility with the existing fuel infrastructure and with projected PNGV vehicle designs. Despite the significant advantages of these engines, meeting PNGV goals will require major technological advances that improve their efficiency, power density, and emissions. These advances include improvements in controlling fuel injection, in-cylinder air motion, combustion, and emissions formation.

At the commencement of this research, state-of-the-art HSDI diesels utilized two valves per cylinder and an angled, off-center, speed-dependent fuel injector. PNGV determined that this configuration is not adequate, and that the base engine configuration must have four valves per cylinder and a vertical, center-mounted, high-pressure, common-rail injector (engines conforming to this specification have been introduced in Europe during the last calendar year). In addition, advanced fuel injection and combustion strategies will be needed. The recent introduction of common-rail fuel injection systems with production intent has made possible consideration of advanced fuel-injection techniques, such as rate modulation and the use of split- and pilot-injection strategies. Additional promising techniques for control of combustion and the reduction of emission are: water injection, enhanced (variable) swirl combustion chambers, exhaust gas recirculation (EGR), and use of alternative fuels.

The goal of this research was two-fold: First, to develop an HSDI engine research facility which embodied the characteristics of the newest HSDI diesel engines currently under development in Europe. It was desired that this facility be capable of handling a wide variety of fuel injection equipment, so as to be able to evaluate the potential of new fuel injection technologies on the emissions performance of these engines. In addition, it was desired to incorporate variable swirl and geometric flexibility, such that the effects of different combustion system designs (bowl geometry, swirl level, injection targeting, etc.) can be easily evaluated. Second, to conduct research into the use of two of the most promising new strategies for controlling combustion and reducing emissions: the use of split- or pilot-injection strategies and the use of water injection (emulsions). These two strategies have been investigated in the most appropriate facilities available within the engine combustion group: the existing heavy-duty diesel engine facility, the existing diesel combustion simulation vessel, and the new HSDI diesel engine facility.

The body of the following report is organized as follows: First, the new HSDI engine facility is described, and the unique features relevant to HSDI research are discussed. Second, the use of split-injections in increasing the flame surface area, and thus, potentially, the mixing rate and soot burn-out rate are presented. This work was performed in the constant volume diesel combustion simulation vessel, where ignition delay studies were also performed. Third, the results of experiments on the use of pilot-injection techniques in the HSDI diesel engine facility are presented. Fourth, the water injection experiments and the implications for soot and NO_x reduction in DI diesel applications are presented and discussed. Finally, the major conclusions of the work are summarized.

The HSDI Diesel Engine Facility

As discussed above, the state-of-the-art HSDI diesel engines suitable for meeting the PNGV fuel economy and emissions goals will be characterized by a four-valve geometry, and a vertical, centrally located fuel injector. The enhanced symmetry of the combustion system achieved with this geometry has been shown to lead to a more uniform bowl velocity field near the time of injection [1], as well as to allow a much more uniform fuel spray distribution as a result of the vertical injector and the accompanying symmetry of the fuel injector nozzle. Additionally, several studies have demonstrated the improvement in fuel consumption, NO_x , HC, and particulate matter [1-3] attendant with four-valve designs. Specification of a four-valve, central injector geometry for the HSDI diesel engine facility was therefore deemed a requirement.

Similarly, a variable swirl capability was deemed a necessity for an HSDI research facility. Full-load smoke and fuel consumption have been shown to be optimized at different swirl levels for different engine speeds in 4-valve prototype HSDI designs [4]. Thus, a swirl ratio which results in good high-speed smoke performance can result in approximately three times the particulate emissions of a swirl ratio giving good low speed performance. Understanding the interaction of physical processes responsible for this behavior, while not a topic of this report, is an aspect of HSDI diesel combustion on which considerable additional research is required.

Additionally, compatibility with current common-rail fuel injection equipment (FIE) was deemed necessary. Common-rail FIE has been shown to result in both better fuel economy and reduced emissions as compared to conventional pump-line-nozzle systems [5,6]. These advantages stem, in part, from the de-coupling of the injection pressure from the engine speed achieved with common-rail technology. Hydraulically-intensified common-rail systems have also been developed [7], which can achieve higher effective injection pressures and have significant safety advantages. These systems require additional features within the engine head to provide internal fuel and hydraulic oil feeds to the injector. Specification of the HSDI diesel engine head thus included compatibility with the two common rail systems available: the Bosch/Fiat Unijet system and the Ganser Hydromag system, as well as with the hydraulically-intensified (HEUI) system developed by Caterpillar.

Because no heads with a 4-valve, central-injector geometry were available commercially, a custom head was designed and procured for the HSDI diesel engine facility by Ricardo, Inc., a firm with extensive diesel engine design experience. The resulting head also incorporated the variable swirl and FIE compatibility features discussed above, as well as additional geometric specifications intended to facilitate computer modeling and mating of the head to the base crankcase. The combustion system (bowl, fuel injection nozzle geometry, and base swirl ratio) was also designed by Ricardo, Inc., and represents the current state-of-the-art. The bore, stroke, and compression ratio were selected to be comparable to typical HSDI passenger car applications. A summary of the important geometric characteristics of the HSDI diesel engine facility is given in Table 1.

In addition to the standard engine specifications discussed above, the HSDI diesel engine research facility is required to have optical access to enable the application of various optical diagnostic techniques to the study of the combustion process. A schematic view of the optical access incorporated into the base engine design is shown in Fig. 1.

Table 1
HSDI Diesel Engine Geometry and Features

Basic Geometry:	Bore	79.5 mm
	Stroke	85.0 mm
	Compression Ratio	19.5:1
	Speed Range	0-4000 rpm
Combustion System:	Bowl Volume	17.3 cm ³
	Bowl Lip Diameter	36.25 mm
	Bowl Depth	15.8 mm
	Re-entrancy	15%
	K-Factor	0.76
	Port Swirl Ratio	1.5-4.0
FIE Compatibility:	Bosch/Fiat Unijet	
	Ganser Hydromag	
	Caterpillar HEUI HI-90	
Target Performance:	Peak IMEP	17.9 bar
	Specific Power	50 bkW/liter

Features to be noted from Fig. 1 include:

1. The optical engine incorporates an extended (Bowditch) piston design, which permits visualization of the combustion process through the bottom of the piston top via a slotted, extended piston and a 45° mirror. The entire bowl volume is visible from this viewing direction.
2. Four orthogonal side windows provide access to the full depth of the bowl for ±30 crank angle degrees about top center. These side windows can be utilized alternately for introduction of laser illumination or viewing.
3. The engine design incorporates a hydraulically supported liner, which can be rapidly lowered to permit cleaning of the combustion chamber windows. Rapid cleaning access is a requirement and an enabling technology to permit meaningful optical measurements to be made in a diesel engine environment.
4. Provision has been made for optical access to the squish volume through replacement of an exhaust valve with an optical window. This feature is incorporated in only one of the two heads procured for the HSDI diesel engine research facility.

Figure 1: Cross section of the HSDI diesel engine showing the optical access.

The HSDI diesel engine laboratory has ancillary systems and instrumentation which enhance the overall research capabilities. A photograph of the engine and laboratory is provided as Fig. 2. These systems include:

1. Provision of high-pressure, dry air to simulate a turbocharged engine. This includes the capability of pre-heating the combustion air to obtain intake air temperatures typical of non-intercooled, turbocharged engines or engines using non-cooled EGR.
2. Critical-orifice flow meters to permit simulation of EGR in the intake charge. Because current HSDI engines can run with over 50% EGR rates, this capability is important to ensure that we have achieved a representative operating condition.

3. Large plenum tanks for both the intake and exhaust flows, which are closely coupled to the head through short runners. These tanks ensure the existence of a constant pressure boundary condition close to the head, and the short (tapered, in the case of the intake runner) runners minimize the complicating effects of pressure wave dynamics in the gas exchange process. The plenums are instrumented for both temperature and pressure, and the intake ports are further individually instrumented for pressure. This plenum/runner geometry and instrumentation will facilitate CFD modeling efforts of the research engine.
4. Controlled coolant temperature to provide for pre-heating the engine liner and head to realistic operating temperatures.
5. Computer control and monitoring of all engine variables and functions. This provides for the ability to implement complex skip-fired operating schemes and for synchronization of the engine with the diagnostic equipment.

Figure 2: The HSDI diesel engine laboratory.

Split-Injection Strategies for Enhanced Mixing and Soot Burnout

As noted above, the HSDI engine facility has been designed to accommodate both available high-pressure common-rail fuel injection systems currently available. One of these systems, the Bosch/Fiat Unijet system, has been employed in the diesel engine combustion simulation facility to visualize the combustion process associated with split-injection strategies. Recent studies have demonstrated that these strategies have the potential to simultaneously reduce both NO_x and particulate matter emissions [8]. The Bosch system is currently the most promising system for mass production, and ensures that our measurements will be directly useful

to our PNGV colleagues. This system permits the injection rate to be modulated in a dual pulse mode, a capability that allows us to examine the effects of both small pre-injection and split, pulse-modulated main-injection strategies for noise and emission reduction, respectively. A second set of prototype injectors, fully compatible with the Bosch high pressure source and the Bosch VCO injector nozzles, has also been acquired from Ganser-Hydromag. These injectors will enable extension of the rate modulation to multiple pulses, and additionally permit the adjustment of the initial slope of the injection rate profile. The Ganser injectors have been used for the pilot injection studies described in the following section.

Studies performed in the combustion simulation vessel have focused on characterizing the operation and repeatability of the injectors, determining ignition delays to provide a data base for pilot-injection experiments in the engine, developing visualization capabilities, and investigating the interaction of the spray pulses in a pulsed, rate-modulated main injection event. To characterize the thermal aspects of the ignition delay reduction (relevant to combustion noise abatement), we have measured the ignition delay as a function of ambient gas temperature with all other injection parameters fixed. Simultaneously, we examined the maximum rates of pressure increase and their correlation with observed high frequency structure on the pressure signal associated with diesel “knock.” The measured dependence of ignition delay on ambient temperature is shown in Fig. 3, for two different measures of delay time. The ignition delay begins to increase dramatically below approximately 850-900K, at which point the maximum rate of pressure rise and the high frequency components on the pressure signal show marked peaks. These data indicate that an ambient injection temperature of approximately 900K is required for significant noise reduction. In addition, the measured ignition delays are employed to determine the required pre-injection timing in the HSDI diesel engine experiments.

Figure 3: Ignition delays measured as a function of ambient gas temperature.

We have also obtained flame luminosity image sequences in a pulsed, rate-modulated injection event, as shown in Fig. 4. This image sequence clearly illustrates the formation of two distinct combustion zones, with a concomitant increase in the combustion zone surface area. Increased surface area provides the potential for enhanced fuel-air mixing and consequently a reduction in particulate emissions. Although recent spray modeling work has suggested that these injection rate modulation techniques could be effective in enhancing mixing and reducing emissions, the image sequence shown in Fig. 4 represents the first known experimental data illustrating the evolution of a rate-modulated injection event. These images furnish a clear picture of the fluid dynamics and mixing associated with injection rate modulation. Studies in the HSDI diesel engine environment where the jet evolution is modified by flow swirl and

jet/wall interaction, will provide additional information needed to clarify the potential of these techniques for emission reduction in passenger car applications.

Figure 4: Temporal evolution (proceeding from left to right, then top to bottom) of the spray structure in a split injection event.

Pilot-Injection Strategies in the HSDI Engine Facility

Pilot-injection techniques for reducing combustion noise (and, potentially, emissions) were investigated in the HSDI engine facilities at a light-load, simulated-idle condition. Noise levels at this condition are one of the factors most likely to influence consumer acceptance of HSDI diesels for passenger car applications. Additionally, a significant percentage of urban driving time is spent at idle, and emissions at this load condition can be a significant contributor to urban air pollution.

Prior to investigation of the effects of pilot injection on the ignition and early combustion process, it is desirable to characterize the engine operation under conventional operating conditions using a single injection event. To ensure that the operating conditions employed were representative of actual engine conditions, we took care to match the idle operating conditions employed by the GM 2.0 liter ECOTEC HSDI engine. The cylinder pressure traces and apparent rate of heat release for this engine are compared against those measured in the Sandia HSDI engine facilities in Figures 5 and 6. The operating conditions employed are summarized in Table 2. The intake pressure was selected to give a slightly higher motored in-cylinder pressure than the GM engine, consistent with the higher compression ratio. Note from Fig. 5 that the most prominent difference between the pressure traces is a more rapid decrease in pressure in the Sandia HSDI engine. This is an inevitable result of the increased heat-transfer associated with the skip-fired mode of operation of the Sandia engine.

Table 2
Light-load Operating Conditions for the Sandia HSDI Diesel Engine

Speed	900 rpm
IMEP	120 kPa
Diluent	47% by mass (O ₂ and N ₂ only)
Intake Pressure	115 kPa
Intake Temperature	90 C
Coolant Temperature	87 C
Injection Pressure	250 bar

Figure 5: Comparison of in-cylinder pressure between the Sandia HSDI diesel engine and the 2.0 liter GM ECOTEC engine.

This higher rate of heat loss in the Sandia engine is also evident in the apparent heat release rates shown in Fig. 6, and is indicated by the fairly large negative region prior to 0 CAD (crank angle degree). In general the placement of the heat release is comparable between the two engines, although the Opel engine has what appears to be a more significant diffusion-like burn period beyond about 10 CAD. For both engines, injection ends at 2-3 CAD ATDC (after top dead center), and any heat release during this later period is likely associated with soot burnout. Higher heat losses in the Sandia engine also likely account for the lower apparent heat release in the Sandia engine during this time period.

Figure 6: Comparison of the rate of apparent heat release between the Sandia HSDI diesel engine and the 2.0 liter GM ECOTEC engine.

The ignition and early combustion processes were investigated in this engine using imaging of natural combustion chemiluminescence onto an intensified CCD camera. The images were acquired by viewing the combustion chamber from below, through the extended piston. The field of view and its relationship to the bowl geometry are shown in Fig. 7, and a sequence of images obtained between 0.5 and 3.0 CAD ATDC is presented in Fig. 8. The earliest visible

chemiluminescence, observed at 0.5 CAD, is approximately 4.5 CAD after the start of injection, indicating an ignition delay of about 830 μ s. Though not clearly visible in Fig. 8, two zones of early chemiluminescence are generally observed: one inside the small circle denoting the central pip diameter and another just outside this circle. Both zones generally align with the individual jet axis.

Figure 7: Field of view of the images obtained through the piston top. The gray region illustrates the effective field of view; a mask (the black region) has been applied over the remaining portions to eliminate reflections associated with the quartz piston top holder. The two large white circles represent the major bowl diameter and the bowl lip diameter, while the smallest white circle corresponds approximately to the diameter of the central bowl pip. The six spokes correspond to the axes of the individual fuel jets.

It is conjectured that the ignition and early combustion process observed in this HSDI diesel engine is substantially similar to that observed in heavy-duty size-class engines [9]. In the heavy-duty size-class engine, some early chemiluminescence is observed near the injector, which corresponds to that observed above the central bowl pip. The majority of the chemiluminescence, however, is observed near the head of the jet, some 30-40 mm from the injector. This is believed to correspond to the larger chemiluminescent zones observed outside the central pip. In this HSDI combustion system, however, the fuel jet is thought to strike the lip of the bowl, and subsequently to flow along the bowl periphery back to the central pip where it is directed vertically upward. This trajectory can be visualized by considering the relative spray/bowl geometry shown in Fig. 7. The lack of significant radial displacement of the outer chemiluminescent zones during this period tends to substantiate this view. Additional data, however, including images obtained through the side windows of the combustion chamber, must still be obtained to provide an unambiguous picture of the combustion process.

Figure 8: Images of early combustion chemiluminescence obtained using a single, main-injection.

Furthermore, note that through approximately 2.0 CAD the chemiluminescent zones are not displaced significantly by the swirl flow (which rotates in the clockwise direction). This suggests that the initial momentum of the fuel jets dominates the fuel jet trajectory. Beyond approximately 2.0 CAD, the onset of significant soot luminosity is observed in locations which are consistent with the above description of the chemiluminescent zones. At these later crank angles the effect of the swirl flow in displacing the combustion luminosity downstream of the injector jet axes begins to be observed.

To understand the effects of pilot injection on the combustion process, the same operating conditions were employed with the exception of the fuel injection strategy. Based on the ignition delay data obtained in the diesel combustion simulation vessel, as well as the observed delay under the standard operating conditions described above, a separation of approximately 1000 μs between the pilot and the main injection was used. The timing of the entire injection event was then adjusted to provide the same location of peak pressure as found under the standard injection strategy. The duration of the pilot was adjusted to give a pilot quantity of approximately 1.5 mm^3 , while the duration of the subsequent main injection was tailored to provide the same IMEP of 120 kPa. The in-cylinder pressure trace and rate of apparent heat release obtained with the pilot injection strategy are compared to those obtained with the standard injection strategy in Figures 9 and 10, respectively. Note from Fig. 9 that the peak cylinder pressure and the temporal gradients in pressure are much smaller with pilot-injection. This observation is substantiated by comparison of the apparent heat release rates of Fig. 10. The peak apparent heat-release rate observed with pilot-injection is only approximately 30% of that observed with the standard injection strategy. This lower rate of apparent heat release is directly related to the rate of pressure increase in the cylinder, and correlates directly with combustion noise. The Sandia HSDI engine operation is noticeably quieter when pilot-injection is utilized.

Figure 9: Comparison of cylinder pressures obtained with pilot and standard fuel injection strategies.

Due to a lack of stability in the injector operation when employing the pilot injection strategy, chemiluminescent images corresponding to those presented in Fig. 8 were not obtained. The operation of the injector was such that while the mean pressure and apparent heat release rate, as shown in Figures 9 and 10 were reasonable, the cyclic variability was unusually large. Due to this cyclic variability, it was not possible to obtain a set of representative images that faithfully depict the autoignition and early combustion process when pilot-injection is employed. Work is currently underway (in a CRADA spawned by this work) to find a stable operating regime with this injector, and to use the Bosch/Fiat Unijet injector as well.

Figure 10: Comparison of apparent heat release rates obtained with pilot and standard fuel injection strategies.

Water Injection for Soot and NO_x Reduction

Water injection technology holds the promise of breaking the soot- NO_x tradeoff that often limits the design of diesel engine combustion strategies. It is well known that water addition is effective in reducing NO_x emissions from engines because the water acts as a diluent and cools the combustion process. A new understanding of diesel combustion resulting from recent research at SNL (by the PIs of this LDRD) indicates that, if introduced with the fuel, water could also inhibit soot formation during diesel combustion.

Recent diesel-combustion research at SNL (not related to this LDRD) has indicated that diesel combustion occurs as a two-stage process [10]. First, the fuel passes through a very fuel-rich premixed reaction zone, then the products of this rich premixed combustion burn out in a turbulent diffusion flame at the jet periphery. The partially burned fuel products of the fuel-rich premixed flame lead to soot formation in the diesel engine and provide the reactants for the subsequent combustion downstream. Although most of the soot burns out at the diffusion flame, a small fraction is not oxidized and ends up as an exhaust emission. Both equilibrium and kinetic rate chemistry calculations indicate that if water is introduced with the fuel, it has the potential to dramatically affect the quantity of soot precursors formed in the rich premixed flame and, therefore, the quantity of soot formed downstream. The amount of water required for this soot reduction is estimated to be significantly less than that typically used to control NO_x production by dilution techniques, but additional water should not be a detriment to the soot reduction, if it is introduced correctly.

Injecting the water as a liquid with the fuel also has the potential for NO_x reduction without the loss of power density associated with more classic diluent techniques such as EGR. When EGR is used to lower combustion temperatures it displaces a sometimes significant fraction of the air in the cylinder. This results in a reduced power output for an engine of a given size. Although the power loss can be partially overcome by additional boosting of the intake air pressure, this requires additional work from the engine, and there are practical limits to the maximum allowable cylinder pressure. Also, EGR can result in increased soot emissions for some operating conditions. In contrast, liquid water injection does not displace any intake air, consumes relatively little power from the engine, and may reduce soot emissions.

To be effective in reducing soot, without seriously compromising engine efficiency, the water must be injected with the fuel. Fuel-water emulsions were determined to be the most cost effective method of achieving this for our investigations. Since the development of fuel-water emulsions is still an area of active research, and special fuel mixtures that are not compatible with traditional emulsifiers are required for some of our optical measurements, a source for custom fuel-water emulsions had to be developed. A small company was located, Clean Diesel Technologies, that could meet our needs. They developed the required emulsifiers and supplied them to us along with blending instructions so that we could make fresh emulsion mixtures as needed.

Although the effectiveness of diluents such as water for reducing NO_x is well known, no information was available on the effect of water injection on the in-cylinder soot levels prior to the current research. To better understand the effects of water injection on soot formation during diesel combustion, two sets of experiments were conducted in the existing optically accessible, heavy-duty diesel engine facility that is shown schematically in Fig. 11. First, two straight fuels were compared with the same fuels plus 10% water (by mass, mixed as an emulsion) using 2-D laser-induced incandescence (LII) imaging to measure the relative soot levels throughout the

midplane of the fuel jet at several crank angles. The second study focussed on the effect of adding even greater quantities of water to one of the fuels. For these experiments, line-of-sight (LOS) absorption was used to measure the in-cylinder soot levels for the straight fuel and for mixtures of 10, 20 and 30% water with the fuel.

Figure 11: Schematic of heavy-duty optical-access diesel engine showing the laser sheet along the fuel jet axis as used for the LII imaging measurements. The images were obtained through the piston-crown window (lower image).

LII Imaging Measurements

Two fuels were tested, a standard diesel reference fuel mixture and a low-sooting fuel that reduces optical attenuation by the soot to allow more accurate optical measurements. This low-sooting fuel mixture has been carefully selected to give the same combustion characteristics as the reference fuel, including the onset of soot formation, with the one exception that soot levels are lower [11]. For both fuels, 10% water emulsions were examined as well as control measurements with the straight fuel.

An initial comparison of planar LII soot images obtained with the emulsified and straight fuels showed that the soot concentrations within the reacting diesel fuel jet were greatly reduced by the addition of water. However, the water also produced a slightly longer ignition delay and

liquid-phase fuel penetration. Since these effects will alter the fuel-air mixing favorably for soot reduction, additional experiments were conducted to isolate the chemical effect of water on soot production. In these experiments, straight fuels were run with a slightly reduced in-cylinder air temperature to match the ignition delay and approximately match the liquid-fuel penetration of the emulsions. This reduced the soot concentrations for the straight fuels, but not nearly as much as did the water emulsion.

Figure 12 shows some typical LII soot images with the laser sheet oriented along the axis of one of the eight fuel jets, as shown in Fig. 11. For all three crank angles depicted, the LII image intensity (proportional to soot concentration) is much less for the water emulsion (bottom) than for the straight fuel (top). Similar results were found for the reference fuel. The soot reduction by the water is even more evident in Fig. 13, which shows plots of the LII image intensity averaged over 12 engine cycles. The soot concentration is approximately a factor of two lower for the emulsion up through the peaks in the curves. Beyond the peaks, optical attenuation reduces the signal in both data sets; however, the peak occurs later for the emulsion, indicating that the development of soot concentrations sufficient to cause optical attenuation is delayed by the water. These data provide the first hard evidence that water injection can directly reduce soot formation during diesel combustion. Even the modest 10% water mixture was found to be very effective in reducing soot, indicating that water injection could be effective in reducing both soot and NO_x .

Figure 12: Temporal sequence of planar LII relative soot-concentration images for the low-sooting fuel. The number in the upper corner of each image is the relative camera gain. The fuel jet flows from left to right and the laser sheet propagates from right to left along the axis of the fuel jet.

Figure 13: A comparison of the relative soot concentration (averaged LII signal intensity) for the low-sooting fuel and a 10% water emulsion. Each data point represents the crank-angle-resolved LII signal averaged over the field of view in the images and over 12 engine cycles.

LOS Absorption Measurements

In order to more quickly and accurately measure the in-cylinder soot levels throughout the combustion event, an LOS absorption (extinction) diagnostic was implemented. A schematic of this diagnostic is shown in Fig. 14. Although the principles of LOS absorption are straightforward, applying it to the operating diesel engine involved three special adaptations. First, the engine was equipped with a special 7-hole injector tip rather than the standard 8-hole tip. This eliminated the reacting fuel jet opposite the one in which the measurement was being made so that the laser beam was absorbed by the soot in only one of the jets as it passed through the combustion chamber (see Figs. 11 and 14). Second, an integrating sphere was used in the detecting optics to eliminate signal fluctuations caused by beam steering as the laser passed through the large density gradients in the combustion chamber. Third, the second harmonic of an Nd:YAG laser was aligned to be co-linear with the absorption laser beam as it passed through the chamber. This laser was fired after each combustion event to “clean” the accumulated soot off the windows. (In the diesel engine, soot deposited on the windows can quickly block the absorption laser; however, with sufficient laser energy this soot can be vaporized off the windows leaving them quite clean.)

Figure 14: Schematic of the LOS absorption diagnostic as applied to the heavy-duty diesel engine. Note the integrating sphere that eliminates signal fluctuations due to beam steering and the green Nd:YAG beam used to “clean” the window prior to each measured combustion event.

Using the LOS diagnostic, an expanded data set was obtained for the low-sooting fuel. This expanded data set included three emulsion concentrations and parametric variations of engine operating conditions (TDC temperature, TDC density, and fuel loading) for some emulsion mixtures. The following studies were conducted:

1. The straight fuel and an emulsion with 10% water in the fuel were measured with the LOS diagnostic. These measurements were made at the base condition ($T_{TDC} = 992 \text{ K}$, $\rho_{TDC} = 16.6 \text{ kg/m}^3$) and with the TDC temperature adjusted as discussed below. The LOS absorption measurement showed that the emulsion reduced the in-cylinder soot levels by about a factor of two, which is in good agreement with the LII measurements presented above.

These results are presented in Figs. 15a and 15b which give the apparent heat release rates (AHRR) and the LOS absorption measurement reduced to a KL factor that is directly proportional to the total in-cylinder soot along the path of the laser. As discussed in the preceding section, adding 10% water increased the ignition delay which could be contributing to the total soot reduction along with the chemical effect of the water within the rich-combustion product gases. The same change in ignition delay was achieved with the straight fuel by reducing the TDC air temperature from 992 to 950 K. Figure 15a shows that with this temperature change, the AHRR for the straight fuel is virtually identical to that of 10% emulsion. Figure 15b shows that this shift in ignition delay reduces the in-cylinder soot, but that the addition of 10% water reduces the peak soot levels by an additional factor of two.

Although the water significantly reduced the peak soot levels, as our understanding of diesel combustion indicated it would, the KL plot in Fig. 15b suggests that the water might inhibit the final burnout of the soot. For the straight fuel cases, the KL factor has gone to zero (no soot) by 390° , whereas for the 10% emulsion, some laser attenuation still occurs beyond 400° . However, this trend is not consistent as additional water is added (discussed below), and additional measurements are needed to determine whether this apparent effect is real or due to deposits on the window, and the extent to which it might limit the use of water injection.

2. Parametric variations were made to the TDC (top dead center) temperature, TDC density, and fuel loading for both the straight fuel and the 10% emulsion. For both fuel mixtures, soot levels changed considerably across the parameter space; however, the 10% emulsion consistently produced lower soot levels for all conditions.
3. For the base operating condition, the water concentration in the emulsion was progressively increased to be 10, 20, and 30% of the total mass. These results are presented in Fig. 16a and 16b. Increasing the amount of water resulted in a further reduction of in-cylinder soot levels as shown in Fig. 16b. Note that the integrated KL factors, given as the “area” in the legend of Fig. 16b, show a progressive reduction in soot with the increased water addition. However, the amount of soot reduction is less for the higher water concentrations, indicating that we were reaching a point beyond which additional water would not offer further improvement.

As discussed above relative to the 10% emulsion, some of the soot reduction with the 20 and 30% emulsions is due to the increased ignition delay and changes in mixing as well as the effect of the water on the soot-formation chemistry. To help isolate this effect, the straight fuel case was run with lower TDC temperatures similar to the 10% emulsion results in Fig. 15. Figure 17a and 17b present the results for the 20 and 30% emulsions and for straight fuel at TDC temperatures of 900 K and 800 K. As can be seen in Fig. 17a, these temperatures bracket the ignition delay for the 20% emulsion, but are not quite low enough to match the delay of the 30% case. The data in Fig. 17 show that 20% water reduces the in-cylinder soot even below the levels of the 0%, 800 K condition which has a longer ignition delay. This indicates that the water is still favorably altering soot formation chemistry at the 20% level.

Although the incremental improvement in soot is small as the water fraction is increased from 20 to 30%, these higher-water-concentration results have two important ramifications for emissions reduction. First, the data in Fig. 17b show that if additional water is used to improve NO_x emissions, it need not come at the expense of increasing soot, and it may even reduce the soot slightly. (Additional water will continue to dilute the combusting mixture and therefore reduce NO_x formation due to the lower flame temperatures.) Second, the amount of apparent soot remaining after 390° (the small, but non-zero, KL value) does not continue to increase as the water concentration in the fuel increases. In fact, the KL values at 400° are slightly less for the 20 and 30% emulsions than the KL value for the 10% emulsion. This suggests that the cause of the higher residual KL might not be soot in the cylinder, but that it is due to some other effect such as soot buildup on the window during the combustion event. Additional measurements such as exhaust soot sampling and/or “cleaning” the windows with the Nd:YAG laser after the main combustion is over (i.e. at about 390°) are needed to determine whether these higher residual KL values are evidence of a problem that might limit the use of water injection.

Figure 15a. Comparison of AHRR for straight fuel and 10% water emulsion at the base condition ($T_{TDC}=992\text{ K}$, $\rho_{TDC}=16.6\text{ kg/m}^3$) and for the straight fuel at the base condition, but at reduced temperature.

Figure 16a. Comparison of AHRR for straight fuel and 10, 20, and 30% water emulsions at the base operating condition ($T_{TDC}=992\text{ K}$, $\rho_{TDC}=16.6\text{ kg/m}^3$).

Figure 17a. Comparison of AHRR for straight fuel at reduced TDC temperatures and the 20 and 30% water emulsions at the base TDC temperature. For all cases $\rho_{TDC}=16.6\text{ kg/m}^3$.

Figure 15b. Comparison of KL factor (proportional to total soot along the laser path) for straight fuel and 10% water emulsion at the base condition and base condition with adjusted temperature.

Figure 16b. Comparison of KL factor (proportional to total soot along the laser path) for straight fuel and 10, 20, and 30% water emulsions at the base operating condition ($T_{TDC}=992\text{ K}$, $\rho_{TDC}=16.6\text{ kg/m}^3$).

Figure 17b. Comparison of KL factor (proportional to total soot along the laser path) for straight fuel at reduced TDC temperatures and the 20 and 30% water emulsions at the base TDC temperature. For all cases $\rho_{TDC}=16.6\text{ kg/m}^3$.

Summary and Conclusions

A high-speed, direct-injection diesel engine facility has been developed which enables research into the in-cylinder combustion processes important to achieving the emissions and fuel economy goals of the PNGV program. The engine geometry represents the current state-of-the-art, and is characterized by 4-valves and a central, vertically located injector. Additionally, features important to the optimization of these engines, such as variable swirl, easily modified combustion system geometry, and compatibility with several different fuel injection systems have been incorporated. The facility further permits simulation of turbocharged engines using high levels of EGR by providing metered high-pressure gases at variable temperatures to the engine induction system. The engine is designed and instrumented to simplify computer modeling efforts, and is equipped with flexible control systems which permit complex operating modes and interfacing with a wide range of diagnostic equipment.

The engine is shown to be capable of being run in a manner typical of new, HSDI production engines, as indicated by comparison of the in-cylinder pressures and the rates of apparent heat release. Chemiluminescence imaging performed in this engine is demonstrated to be an effective tool for the study of the locations of ignition and the early combustion process. Preliminary imaging results indicate substantial similarity to the ignition and early combustion processes observed in heavy-duty size-class diesel engines.

Studies have been conducted on two candidate technologies for improving the emission and noise performance of HSDI diesel engines: injection rate modulation and water injection. These studies have been performed in the heavy-duty diesel engine research facility, the diesel combustion simulation facility, and the new HSDI diesel engine facility as appropriate.

Conclusions reached from the injection rate modulation studies are:

1. Pilot-injection strategies are unlikely to achieve significant noise reduction at low temperatures, such as might prevail under cold start conditions.
2. Split-injection can lead to a large increase in the flame surface area which, in turn, may increase mixing and soot oxidation rates, thereby lowering emissions.
3. Pilot injection techniques are effective in reducing the noise levels of HSDI engines, but can lead to unstable combustion behavior.

Conclusion reached from the water injection studies are:

1. Injecting as little as 10% water with the fuel (as a fuel-water emulsion) in a DI diesel engine can reduce the peak in-cylinder soot concentration by a factor of two.
2. Parametric variation of the TDC temperature, TDC density, and fuel load showed that the 10% emulsion consistently produced less soot than the straight fuel.
3. Increasing the water concentration to 20 and 30% produced further reductions in the in-cylinder soot levels, although at a decreasing rate.
4. Since the addition of water is well known to reduce NO_x by lowering combustion temperatures, the reduction of in-cylinder soot levels found in this study indicates that

the use of fuel-water emulsions or dual-fluid, fuel-water injectors have a strong potential for breaking the soot- NO_x tradeoff and reducing diesel-engine emissions.

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