

The Influence of Diesel End-of-Injection Rate Shape on Combustion Recession

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ABSTRACT

The effect of the shape of the EOI was investigated through a pressure-modulated injection system in order to improve the understanding of the last portion of the traditional diesel diffusion combustion process. Here, the combustion recession at EOI is when the combustion of a mixing controlled diesel jet recedes backwards toward the fuel injector nozzle orifice.

Combustion recession was observed using combustion luminosity imaging filtered at 309 nm to capture OH* chemiluminescence and 430 nm to capture CH* chemiluminescence, although soot Natural Luminosity (NL) will also be visible in these measurements. Experimental spray vessel results show that for relatively slow EOI decelerations below 1×10^6 to 2×10^6 m/s², combustion strongly recesses completely back to the nozzle in both OH* and CH*/NL imaging. 1-D jet mixing calculations add support that this strong recession is indeed fuel rich. Ambient temperature (860 to 915K range) and dilution (18.5 to 20.9% O₂ range) influence the weaker combustion recession, mainly for OH* chemiluminescence imaging. The influence of temperature variation is stronger than the influence of dilution variation over the present ranges. Weak combustion recession under high EOI deceleration conditions shows only OH* recession, as characterized by temporal LOL analyses, with an absence of significant CH*/NL combustion recession. Additionally, the strength of the combustion recession can be inversely ordered by EOI deceleration for a given ambient condition. Rate shape and EOI deceleration had a stronger influence on combustion recession behavior than ambient conditions. The link between combustion recession at EOI and engine emissions is further discussed with multiple hypotheses proposed.

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INTRODUCTION

Diesel engines are the dominant source of power for the heavy duty on-highway and nonroad equipment industries. The efficiency and emissions from these engines face continuous pressure from the market place and legislation throughout the world. While many modern diesel engines utilize aftertreatment to achieve the required low emissions levels, reducing the emissions that come out of the engine remains important on the system level to reduce the requirements of the aftertreatment, increase efficiency, and reduce costs.

The spray and combustion of liquid fuel jets is the means of producing power and also forming pollutant emissions in Diesel engines, and understanding and controlling the spray and combustion process is vital to making engines that are efficient and produce low levels of pollutant emissions. While the Start of Injection (SOI) and quasi-steady processes have been studied in detail [1,2,3,4,5,6,7,8,9,10,11,12,13] significantly less work has focused on EOI [14,15,16]. However, the spray, fluid dynamics, and mixing process at EOI have specifically been linked to hydrocarbon emissions for both conventional combustion [17] and low temperature combustion strategies [18]. In addition, EOI processes have also been linked to soot emissions, with a slower decrease in fuel delivery reducing soot emissions [19, 20].

The behavior at the EOI is a complicated, unsteady process that includes two-phase flow, turbulent mixing, chemical kinetics, and other inter-related phenomena. Measurements of the EOI mixing field [18] showed that there is fairly rapid mixing at EOI, which was later investigated in more detail and termed an "entrainment wave" [21]. As the injector fuel flow decreases during the EOI transient, more air is entrained into the jet from the surrounding air. This increased air entrainment travels down through the jet like a wave. This increased air entrainment was shown to have significant effects on the evaporation of the liquid fuel after the EOI, with the liquid length receding from its steady position and also evaporation of the near-nozzle fuel due to increased entrainment near the nozzle [22].

In this work, an analytical model was applied to varying slopes of decrease in the fuel rate during the EOI transient, and significant differences in the overall mixing field were predicted, with the liquid length recession occurring faster with a faster ramp and significant differences in the transient mixture fraction field for the two cases. It is reasonable to expect similarly different reaction histories with varying EOI rate shape as it is clear that the mixture fraction and temperature histories around EOI differ significantly. In other studies, particle image velocimetry measurements of the flow field of a fuel jet after EOI qualitatively and quantitatively support the entrainment wave concept [23, 24]. Additionally, measurements of the EOI

process with laser absorption scattering and advanced simulations have confirmed the presence of increased entrainment after EOI consistent with an entrainment wave [25, 26].

Measurements of the combustion in the near-nozzle region after EOI have been shown in previous research. Schlieren imaging [27] after EOI at the conditions of Spray A of the Engine Combustion Network (ECN) (available at www.Sandia.gov/ECN) showed high temperature heat release progressing back toward the nozzle. Formaldehyde appears to be consumed as combustion occurs in the near-nozzle region, and the fast rate at which combustion recedes toward the nozzle indicates that this is a progression of ignition events towards the nozzle. Bruneaux and Maligne [28] measured OH and Formaldehyde/PAH LIF under different conditions, and found some evidence that high temperature reactions do not propagate back to the nozzle.

From the previous work, it is clear that the processes surrounding EOI are critical for determining the engine-out emission levels. It is also apparent that an increase in air entrainment leads to conditions where different temperature and equivalence ratio field histories can lead to combustion recession or no recession. This combustion recession is undoubtedly important to emissions levels. Fuel that is unburned or partially burned in the near-nozzle region is known to cause HC emissions [18]. In addition, fuel that is dribbled out of the sac volume after injection would be exposed to the near-nozzle environment, and the temperature and species in this region would be very different depending on if combustion recession occurred or not. Thus, the eventual outcome of dribbled fuel is likely directly impacted by the presence, or lack thereof, of combustion recession back to the injector tip.

The objective of this work is to examine how the EOI rate shape impacts the presence of combustion recession. Since this is a parameter that can be tuned using different fuel system parameters, it presents a potential way to control the combustion characteristics at EOI. In addition, this work will also examine the effects of some of the in-cylinder conditions on this phenomenon with the intention of understanding if EOI rate shape is a strong enough factor to overcome differences in engine operating conditions and characteristics.

EXPERIMENTAL SETUP

Fuel Injection System

The fuel injection system used for the present EOI variation study was a Cat® MEUI™-C (Mechanical Electronic Unit Injector) injector sized for 15-Liter, 6 cylinder engines. This injector utilizes camshaft motion to build fuel injection pressure and has the ability to separately control pressure and injection valve opening pressure through the uses of a High Pressure Spill Valve (HPSV) and Direct Operated Check (DOC) similar to previous MEUI's [29, 30]. The fuel injector fits in a specially designed fixture, which is attached to a modified 15-Liter engine cylinder head. Measurements of injection pressure are attained via a push-tube and strain gauged rocker arm (calibrated to relate strain to injector plunger pressure) which is actuated by an overhead camshaft attached to a belt driven variable

speed electric motor. The injector current is controlled using a modified Electronic Control Module (ECM). This entire apparatus is horizontally attached to each of the pressure vessels described hereafter. The high-speed data collected for the injection system are the current traces, the rocker arm strain (injection plunger pressure), and camshaft position. Further specifications about the injection system can be found in Table 1.

The unique nature of the mechanically driven MEUI-C is the link to the source injection pressure (plunger pressure) modulation for EOI variation. By controlling the camshaft and injector plunger pressure, the EOI variation is enabled. The EOI rate shape/velocity could be controlled and varied through the plunger pressure modulation. This was achieved without throttling the flow into the sac of the injector tip via slowed needle closing, as is a common alternative method for rate shaping.

Table 1. Fuel Injection System Details

Injection System	Unit	Value
Type	-	Unit Injector, MEUI-C
Pressure Range	MPa	50-250
Minimum Valve Opening/Closing Pressure	MPa	30
Number of Holes	-	5
Hole Size (from X-Ray)	μm	300
Included Spray Angle	deg	130
K-factor, (d _{in} -d _{out})/10 in μm	-	0
Nozzle C _d at 41 MPa	-	0.735

Momentum Rate Measurements of Injection

The experimental apparatus used for the momentum rate and mass collection experiments is a nitrogen filled spray vessel at room temperature, and is the same as used in the prior work of [31]. The vessel size is approximately a 200 mm cube with optical access from four sides. The vessel is sealed so that the back pressure, or ambient gas density, can realistically simulate the condition in an engine at SOI. Hence, the density is controlled by adjusting the nitrogen pressure.

Momentum rate measurements combined with injection mass measurements allowed injection mass flow and velocity to be directly computed utilizing the Bernoulli equation and the methods described in [31]. A high confidence in injection velocity is achieved if both total injection mass and injection force are measured, since velocity can be directly computed using equation (1) and (2).

$$F = ma = \dot{m}V = \rho A V^2 = \dot{M} \quad (1)$$

$$\dot{m} = \frac{\sqrt{F}}{\int_{t_{SOI}}^{t_{EOI}} \sqrt{F} dt} \times m_{injection}$$



High Temperature Pressure Vessel (HTPV)

Combusting sprays were imaged under engine like conditions in the High Temperature Pressure Vessel (HTPV), a flow-through optical vessel capable of maintaining pressures and temperatures up to 150 bar and 1000 K [32]. The vessel, designed by Advanced Combustion GMBH in Aachen, Germany, has a two layered construction where the outer shell contains the pressure and the inner shell contains the heated flow providing an optically accessible section with an inner diameter of 200 mm and an axial height of approximately 100 mm above and below the injector. Three windows and a replaceable injector holder allows for testing a wide range of fuel injectors. The injector holder is water and fuel cooled to provide engine-similar-temperatures.

The vessel is supplied with a controlled mixture of dry air and nitrogen allowing for oxygen concentrations between 0 and 20.9% as a continuous flushing flow through the test section. The incoming air/ N_2 mixture is heated as it passes through two 15kW heater cartridges immediately below the test section, as seen in the bottom of Figure 1. The air then passes into the optically accessible test section where the fuel injector is located.

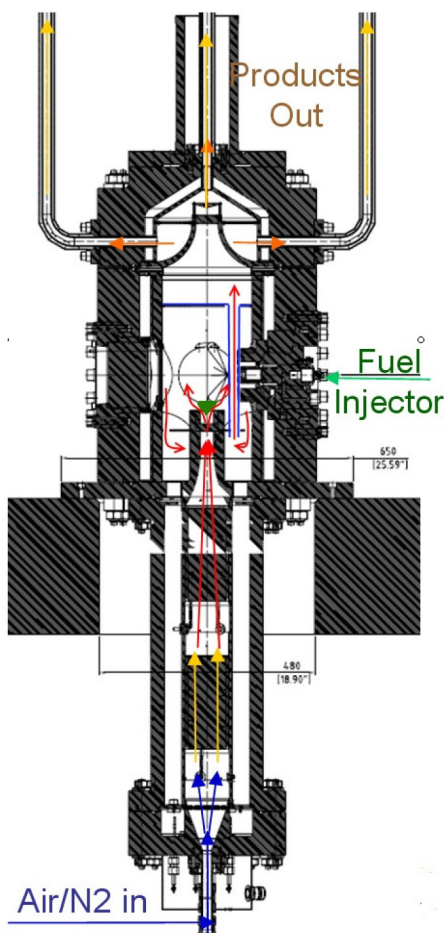


Figure 1. Cross section of the HTPV.

For the current experiments, injection and camera timing was accomplished with a modified ECM connected to the MEUI-C injector cart. Ambient conditions of pressure, temperature, oxygen concentration and flushing flow rate were recorded with a separate Data Acquisition (DAQ) system before and during each injection

event to verify operating conditions were well maintained. Utilizing thermocouples with two sheath diameters in the test section, a radiation correction was applied to better characterize the ambient temperature. US ULSD certification fuel (Cetane Number of 45.0) and four ambient operating conditions were selected for the MEUI-C injection rate shape testing as shown in Table 2.

Table 2. HPTV operating conditions

Pressure [MPa]	Temperature [K]	O ₂ [mole%]	Density [kg/m ³]	Fuel
12	915	20.9%	45.7	US ULSD Cert.
11.3	860	20.9%	45.8	
12	915	18.5%	45.7	CN = 45.0
11.3	860	18.5%	45.8	

OPTICAL SETUP AND IMAGE PROCESSING

Figure 2 shows a schematic for the optical diagnostics setup that was used in the HTPV. Three high-speed Complementary Metal-Oxide-Semiconductor (CMOS) cameras combined with two dichroic mirrors centered at 309 and 430 nm enabled simultaneous imaging of OH* and CH* chemiluminescence and Natural Luminosity (NL).

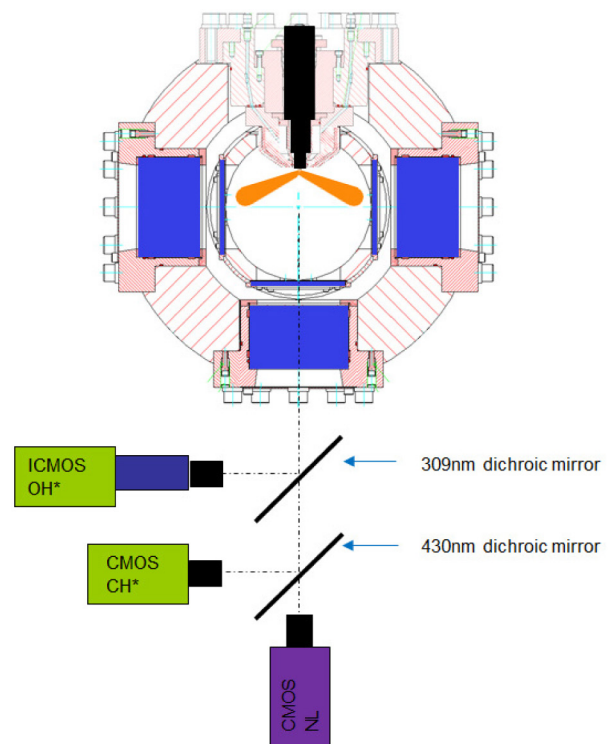


Figure 2. HTPV Optical Setup for simultaneous imaging of OH*, CH*, and natural luminosity with three high speed cameras.

Light reflected from the first mirror was further filtered using a narrow bandpass filter centered at 309 nm and a piece of UG11 Schott glass before imaging OH* through an optically coupled VideoScope VS4-1845HS high speed image intensifier and Vison Research V710 Phantom camera. The OH* camera recorded at 560×560 resolution at 19,005 frames per second (fps). Similarly, the light reflected by the 430 nm dichroic mirror was further filtered.

using a narrowband filter before imaging the CH* with a Vison Research V12 Phantom camera. The CH* camera recorded at 320×320 resolution at 38,017 fps. Since the camera gate was maximized at 25µs to enhance light collection from CH* chemiluminescence near the LOL of the jets there is significant interference from soot and/or Polycyclic Aromatic Hydrocarbons (PAH) light emissions in the images. Therefore, only a small portion of the jet very near the LOL is likely to be primarily limited to CH* emissions upstream of the soot inception point. Any part of the jet that is obviously saturated in the image will likely be primarily from soot luminosity. Additionally, Mie scattering allows for visualizing the liquid fuel upstream of the LOL, which can be used to verify the EOI timing. Finally, a Photron Fastcam Ultima APX camera was utilized to image the remaining natural luminosity over approximately 450 to 1100 nm, dominated by light emissions from soot. The NL camera recorded at 256×256 resolution at 15,000 fps. A combination of neutral density filters, lens f-stop and camera gate were selected to minimize any image saturation for the NL camera. This allows for a qualitative comparison of soot levels between injection modes for a given ambient condition, but the extreme temperature dependence of NL to local combustion conditions significantly limits comparisons.

The high speed movies were processed for LOL, jet penetration, and cone angle with the assistance of a Matlab image processing code. These values are corrected for the included angle of the fuel jets and calibrated to provide measurements along the centerline of each jet. Image processing is accomplished with an adapting threshold technique to find the jet edges.

RESULTS

The MEUI-C injection system was used to generate varying pressure modulated EOI rate shapes. The EOI rate shapes of interest are listed in Table 3, and show that a widely varying EOI deceleration was achieved. There is over an order of magnitude spread between the fastest EOI and slowest EOI rate shapes. Here the average deceleration is calculated from the time to travel from 300 m/s to 100 m/s during the EOI period.

Table 3. Description of the varying EOI injection cases and relevant injection characteristics.

EOI Variation Test Matrix	Case #	Maximum Pressure	Maximum Velocity	Avg. EOI Deceleration
Unit	-	MPa	m/s	10 ⁶ m/s ²
Base-Fast EOI	01	178	617	2.82
Base-Slow EOI	02	175	613	0.54
Falling-Slow EOI	04	182	625	0.62
High Pressure-Fast EOI	07	236	713	4.08
High Pressure-Slow EOI	08	223	693	1.13
Low Pressure-Fast EOI	09	127	520	2.04
Low Pressure-Slow EOI	10	127	520	0.33

The measured rate shapes for the cases listed in Table 3 are presented in Figure 3. It can be observed that the rate shapes have a very fast front end, indicative of a modern square/top-hat injection profile, with varying peak injection velocities and even a case with significant falling behavior. The large oscillation at the beginning of the injection is characteristic of a mechanical fuel injector and is a byproduct of the hydraulic behavior of the injector type. To better examine the EOI differences, a second plot with the EOI time-aligned to zero is shown in Figure 4.

Figure 4 clearly shows the varying EOI deceleration and the spread in the selected injection cases. The injection deceleration is pressure modulated, so the linearity of the deceleration is subject to the specific details of the injector hydraulic flow areas, geometries, and camshaft profile. Thus, the linearity is not completely controllable over the large range of deceleration and results in the not completely smooth features observed in Figure 4. Regardless, there are cases which are on the fastest and slowest end of the deceleration spectrum. Two cases that clearly show distinct differences in EOI deceleration are the Base Fast EOI case 01 and the Low Pressure Slow EOI case 10, marked in bold in the figure. The HTPV combustion imaging of these two cases is laid out in Figure 5 and Figure 6 in order to illustrate the extremes.

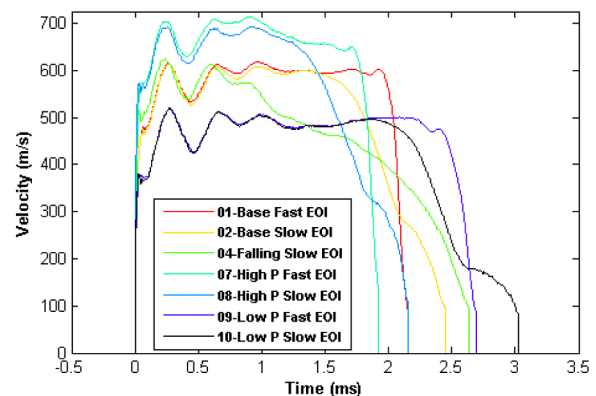


Figure 3. Velocity injection rate shapes for the cases listed in Table 3 calculated from momentum rate measurements.

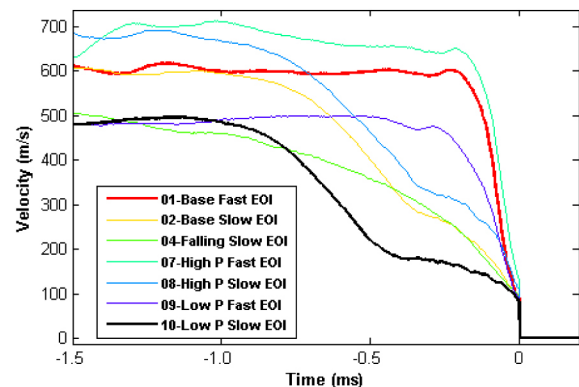


Figure 4. EOI time-aligned velocity injection rate shapes for the cases in Table 3 showing the variation in the EOI deceleration.