

Effect of Fuel Volatility and Ignition Quality on Combustion and Soot Formation at Fixed Premixing Conditions

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ABSTRACT

This paper presents experimental results for two fuel-related topics in a diesel engine: (1) how fuel volatility affects the premixed burn and heat release rate, and (2) how ignition quality influences the soot formation.

Fast evaporation of fuel may lead to more intense heat release if a higher percentage of the fuel is mixed with air to form a combustible mixture. However, if the evaporation of fuel is driven by mixing with high-temperature gases from the ambient, a high-volatility fuel will require less oxygen entrainment and mixing for complete vaporization and, consequently, may not have potential for significant heat release simply because it has vaporized. Fuel cetane number changes also cause uncertainty regarding soot formation because variable ignition delay will change levels of fuel-air mixing prior to combustion.

To address these questions, experiments are performed using a constant-volume combustion chamber simulating typical low-temperature-combustion (LTC) diesel conditions. We use fuels that have the same ignition delay (and therefore similar time for premixing with air), but different fuel volatility, to assess the heat-release rate and spatial location of combustion. Under this condition, where fuel volatility is decoupled from the ignition delay, results show almost the same heat release rate and spatial location of the premixed burn.

The effect of ignition quality on soot formation has also been studied while maintaining similar levels of fuel-ambient mixing prior to combustion. To achieve the same ignition delay, the high-cetane-number fuel is injected into an ambient gas at a lower temperature and

vice versa. The total soot mass within the spray is measured and compared for fuels with different cetane numbers but with the same premixing level (e.g. the same ignition delay and lift-off length). Experimental results show that the combination of high cetane number and low ambient gas temperature produces lower soot than the other combination, because the ambient temperature predominantly affects soot formation.

INTRODUCTION

To compensate for shrinking supplies of easily-accessible petroleum, liquid fuels from a variety of feed stocks and refinement processes are now being proposed. Some predictions show that synthetic fuels produced from gas and coal via Fischer-Tropsch processes will account for about 25% of the transportation fuel supply in 2050 [1]. Potential changes to the fuel supply such as this bring up important questions about how the new fuels with various properties will perform in modern combustion systems, e.g., advanced diesel engines.

FUEL VOLATILITY

The boiling point (BP) temperature of a fuel affects its vaporization and combustion. Since a low-BP fuel evaporates quickly, the spray's liquid penetration is shorter than that of a high-BP fuel [2-4]. As a result, liquid wall wetting and fuel-in-oil dilution problems might be avoided. Some studies report that a low BP fuel causes a decrease in particulate matter (PM) emissions [5-6], but an increase in nitrogen oxide (NO_x) emissions [7]. This tradeoff is typical for fuels with an increased premixed burn heat release [8].

A potential cause for the higher NO_x emissions is that fast evaporation of a fuel can increase the percentage of fuel that is mixed with air before the start of combustion. This may lead to an increased combustible mixture volume, thereby resulting in more intense premixed burn and higher heat release. However, if the vaporization is mixing-limited at diesel conditions [9], it does not increase the amount of oxygen mixed with the fuel. Low BP fuel sprays will have a greater fraction of vaporized fuel, along with a shorter liquid penetration length, but sections of the vaporized fuel-air mixture may be quite fuel rich, and have little potential for significant heat release. Therefore, the direct influence of the fuel BP on the in-cylinder combustion process is still in question. To address this question, one may compare reacting sprays that have similar levels of oxygen entrainment at the time of combustion, *i.e.*, at fixed premixing conditions.

FUEL CETANE NUMBER

The premixing (*i.e.* fuel-ambient mixing before the onset of combustion) is strongly influenced by the cetane number of fuels. As a result, the ignition quality of fuel can affect soot and NO_x formation as well as unburned hydrocarbons (UHC) and carbon monoxide (CO) emissions. For instance, fuels with high cetane number can cause high soot production because faster auto-ignition results in a shorter lift-off length with more fuel-rich combustion [10]. The downstream soot formation increases because of less partial premixing (air entrainment) upstream of the flame lift-off length [10-13].

Another important parameter strongly affecting soot formation is ambient temperature, which also influences the lift-off length, as well as soot formation directly [12,14]. These interrelated parameters may explain why conclusions from some cetane number studies are directly opposite to those from others. In diesel engines, some report that a low cetane number causes a decrease in PM (*e.g.* [15-17]). However, the deterioration of UHC and CO emissions [16] requires a high compression ratio design (*i.e.* high ambient temperature), which, in turn, can increase NO_x emissions [17]. On the other hand, some studies showed that a high-cetane number fuel, in combination with a low engine compression ratio, produces better emissions than the other combination [18]. Surprisingly, a high cetane number fuel can show significant particulate matter (PM) reduction [5, 19], often with a decrease in UHC and CO emissions [19]. Accordingly, care should be taken to interpret the engine-out emissions trend when fuels with different cetane numbers are used.

SCOPE OF THE CURRENT STUDY

In this study, we investigated the fundamental causes for fuel volatility and cetane number related trends in combustion and emissions. First, we will compare the reacting jet penetration, premixed burn location, and apparent heat release rates from fuels that have the same ignition delay (at fixed ambient conditions), but

different volatility. The details of fuel volatility effects on in-cylinder combustion processes will be discussed.

Second, the soot formation is quantitatively measured for fuels with different ignition characteristics, but with the same lift-off length. Holding the lift-off length constant is a reasonable approach to ensure that combustion occurs in a mixture that has similar levels of fuel-oxygen mixing. However, to achieve this same lift-off length, the high-cetane-number fuel is injected into an ambient gas at a lower temperature. As the temperature directly affects soot formation, we will determine the combination of fuel cetane number and ambient gas temperature that produces the lowest soot formation.

EXPERIMENTS

EXPERIMENTAL APPARATUS

Experiments were performed using an optically accessible high-temperature/high-pressure combustion chamber where the thermodynamic and injector conditions were controlled to mimic low-temperature-combustion (LTC) diesel engine operating conditions [20-21]. Details of combustion chamber design and operation are provided in [22] and, therefore, only a brief summary is given below.

A schematic of the vessel and optical measurement setups are shown in Fig. 1. The vessel has a cubic combustion chamber, 108 mm on a side. Sapphire windows are installed in three sides of the chamber, enabling extensive optical diagnostics. The fuel is injected into the center of the chamber via a common-rail fuel injector (2nd generation Bosch) with a mini-sac-type, axially drilled, single-hole nozzle (94 μm in diameter). The injection pressure was set to 150 MPa. These operating conditions are summarized in Table 1.

AMBIENT CONDITIONS

The selected ambient oxygen mole fraction (15%) simulates significant exhaust-gas recirculation (EGR) use in engines, allowing operation in low-temperature combustion regimes. The 900-K temperature and 6-MPa pressure (22.8 kg/m³) represent engine conditions with EGR cooling and turbocharging (boost), consistent with current technology trends [23]. While other conditions are fixed, a 1000-K ambient temperature was also tested to represent higher load and mixing-controlled combustion after the premixed burn. In addition to the reacting, 15% ambient oxygen condition, a non-reacting, 0% ambient oxygen condition was also created to measure the liquid and vapor penetrations decoupled from the complex combustion process. These settings were held constant while varying the fuel.

FUELS

One diesel and four jet (kerosene) fuels were tested in this study. The fuels were selected to represent a large

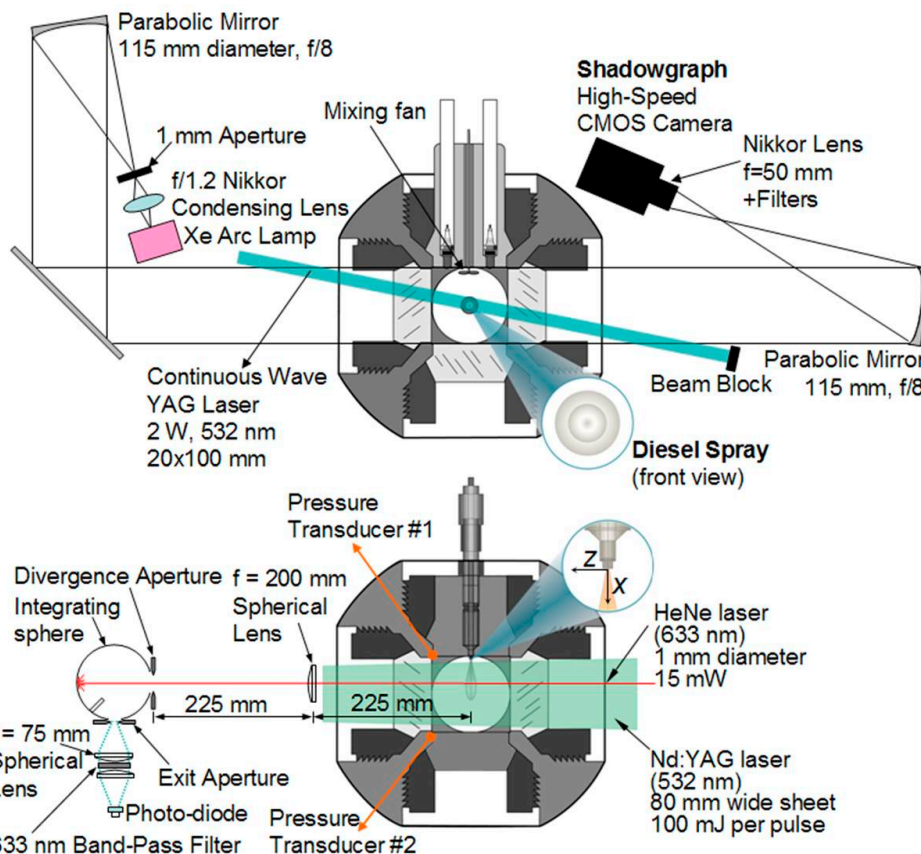


Figure 1 Constant-volume combustion vessel and optical setup.

Table 1 Operating conditions

Injector conditions		
Type	Bosch common-rail	
Nozzle	Single-hole, KS1.5/0.86	
Nozzle diameter	94 μm	
Injection pressure	150 MPa	
Ambient conditions		
O ₂	15%	0%
N ₂	75.15%	89.71%
CO ₂	6.23%	6.52%
H ₂ O	3.62%	3.77%
Molecular weight	29.24	28.68
Temperature	900, 1000 K	
Density	22.8 kg/m ³	
Pressure	6, 6.7 MPa	

of boiling points, fuel densities, and cetane numbers, as listed in Table 2. These fuels are: a Fischer-Tropsch synthetic jet fuel (JS), a surrogate jet fuel of a blend of 23% m-xylene and 77% n-dodecane (SR), a certification-grade no. 2 diesel (D2), a conventional JP-8 (JC), and a coal-derived jet fuel (JP). The JS and SR properties provide a good comparison of fuel boiling point as both are highly reactive (high cetane number)

and potentially have a similar ignition delay at fixed ambient conditions. The D2-JC comparison shows major differences in boiling point and similar cetane number range. For ignition quality effect on soot formation, SR, D2, and JP fuels were selected due to measurable variation in cetane number and aromatic content.

DIAGNOSTICS

The optical diagnostics employed in this study include Mie-scatter and shadowgraph imaging (Fig. 1 top), OH chemiluminescence imaging, and Planar Laser-Induced Incandescence (PLII) and Light Extinction measurement (Fig. 1 bottom).

To determine the penetration rate of the liquid and vapor sprays for both reacting and non-reacting conditions, simultaneous high-speed visualization by Mie-scatter and shadowgraph imaging were performed. For Mie-scatter imaging, a continuous-wave Nd:YAG laser (532 nm) operating with 2-W power was used as a light source. A 100-mm wide and 20-mm thick laser sheet was formed to volumetrically illuminate the liquid-phase spray. A high-speed CMOS camera (not shown in the setup) with a 532-nm band-pass filter (10 nm FWHM) and a 50-mm focal length, f/1.2 lens collected Mie-scattered light from the fuel droplets at approximately 50,000 frames per second. Simultaneously, high-speed shadowgraph imaging was performed to visualize the

Table 2 Fuel properties

		"JS" Gas-To-Liquid Jet Fuel	"SR" Surrogate Jet Fuel ¹	"D2" No. 2 Diesel	"JC" JP-8	"JP" Coal-To-Liquid Jet Fuel
Distillation temperature [°C]	T _{10%}	167	-	211	170	192
	T _{90%}	254	-	315	240	243
	T _{100%}	276	216	350	266	270
Density at 15 °C [kg/m ³]		755.9	778.9	843	812	870.2
Lower heating value [MJ/kg]		44.1	43.33	43.0	43.2	42.8
Cetane number		62	70	46	38	34
Aromatics [%]		0.4	23	27	11	1.9

¹ 23% m-xylene, 77% n-dodecane, volume-average properties are given except T_{100%} for n-dodecane (m-xylene boiling point is 139 °C).

vapor-phase fuel spray. A 150-W (electrical) mercury-xenon arc lamp was used for the light source. The emitted beam passed through a 50-mm focal length f/1.2 Nikkor lens and 1-mm aperture. The beam was collimated by an f/8 mirror (115 mm diameter), passed through the chamber windows and then refocused to another high-speed CMOS camera. A zero-incidence 532-nm mirror was used to block laser scatter from the liquid droplets.

OH chemiluminescence imaging was conducted to identify the lift-off (autoignition) location of the reacting jet (setup is not shown but the view field is as in Fig. 1 bottom). By using an intensified CCD camera (Xybion ISG-250) coupled with 310-nm band-pass-filter, a line-of-sight integration of OH chemiluminescence was imaged during the quasi-steady period of fuel injection. The camera gate (exposure) time was set to 3 ms to obtain time-averaged images.

PLII images of soot are collected to analyze the location of soot along a thin plane at the jet axis. A high energy (100 mJ) laser pulse at 532 nm (SpectraPhysics Nd:YAG laser) was used for this measurement. The laser timing was set to 4 ms after the start of injection to image the soot spatial location for a steady jet. Figure 1 (bottom) shows that the 80-mm wide and 100-μm thick laser sheet passes through the jet axis which creates the soot incandescence signal. This soot signal was imaged by a second intensified CCD camera. A 450-nm short-pass-filter was used to block the soot luminosity and beam reflections from other sources, e.g. liquid fuel.

Simultaneous to the PLII data acquisition, a helium-neon (HeNe) laser beam is passed through the center of the fuel jet and collected with an integrating sphere to measure the soot extinction along this beam path. These data were used to obtain quantitative, two-dimensional soot distributions for comparing a soot level for tested fuels, similar to Refs [14, 24].

The chamber pressure was also measured to acquire the ignition delay and apparent heat-release rate. To improve the accuracy of the pressure measurement, we used two pressure transducers at the same time and

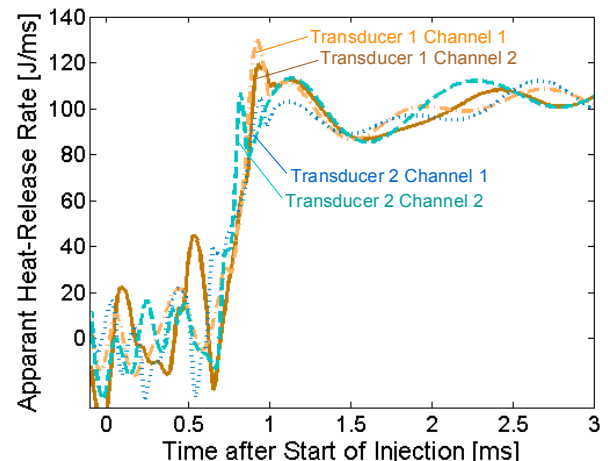


Figure 2 Apparent heat-release rates calculated from cylinder pressures measured by two pressure transducers and four channels.

also enabled a two-channel measurement for each pressure transducer. This approach minimizes potential measurement error and also increases the data acquisition rate. An example is shown in Fig. 2 for D2 fuel at 900 K. The figure shows the apparent heat release rate curves versus the time after start of injection. In the simple energy equation, the apparent heat release rate (dQ/dt) for a constant-volume chamber ($dV/dt = 0$) is proportional to the pressure-rise rate (dP/dt):

$$dQ/dt = \gamma/(\gamma-1) \cdot P \cdot dV/dt + V/(\gamma-1) \cdot dP/dt \quad (1)$$

where V is the chamber volume ($1.167 \times 10^{-3} \text{ m}^3$) and γ is the specific heat ratio (1.32 at 15% O₂). Each of the four heat release rate records shown in Fig. 2 is an ensemble-average of more than 20 injection cycles. The average of these four is then used for the fuel-to-fuel comparisons.