

The Influence of Ethanol Blending in Diesel fuel on the Spray and Spray Combustion Characteristics

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ABSTRACT

The influence of ethanol blending in Diesel fuel on the spray and spray combustion characteristics was investigated by performing experiments in an optically accessible high-pressure / high-temperature spray chamber under non-evaporating, evaporating and combusting conditions. Three fuels were investigated: (1) Diesel - a European Diesel based on the EN590 standard; (2) E10 - a blend of Diesel containing 10% ethanol and 2% emulsion additive; and (3) E20 - a blend of Diesel containing 20% ethanol and 2% emulsion additive. A constant gas density of 24.3 kg/m³ was maintained under non-evaporating (30 °C, 21.1 bar), evaporating (350 °C, 43.4 bar), low combustion temperature (550 °C, 57.3 bar) and high combustion temperature (600 °C, 60 bar) conditions. A single-hole injector with a nozzle diameter of 0.14 mm was used and injection pressure was held constant at 1350 bar. Various optical methods were used to characterize the non-combusting and combusting sprays.

Despite the differences in the fuels' compositions, they did not differ significantly with respect to their liquid phase spray penetrations or cone angles under non-evaporating or evaporating conditions. However, under combusting conditions, reducing the ambient temperature increased the ignition delay and delayed the onset of soot formation for all fuels. Under equivalent combustion conditions, E10 and E20 had longer ignition and soot formation delays than Diesel. As the ethanol content of the fuel was increased from 0% to 20%, the lift-off length increased and the detectable soot luminescence decreased.

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INTRODUCTION

Two key objectives for the transport sector are to reduce vehicular emissions of pollutants and greenhouse gases, and to develop sustainable energy sources. One promising way of achieving both these goals is to increase the use of renewable fuels. Of the existing renewable fuels, ethanol is considered particularly promising because it can be produced in large volumes via the second generation process. Diesel combustion produces large quantities of particulate emissions and NO_x, both of which are troublesome pollutants. It has been reported that such emissions from light duty Diesel engines can be reduced by replacing neat Diesel with Diesel-ethanol blends [1, 2]. Similarly, a study on a heavy duty Diesel engine showed that its smoke emissions could be reduced significantly by replacing neat Diesel fuel with blends containing 5% or 10% ethanol [3].

In addition to these engine experiments, it has been shown that Diesel-ethanol blends exhibited shorter a spray penetration and a larger spray cone angle than pure Diesel fuel [4, 5]. Spray combustion characteristics, soot formation and oxidation of a 20% ethanol in soybean biodiesel blend

have also been investigated [6]. However, there is little detailed information on the spray characteristics of Diesel-ethanol blends under non-combusting and combusting conditions. Such data would be very useful in explaining the influence of ethanol blending on sprays and spray combustion in general, and on soot formation in particular. For this reason, spray experiments were conducted using conventional Diesel and two Diesel-ethanol blends to investigate the resulting sprays' properties as well as their ignition and combustion characteristics. The effects of fuel composition on spray properties such as penetration and cone angle were studied under non-combusting conditions, while effects on combustion characteristics such as the ignition delay, OH* chemiluminescence, lift-off length and soot luminescence were studied under combusting conditions.

EXPERIMENTAL METHODS

The experimental rig is a high-pressure / high-temperature chamber (see Figure 1). Compressed air at pressures of up to 100 bar is delivered continuously by a 4-stage piston compressor and can be heated to a maximum of 900 K before

entering the chamber. The compressed air flows through the inner chamber which has a volume of about 2 liters at a flow velocity of ~ 0.1 m/s. This is much slower than the velocity of the injected fuel, so it can be assumed that the gas conditions inside the chamber are quiescent. The temperature of the injector is controlled by circulating cooling water (indicated in dark blue in Figure 1) through the part of the chamber head where the injector is mounted. A Bosch second generation common rail system was used in this experiment and the injection pressure was maintained at 1350 bar. A solenoid single-hole injector with a nozzle diameter of 0.14 mm was used. The energized injection duration was set at 1.5 ms for non-combusting conditions. For combusting conditions it was set at 3.5 ms to ensure that a quasi-steady-state flame was established. The gas density was kept constant at 24.3 kg/m^3 during all experiments. The fuels and the optical methods used to characterize the sprays and spray combustions are described below.

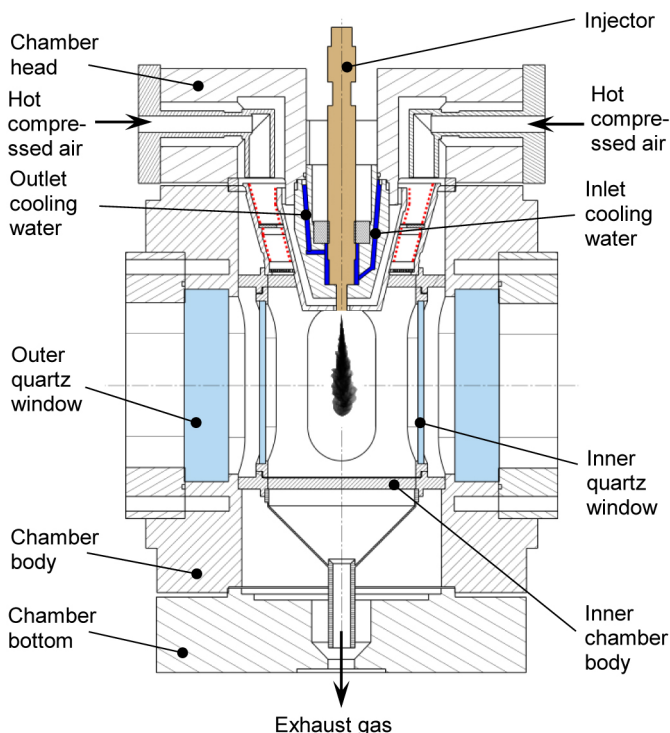


Figure 1. Sketch of the spray chamber

Experimental Conditions

Spray characteristics were investigated under non-combusting and combusting conditions. Table 1 shows the chamber conditions imposed in each case. The injection durations shown in Table 1 are longer than the time the injector was energized and were determined from high speed video recordings.

Table 1. Experimental conditions

Test conditions		Gas Density (kg/m^3)	Ambient temperature ($^{\circ}\text{C}$)	Ambient pressure (bar)	Injection duration (ms)
Non-combusting	Non-evaporating	24.3	30	21.1	~ 1.9 ms
	Evaporating		350	43.3	
Combusting	Lower temperature		550	57.3	~ 4.2 ms
	Higher temperature		600	60	

Fuels

Three fuel mixtures were used in the experiments: Diesel based on the European EN590 standard, E10 (10% ethanol and 88% Diesel) and E20 (20% ethanol and 78% Diesel). Each Diesel-ethanol blend also contained 2% of a solubility-enhancing additive provided by AkzoNobel Surface Chemistry. The additive was mixed with ethanol, and then Diesel was added and mixed in using a propeller agitator. The resulting blends were stable for well over 3 months. Table 2 shows the properties of Diesel and ethanol.

Table 2. Fuel properties

	Diesel	Ethanol
Formula	C_xH_y	$\text{C}_2\text{H}_5\text{OH}$
Density (kg/m^3) at 15°C	842	793.6
Boiling point ($^{\circ}\text{C}$)	192.5-358.0	78.8
Flashpoint ($^{\circ}\text{C}$)	78	13-14
Cetane number	52.0	5-8
Net heat of combustion (MJ/kg)	42.9	26.8
Kinematic Viscosity at 40°C mm^2/s	2.0 – 4.5	1.6
Sulphur content (mg/kg)	7	-

Optical Methods

Several optical methods were used to measure various spray characteristics as shown in Figure 2. Liquid phase spray properties were studied by shadowgraph imaging using a diffuse screen in front of a halogen lamp. The edges of the fuel vapor clouds could be discerned in the shadow images due to refraction at the vapor-air boundary, where there are relatively sharp gradients in composition and temperature. However, to facilitate vapor edge detection and batch image processing, an approach called background grid distortion was adopted [7]. This method was presented by Schardin as "schlieren method no. 2" [8], and then adapted for vapor phase detection in fuel spray imaging by Ochoterena [9]. The optical setup for background grid distortion differs from that for shadowgraph imaging in that a pattern of interchanged transparent and opaque strips is added to the screen; the technique is

discussed in more detail below. Shadowgraph and background grid distortion images were captured using a monochromatic non-intensified high-speed video camera with a 105-mm focal length lens. The exposure time of camera was set at 2 μ m for shadowgraph imaging and 3 μ m for the background grid distortion imaging. The resolution was 528 $\times$ 192 with 12 bits per pixel and the frame rate of the high-speed camera was set at 20,000 frames per second for both methods.

OH* chemiluminescence images and soot luminescence images were acquired using intensified CCD (ICCD) cameras, and a UV-reflecting dichroic beam splitter were placed in front of cameras. A UV-transmitting 94-mm focal length lenses and a 308 nm bandpass filter with a 10 nm FWHM were used for OH* chemiluminescence imaging, and a 630 nm long pass filter was used for soot imaging. The cameras had a resolution of 1024 $\times$ 1024 pixels with 16 bits per pixel, and their gate times were set at 0.08 ms. However, different ICCD gains were used for each camera because the intensity of the soot luminescence was much stronger than that of OH* chemiluminescence. The triggering of the two ICCDs, the high speed camera, and the injector was synchronized using a Stanford Digital Delay Generator DG535.

Integrated OH* and soot luminescence intensities were determined using photomultiplier tubes (PMT) with spectral sensitivity ranges of 250–750 nm. Light entering the PMTs was filtered to permit the passage of UV light for OH* measurement or red light for soot measurement, and the output of the PMTs was recorded by a computer-based data recording system. The resulting data were used to determine the ignition and soot formation delays.

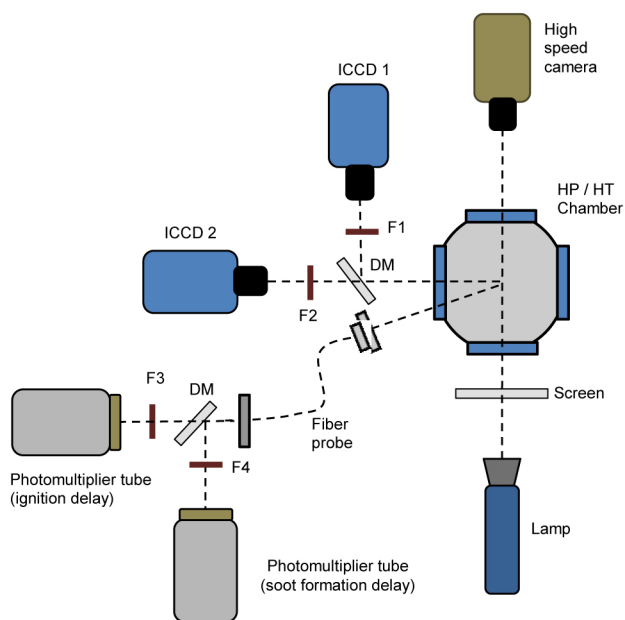


Figure 2. Schematic of the optical setup for shadowgraph imaging, capturing images of OH* and soot luminescence, and determining ignition and soot formation delays. DM: dichroic mirror, F1: 308 nm (10 nm FWHM), F2: RG630, F3: 300 nm (25 nm FWHM), F4: RG610 nm.

RESULTS AND DISCUSSION

This section is divided into two parts discussing spray characteristics under non-combusting and combusting conditions, respectively. Under non-combusting conditions, spray experiments were conducted to study the effects of fuel composition on spray properties such as liquid phase spray penetration and the spray cone angle. Under combusting conditions, experiments were performed to study liquid- and vapor-phase spray penetration as well as the effect of fuel composition on combustion characteristics, such as ignition delay, soot formation delay, OH* chemiluminescence, lift-off length and soot luminescence.

Non-combusting Conditions

Liquid phase spray properties were investigated by capturing shadowgraph images. A representative set of spray images obtained under non-evaporating, evaporating and combusting conditions from one injection event are shown in Figure 5. To obtain statistically reliable data on liquid phase spray parameters for different fuels, all reported spray parameters were calculated by taking averages from around 100 separate injection events, i.e. about 100 high speed videos were recorded under each set of test conditions. The processing of liquid phase spray images is illustrated in Figure 3: subfigure (a) shows a background image recorded just before fuel injection; (b) shows an image acquired at 1.5 ms after start of injection (ASOI); and (c) is the image obtained by subtracting the spray image (b) from the background image (a). The spray boundary was then defined using an intensity threshold of 0.0588 (15/255) and is indicated by the white line around the edge of the spray in image (c). The threshold for converting subtracted spray images to binary images is based on the slope of the declining transmitted light intensity and a threshold slope value is used to define the boundary of the liquid spray. A similar method was used by Siebers [10]. The threshold points for non-evaporating, evaporating and combusting conditions were selected based on the signal-noise level in each case and were 15/255, 20/255 and 20/255, respectively; for further details, see reference [11].

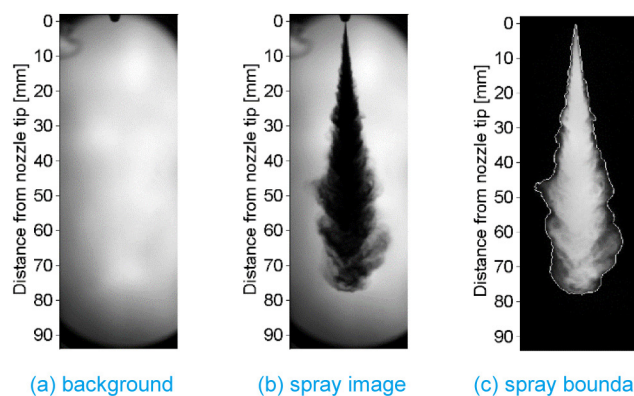


Figure 3. Liquid phase spray image processing. Experimental conditions: Diesel fuel, non-evaporating conditions: ambient temperature 30 °C with ambient pressure 21.