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Microscopic imaging of the initial stage of diesel spray formation

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HIGHLIGHTS

- We captured microscopic images of diesel, kerosene and RME at diesel engine conditions.
- The fluid exits the nozzle with a mushroom-like structures that propels a ligament.
- We propose that fuel can remain trapped in the injector holes after injection.
- We showed this mechanism occurs under typical diesel engine conditions.

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ABSTRACT

Detailed measurements of near-nozzle spray formation are essential to better understand and predict the physical processes involved in diesel fuel atomisation. We used long-range microscopy to investigate the primary atomisation of diesel, biodiesel and kerosene fuels in the near-nozzle region, both at atmospheric and realistic engine conditions. High spatial and temporal resolutions allowed a detailed observation of the very emergence of fuel from the nozzle orifice. The fluid that first exited the nozzle resembled mushroom-like structures, as occasionally reported by other researchers for atmospheric conditions, with evidence of interfacial shearing instabilities and stagnation points. We captured the dynamics of this phenomenon using an ultra-fast framing camera with frame rates up to 5 million images per second, and identified these structures as residual fluid trapped in the orifice between injections. The residual fluid has an internal vortex ring motion which results in a slipstream effect that can propel a microscopic ligament of liquid fuel ahead. We showed that this mechanism is not limited to laboratory setups, and that it occurs for diesel fuels injected at engine-like conditions with production injectors. Our findings confirm that fuel can remain trapped in the injector holes after the end of injection. Although we could not measure the hydrocarbon content of the trapped vapourised fluid, we observed that its density was lower than that of the liquid fuel, but higher than that of the in-cylinder gas. We conclude that high-fidelity numerical models should not assume in their initial conditions that the sac and orifices of fuel injectors are filled with in-cylinder gas. Instead, our observations suggest that the nozzle holes should be considered partially filled with a dense fluid.

1. Introduction

The importance of the problem of spray breakup for various applications is well recognised and has been extensively studied experimentally and theoretically [1–9]. A rigorous theory of spray breakup would be very complex as it would need to involve modelling of nozzle flow, cavitation, instabilities, the initial formation of ligaments and droplets and their subsequent breakup, evaporation, the entrainment of air and the effects of turbulence [3]. Experimental characterisation of the initial stage of diesel jet formation and primary breakup under realistic engine conditions is challenging due to the harsh environment in which they take place. This inherent complexity is compounded by the highly transient nature of the processes involved, along with the elevated velocities and the microscopic scale at which they occur. Direct visualisation techniques are invaluable to improve the fundamental understanding of primary breakup but because of the challenges posed by the conditions under which diesel jets occur, simplified experiments are often used to infer breakup characteristics at normal operating conditions. In particular, the injection and gas pressures are often reduced, the injector geometry simplified, and the fuel replaced by a more convenient fluid.

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Microscopic imaging experiments of diesel sprays have been reported in the literature (e.g. [5,10–13]), although at atmospheric conditions and with varying degrees in the quality of the images produced. Satisfactory lighting can be particularly difficult to obtain at microscopic level. High-power short duration laser pulses may seem appropriate, but speckle patterns caused by the interference of reflections of such coherent monochromatic light conceal the underlying morphology of the spray, thus significantly degrading the quality of the resulting images and making their interpretation limited. Such optical artifacts can be observed in images recorded by Lai et al. [11], Badock et al. [12] and Heimgärtner & Leipertz [5], for example. Speckle patterns can be avoided by using a spark light instead of a laser, but the duration of the spark flashes are significantly longer and lead to motion blurring, even at low spray velocities, unless the exposure can be accurately controlled by the imaging device. The relatively long and random jitter associated with the timing of the spark can also lead to a significant proportion of 'missed' acquisitions which, combined with the long recharge time of the high-voltage electronics, may significantly lengthen the experimental work. The LED technology has advanced rapidly, and can now provide low-jitter sub-nanosecond [14] and high-frequency light pulses [15]. However, the energy output of high-power LEDs is still insufficient to enable blur-free microscopic imaging of high-speed sprays. The challenging lighting requirements for such experiments has limited their application to atmospheric conditions, with the exception of our preliminary studies [16–19], and the recent work of Manin et al. [20]. Additional complications introduced in high pressure and temperature environments include the presence of turbulence, density and temperature gradients in the gas phase, which will result in refractive index fluctuations.

In this study we present high-resolution microscopic, as well as ultra-high-speed, images of diesel sprays at both atmospheric and diesel engine-like operating conditions. The still images were obtained by spectrally diffusing a Nd:YAG laser pulse and provide high-resolution blur-free observations of the injection process at a microscopic scale. A limitation associated with still imaging is the inherent lack of information on the spatio-temporal evolution of the transient jet and droplets observed. Specifically, there is no information on the velocity field, a quantity which is of particular significance for the investigation of breakup and essential for the approximation of relevant parameters such as the Weber and Reynolds numbers. In order to complement the fine spatial information derived from the still images, an ultra-fast framing camera was then used to accurately record the temporal evolution of diesel sprays at microscopic scales, with a second high speed camera simultaneously recording the macroscopic evolution of the complete spray. This allowed a precise tracking of the temporal evolution of diesel jets from the actual start of fuel delivery, thus eliminating the timing uncertainty associated with single images. This is particularly relevant when the transient jets being observed evolve over a shorter timescale than the mechanical and hydraulic jitters associated with solenoid-actuated servo-valve diesel injectors.

2. Experimental configurations and data acquisition

2.1. Rapid compression machine

The experiments were carried out using a reciprocating rapid compression machine (RCM) based around a Ricardo Proteus single cylinder engine converted to liner-ported, 2-stroke cycle operation [21]. The removal of the valve train allowed the fitting of an optical chamber of 80 mm in height and 50 mm diameter into the cylinder head. The optical access to the combustion chamber was provided by three removable sapphire glass windows. Due to the increased volume of the combustion chamber the compression ratio was reduced to 9:1. To simulate a real diesel engine with a compression ratio of 19:1, the intake air was conditioned to give in-cylinder pressures and temperatures up to 8 MPa and 540 K, respectively. For the present experiments the peak in-cylinder temperature was intentionally kept low in order to inhibit autoignition. Prior to motoring the RCM, the cylinder head was heated by a water jacket to 85 °C and immersion heaters heated the oil to 40 °C. The RCM was motored by a dynamometer to 500 rpm, and kept at stable in-cylinder conditions for the duration of the recordings. Scavenging on the in-cylinder gases was done by skipping injections for several cycles. This approach still allowed an acquisition frequency of several fuel injections per second. The test conditions are summarised in Table 1, including the in-cylinder motored peak pressure, gas temperature and injection pressure. For each condition, microscopic images were recorded at a range of locations within the spray.

2.2. Fuel injection equipment

The fuel was delivered by a Delphi common-rail system, comprising a DFP-3 high-pressure pump rated at 200 MPa, and a seven hole DFI-1.3 injector with a VCO type nozzle. The high-pressure rail and the delivery pipe were both instrumented with pressure transducers. The rail pressure, timing and duration of the injection were independently controlled by a purpose-built EmTronix fuel injection controller. The nozzle's orifices were cylindrical with a diameter of 135 μm and a length of 1 mm. The nozzle had an equivalent cone angle of 154°, and the injector was mounted horizontally relative to the cameras. This injector was extensively characterised on a macroscopic scale by high-speed video and laser diagnostics [22]. Since the focus of this study is on the initial spray formation, and as all images were captured long before the end of the injection event, it was not necessary to control the total mass of injected fuel. Instead, an injector trigger pulse with a fixed duration of 550 μs was used for all conditions.

The fuels, listed in Table 2, were chosen to obtain a wide range of physical properties. The fossil diesel fuel was an ultra-low sulphur, non-additised, reference fuel representative of automotive diesel. The RME, compared to the fossil diesel, has a substantially increased viscosity and lubricity with a small increase in surface tension. Kerosene was chosen for its opposite trend in physical properties compared to RME, which can assist to indirectly substantiate comparisons between RME and fossil diesel.

2.3. High-resolution microscopy

The optical experimental setup is shown in Fig. 1. The pump light source used for still imaging conditions was a frequency-doubled Nd:YAG laser with a pulse duration of 7 ns. The light pulse was spectrally broadened using a fluorescence diffuser, and spatially expanded from 8 mm to 100 mm in order to provide homogeneous illumination over a sufficiently large area, with an effective exposure of 20 ns. Two dual-frame Peltier-cooled 12 bit CCD cameras were used to simultaneously visualise the sprays at the microscopic and macroscopic scales. The camera facing the light source was fitted

Table 1
Operating conditions for microscopic imaging.

Gas pressure (MPa)	Gas temperature (K)	Injection pressures (MPa)
0.1 MPa	293	40; 100
4 MPa	540	40; 100; 160
6 MPa	540	40; 100; 160
8 MPa	540	40; 100; 160