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Preliminary Investigation of Propane Spray Structure in an Optically Accessible Direct-Injection, Spark-Ignition Engine

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Abstract

Liquefied petroleum gas (LPG) has attained a significant position in various markets throughout the world, as it has numerous benefits as an automotive fuel in spark-ignition (SI) engines. Fuelling a direct injection (DI) engine with LPG, rather than conventional, liquid fuels, has the potential to improve fuel efficiency and emissions output. However, there is little information pertaining to the operation of LPG in such vehicles. Therefore, this study aims to begin to characterise DI propane sprays, acting as a surrogate for LPG, in a DISI engine at injection timings corresponding to both an early, homogeneous strategy and a late, stratified strategy. Fuel spray structures are imaged using a production DISI engine modified to have optical access through a fused silica cylinder liner. Using Mie-scattering to resolve the liquid phase injection, propane sprays are observed to be heavily flash-boiling at both injection conditions. This is in contrast to heavier, liquid fuels where flash-boiling generally occurs only for chamber conditions well below atmospheric pressure.

Introduction

Modern SI engine research is focused on the improving fuel efficiency and reducing the emissions output of the engine. In order to achieve these goals a combination of innovations and advanced technologies will be required. DI is an internal combustion strategy that offers several known benefits. Compared with port fuel injection (PFI), DI engines improve fuel economy due to a more precise metering of the air-fuel ratio. Additionally, DI is not subject to intake manifold wall-wetting as is PFI, and DI has a thermodynamically beneficial cooling effect on the in-cylinder charge. This charge cooling effect helps suppress autoignition of the fuel charge, and allows for higher compression ratios, as well as lower heat losses to the cylinder walls [4, 8]. Some DI implementations have as much as 20 % higher fuel economy than PFI equivalents [3]. Moreover, a DI strategy enhances the fuel injection transient response with respect to the crank angle position [11]. This transient response and the ability for accurate fuel placement within the combustion chamber improve cold-start emissions [2] and CO_2 output is decreased by virtue of the increased fuel efficiency of a DI engine.

In contrast with the previous emissions regulations, Euro 6b legislates not only the particulate mass production limit, but also the particulate number production. A further emission restriction is proposed in Euro 6c effective in September 2017 and this will likely require additional advances in DI technology [1]. One potential solution to comply with this proposed legislation is to use an alternative fuel, such as LPG. LPG is an attractive alternative fuel for SI engines, as it offers a higher octane number and more knock resistance than conventional pump gasoline. LPG also has the benefit of producing less energy-specific CO_2 emissions, and it has less tendency to produce particulate emissions compared to heavier, liquid fuels. A thorough study by Krieck et al. [5] supports the idea, as they found that LPG fuel produces a negligible amount of soot and around 33 % lower hydrocarbon emissions compared with traditional liquid fuel (gasoline) in all engine conditions. LPG is also relatively less expensive than gasoline even when accounting for density differences, making the fuel financially attractive to consumers.

There are several obstacles that must be overcome in order to realise the potential benefits of DI LPG in production vehicles. One of the challenges in using LPG is that its composition is not standardised and varies in different countries. At this point in time, there is limited literature regarding the performance of LPG in SI engines, and a dearth of information about DI LPG fuel delivery and spray mechanisms. As the implementation of a DI system in an engine is strongly dependent on a comprehensive understanding of the fuel spray, the lack of knowledge regarding DI LPG currently prevents the commercial viability of this technology.

Some of the first optical investigations of DI propane (used as a surrogate for LPG) at engine-like conditions was conducted by Lacey et al. [6] in a constant volume chamber. In this study, a range of chamber pressures and temperatures representative of GDI cylinder conditions was explored using DI propane in an experimental GDI injector. The results indicated that the spray structure of propane (used as an LPG surrogate) exhibits significantly more variability than that of iso-octane (used as a surrogate for gasoline) throughout a range of potential combustion chamber conditions. Because of its high vapour pressure, propane fuel sprays are subject to severe flash-boiling throughout the majority of chamber conditions corresponding to the GDI operating range, whereas heavier fuels like iso-octane tend to flash-boil only in a narrow range of chamber pressures well below atmospheric pressure. The similar result patterns are also observed in an earlier study of LPG spray behaviour at different back pressures by Mesman and Veenhuizen [7] from investigating propane spray behaviour in a constant-volume cylindrical chamber. In different engine back pressures, they found that propane spray penetration decreases following the increase the back pressures. Flash-boiling spray developments were also exhibited in their results as the back pressure decreases to atmospheric pressure, due to the pressure difference between back pressure and rail pressure. Spray angle was also the parameter of interest in their study, and they observed that it is only affected by the back pressure; variation in fuel injection pressure does not exhibit any correlation with the spray angle. Regardless the very few studies that have been performed to characterise the DI propane spray, to date none has contributed to the DI propane characterisation study in an actual, practical DI engine.

Thus, despite the promising benefits of an LPG-fuelled, DISI engine, more study of the fuel delivery mechanisms are required in light of the high degree of structural variability in propane sprays. Therefore, this study is intended as an initial investigation of how DI propane spray is expected to behave in the

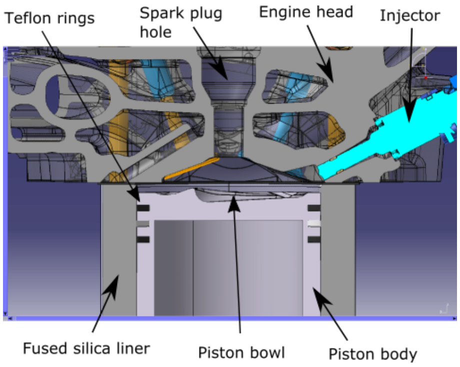


Figure 1: Cross-section of the optical cylinder of EcoBoost engine

2.0L Ford GTDI (EcoBoost)	
Bore (mm)	87.5
Stroke (mm)	83.1
Compression ratio	9.3

Table 1: Specification of the optical engine

combustion chamber of a production engine.

Experimental Apparatus

Modified Direct-Injection Engine

A 4-cylinder, 2.0L Ford EcoBoost DI engine was modified for optical access to perform the experiments. In its optical configuration, the cylinder head and engine block were separated from one another to allow the installation of a fused silica cylinder liner in the cylinder 1 position. The internal geometry of the combustion chamber was designed to closely resemble the stock configuration using extended pistons to preserve the factory compression ratio and mimic the stock piston crown geometry. A cross-section of cylinder 1 in the optical EcoBoost engine is shown in figure 1. The injector used on this EcoBoost engine is a 7-hole, Bosch HDEV 5.1.

Test Conditions

For this initial investigation, two different injection timings were selected to represent cylinder conditions for part-load operation; an early, throttled, homogeneous injection, as well as a late, stratified injection. These were both performed at 600 RPM in a room temperature, motoring engine. The tested conditions are summarised in table 2.

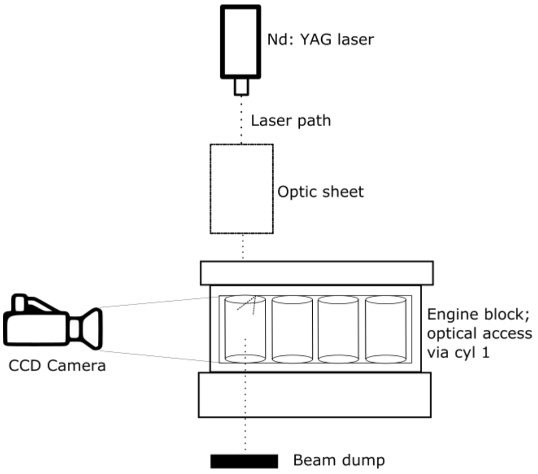


Figure 2: Simplified schematic diagram of the experimental setup

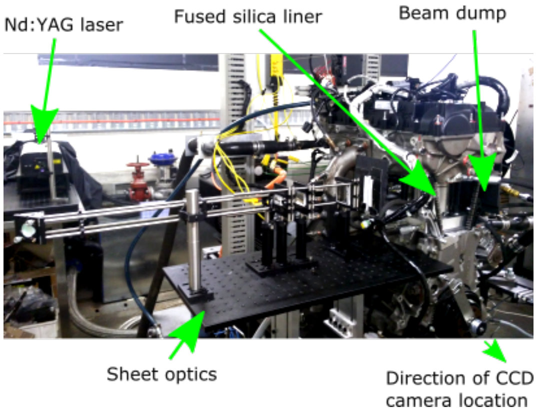


Figure 3: Mie-scattering experimental setup

Optical Spray Imaging Setup

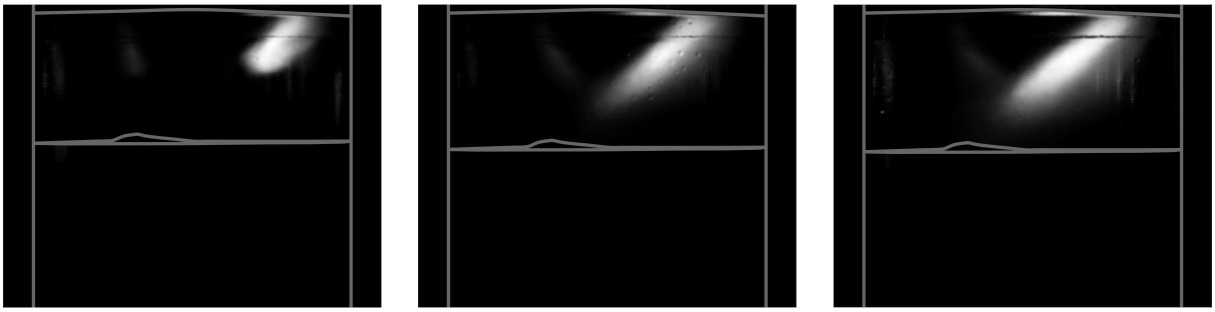
Mie-scattering is used to resolve the liquid phase of the DI propane sprays in this study. It is applicable to the scattering of light through a dense particle of similar wavelength as the incident light [9]. It is commonly used to image automotive fuel sprays, as the wavelength of commercial laser systems and the expected size of liquid fuel droplets are comparable.

The Mie-scattering illumination was provided by a Quantel Brilliant B Nd:YAG laser. The 2nd harmonic of the laser's fundamental wavelength was utilised, so that a 532 nm beam was passed through a set of sheet optics and into the optical cylinder liner of the engine. The light sheet was located through the center of the cylinder bore (orthogonal to the piston surface), and with a height of 45 mm, extending down from the interface between the liner and cylinder head. At its focal point in the center of the bore, the thickness of the sheet is approximately 1 mm. A CCD LaVision Flowmaster camera has a 105 mm Nikkor lens at f/8 was used to image the fuel spray. A simplified schematic of the setup is shown in figure 2 and the light path hardware is illustrated in figure 3.

Conditions	Early Injection Event	Late (Stratified) Injection Event
Start of injection, SOI (CAD)	290 bTDC	100 bTDC
Image timing (CAD ASOI)	3, 5.4, 6.5	
Intake manifold air pressure, IMAP (bar)	0.6	0.8
In-cyl pressure at SOI (bar)	0.6	1.03
Injection duration (ms)	1.5	
Engine speed (RPM)	600	
Injection pressure (bar)	45	
Fuel temperature (°C)	20	

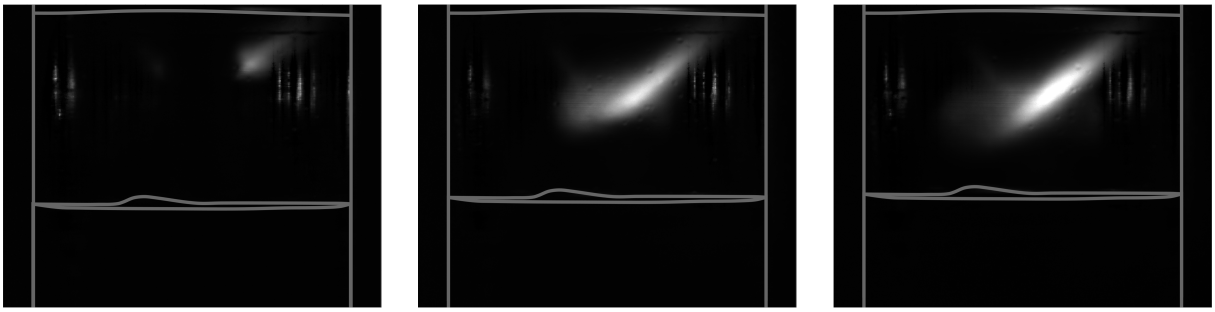
Table 2: Optical EcoBoost engine test conditions for early and late injection cases

The YAG laser runs at a frequency of 10 Hz and each laser pulse has a duration of 5 ns. The rising edge of the flashlamp pulse was synchronised with a timing trigger generated from the ECU at a configurable crank angle position. With a known engine



(a) (b) (c)

Figure 4: Early spray injection event at 290 bTDC at different times ASOI: (a) 3 CAD ASOI (at 287 bTDC); (b) 5.4 CAD ASOI (at 284.6 bTDC); (c) 6.5 CAD ASOI (at 283.5 bTDC)



(a) (b) (c)

Figure 5: Late spray injection event at 100 bTDC, at different times ASOI: (a) 3 CAD ASOI (at 97 bTDC); (b) 5.4 CAD ASOI (at 94.6 bTDC); (c) 6.5 CAD ASOI (at 93.5 bTDC)

speed and Q-switch delay configured internal to the laser, it was possible to accurately determine the CAD position of the laser pulse.

Image Processing and Piston Location Tracing

A camera calibration was initially performed to correct any aberrations from the camera lens or distortions due to the cylindrical shape of the optical liner. A standard checkboard target was placed inside the optical liner, and using the MATLAB camera calibrator toolbox, a transformation matrix was generated to correct for the cylindrical liner lensing effect. The images were collected using the full sensor frame, resulting in an image size of 1280 by 1024 pixels. Future work will focus on further post-processing of these images.

For each experimental condition, fifty spray images were collected. After some rudimentary corrections using the distortion correction matrix, the processed images were ensemble-averaged. Then, the piston crown position is superimposed onto each ensemble-averaged image using a high contrast version of the raw images to scan and locate the piston edge.

Results and Discussions

Optical EcoBoost DI Engine Spray Structure Analysis

Figures 4 and 5 show the evolution of the DI propane spray for early and late injection timings, respectively. In both cases, the pressure of the chamber is below the saturation pressure of propane ($\sim$8.4 bar) at its temperature in the fuel rail. This is highlighted in figure 6, which shows the condition of the propane in the rail against the saturation dome and the pressures of the cylinder for each injection timing in this study. To reach the chamber pressure, the liquid phase propane must pass through the saturation dome, therefore there will be significant vaporisation due to flash-boiling. Both sprays in figures 4 and 5 exhibit a collapsed spray structure that is indicative of severe flash-boiling [10, 6]. The flashing ratio, commonly used to quantify the severity of flash-boiling, can be calculated at each condition using equation 1.

$$R_p = \frac{P_{sat}(T_{fuel})}{P_{ambient}} \tag{1}$$

For the early injection, the flashing ratio is 14 and for the late injection it is 8.15. Both are significantly greater than unity and past the point of ”flare-flashing” as defined in [10]. Unlike fuels that are liquid at standard conditions, propane is heavily flash-boiling at all chamber conditions relevant to GDI strategies. Because of this, propane is expected to be governed by flash-boiling mechanisms at both early and late injection timings.

Though the propane sprays at each injection timing are in the flash-boiling regime, they are subject to different flashing ratios and chamber densities, therefore there is some contrasting behaviour in the time evolution of the sprays. At time 3 CAD ASOI, the liquid phase of the late injection penetrates less into the combustion chamber in figure 5a, and the overall liquid core is less broad than that of the early injection in figure 4a. This behaviour is consistent with classical studies of liquid-phase injection, as decreasing the backpressure will increase spray penetration into the chamber (0.6 bar and 1.03 bar figures 4a and 5a, respectively). However, one key difference between DI propane sprays and conventional fuels is that in both cases the propane sprays are severely collapsed, even when the chamber is above atmospheric pressure in figure 5a. Conventional, liquid fuels,

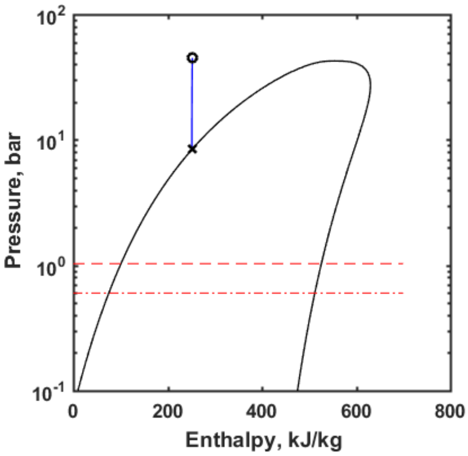


Figure 6: Transition of propane during the fuel injection event; ○ indicates the fuel rail condition (45 bar, 20 °C); × indicates the conditions of saturated, liquid propane (8.36 bar, 20 °C); — indicates a simple isothermal transition; - - - illustrates chamber pressure at late injection (1.03 bar); -.- illustrates chamber pressure at early injection (0.6 bar).

particularly at the low temperatures in these tests, would only experience severe flash-boiling at highly throttled conditions.

The spray images in figures 4b/4c and 5b/5c, corresponding to the early and late injections at 5.4 and 6.5 CAD ASOI, illustrate the continued evolution of the sprays as they penetrate into the chamber. By comparison, the maximum extents of the liquid phase in the horizontal and vertical directions are similar between the early and late injection cases at 5.4 and 6.5 CAD ASOI. In contrast, the overall area of the liquid cores are dissimilar, as the late-injected propane spray in the higher chamber pressure is more thin and elongated in figures 5b and 5c than that of the early injection in figures 4b and 4c. This trend is intriguing, as the sprays in figures 4b and 4c have a higher flashing ratio and should collapse more severely (appear more elongated) than those of figures 5b and 5c. This intuition is largely based on the results of sprays in quiescent chambers, and highlights the potential impact of a non-quiescent chamber on DI propane flows. As the DI propane at both SOIs have highly enhanced atomisation due to flash-boiling, it is possible that there is an additional effect from the increased aerodynamic drag forces and turbulence in the higher pressure chamber of the 100 bTDC SOI case. As it is injected into a higher pressure chamber with the piston travelling towards the spray, it is feasible that there is increased liquid breakup due to the increased density of the chamber and turbulent motion. The combination of flash-boiling atomisation and faster breakup could explain the smaller liquid core area in figures 5b and 5c compared with 4b and 4c, as liquid residence time is reduced in the chamber. Future efforts to study these effects will be required to conclusively determine the reasons for these phenomena.

Conclusions

Propane fuel spray structures in a production EcoBoost DI engine at early and late injection events were investigated. Utilising the Mie-scattering technique, it was observed at both injection timings that the fuel sprays displayed strong flash-boiling behaviour, with the spray collapsing into a single, liquid jet. Unlike conventional, liquid fuels, propane is capable of severe flash-boiling at pressures well above atmosphere, corresponding to the chamber conditions of a late, stratified GDI strategy. Moreover, the time evolution of severely flashing, DI propane is complex and cannot be explained at all times ASOI with a simple measurement of cylinder pressure. This has potential implications for DI engine design and implementation, as propane operates exclusively in the flash-boiling regime for the entirety of GDI operation, in contrast to gasoline. Further study is warranted to establish a comprehensive understanding of the mechanisms governing DI propane sprays.

Acknowledgements

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