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On the phase and structural variability of directly injected propane at spark ignition engine conditions

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ABSTRACT

This paper presents an experimental and theoretical examination of directly injected (DI) propane at a wide range of conditions relevant to spark ignition engines. The investigated conditions comprise the injection of sub- and supercritical propane, with the latter representing a plausible, operational extreme during engine heat soak.

Optical imaging is first used to study a wide range of observed spray behaviors, highlighting the sensitivity of DI propane to the engine operating condition. These varying behaviors then prompt further consideration of the thermodynamics involved. This extends thermodynamic arguments recently proposed by the authors in another work, and is able to explain when supercritical injection contains the liquid phase, when shock structures appear and when the spray collapses. Spray regime diagrams are then proposed in order to generalize the observed behaviors. These diagrams reveal several, often overlapping regimes that demarcate choked and unchoked injection, collapsed and multi-plume sprays, and the appearance or disappearance of the liquid phase immediately outside of the injector.

1. Introduction

Direct injection (DI) technology in spark ignition (SI) engines is becoming more common due to its superior performance relative to port fuel injection (PFI) [1–3]. The charge cooling of DI allows higher compression ratios. DI also offers accurate fuel targeting, which combined with precise fuel metering, yields improved fuel economy.

The use of some alternative fuels also has the potential to further reduce engine-out emissions and increase fuel efficiency. Liquefied petroleum gas (LPG) is one alternative fuel that offers lower regulated pollutant and greenhouse gas (GHG) emissions compared to conventional liquid fuels. LPG is a mixture that is predominantly propane and butane, and has an octane rating which exceeds that of gasoline. LPG is also of relatively low cost [4–8]. These advantages make LPG an attractive alternative fuel, particularly in DISI applications [9–12].

However, it is well-recognized that the performance of DI technology is tightly coupled with the physical properties of the fuel. While the spray dynamics of gasoline and alcohols have been extensively investigated, e.g. [13–22], those of LPG and its surrogates have received relatively little attention, e.g. [8,23,24]. This lack of knowledge potentially limits the benefits that can be realized from the implementation of DI LPG in SI engines.

The high vapor pressure of LPG and its major constituents makes it susceptible to flash-boiling over almost the entire engine operating range, including late stratified injection conditions [8,24]. It also suggests that at sufficiently low injection pressures (e.g. those typical of low-load and idle DISI engine operation), propane may transition to the vapor phase prior to injection, which is problematic for fueling systems designed for liquid fuel delivery. Such varied behavior presents challenges to DI LPG in SI engines [25].

The low critical temperature of LPG, particularly propane-rich mixtures, also suggests that the fuel may transition to a supercritical state prior to injection under engine "heat soak" [26,27]. This occurs when the engine is turned off and the coolant ceases to circulate. The thermal energy stored in the warmed up engine then passes into the coolant and fuel, raising their temperature for a period, prior to eventual cooling of the entire engine system. Fuel temperatures of 110–120 °C can occur during this time, and if the engine is restarted, fuel at these higher temperatures is then injected [28,25]. Similar temperatures can also be experienced by the fuel at the injector tip

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under firing conditions [15,29]. The impact of supercritical fuel injection on DISI spray structure is presently unclear.

This study therefore investigates the influence of fuel rail and chamber conditions on directly injected propane at modern, SI engine-relevant conditions. Several optical techniques are combined with high repetition rate imaging to explore the phase and structural transitions of multi-plume propane sprays in an optically accessible, constant volume chamber (CVC). The observations are complemented by thermodynamic analyses in order to explain the underlying physics.

2. Methods

2.1. The spray facility

An optically accessible constant volume chamber (CVC) is employed to investigate spray formation under quiescent, non-reactive, DISI engine-like conditions (Fig. 1). This allows for the isolation of certain spray phenomena from the complex flows encountered in the combustion chamber of an IC engine. Fused silica windows with a 90 mm viewing diameter are mounted on three sides of the chamber, allowing both line-of-sight and orthogonal optical access to the fuel spray. The fuel injector is mounted on one side of the vessel using a fixture that incorporates a temperature-controlled cooling jacket. The fuel temperature in the rail is regulated with a length of heat trace. Cartridge heaters embedded in the body of the CVC control the temperature of both the chamber walls and thus the gas inside the chamber. The CVC pressure is controlled using high-pressure nitrogen bottles. Prior to each injection event, the vessel is purged with nitrogen to ensure the presence of a non-reactive environment that is free of residual fuel from previous injections.

The injection hardware used is a symmetrically spaced, 8-hole, experimental GDI injector with a nominal spray angle of 80° (Spray G injector #AV67-018), provided by Delphi through the Engine Combustion Network (ECN) collaboration [30]. The injection duration was 1 ms and the spray images presented are taken at 700 μs after the start of injection (ASI) unless specified otherwise. This particular instant was found to represent the fully developed spray structure.

2.2. Optical diagnostics

2.2.1. Schlieren imaging

Schlieren imaging is a well-established, line-of-sight technique that is commonly used to visualize inhomogeneities in the refractive index of a transparent medium [31]. This technique is commonly used in fuel spray measurements [32–36]. However, it can be difficult to separate the liquid and vapor phases as the level of light extinction by the liquid phase may not be discernible compared to refraction [37,38]. It is therefore sometimes used with other light scattering or extinction-based techniques to distinguish between the liquid and vapor phases, e.g. [8,18].

Fig. 2a demonstrates the schematic of the Schlieren setup. A continuous Xenon light (Olympus CLV-U20) equipped with a fiber-optic light guide was the light source. Passing through a narrow vertical slit of approximately 3 mm width, light was collimated by a 6″ spherical mirror of 60″ focal length and received by an identical spherical mirror placed in a *z-type* configuration. A vertical knife edge was used as the Schlieren cut-off at the focal point of the focusing mirror. The images were sized with an achromatic doublet lens and acquired using a Phantom Miro M310 camera.

A 300 mm lens was employed to visualize the global behavior of an injection event with a 37.6 × 31.4 mm^2 field of view and a scaling factor of 98 μm/px at a 20 kfps sampling rate and a 4 μs exposure duration. A 1000 mm lens was also employed to visualize the time-averaged behavior of an injection event in the near-nozzle region. This had a 15.23 × 10.66 mm^2 field of view with a scaling factor of 23.8 μm/px. The corresponding imaging frequency was set to 10 kfps, and a 80 μs exposure duration was selected.

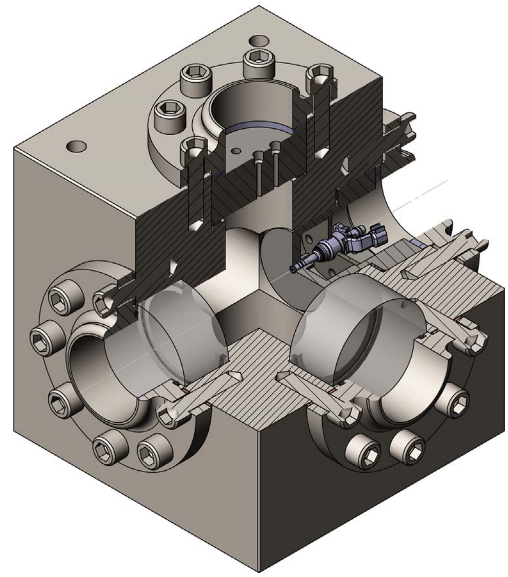

Fig. 1. Schematic of the CVC.

2.2.2. Mie-scattering imaging

This optical technique is based on the elastic scattering of light from liquid droplets of comparable size or larger than the wavelength of the incident light. It is commonly used to visualize the liquid phase of the spray, e.g. [17,38–42]. Fig. 2b illustrates the optical setup for the Mie-scattering imaging. A continuous, collimated, tungsten light source (COOLH dedocool, 500 W in total) was used to illuminate the injection event and a Phantom Miro M310 camera equipped with a 200 mm, $f/4$ Nikkor lens operating at a sampling rate of 20 kfps was employed to capture the scattered light perpendicular to the direction of illumination. Volume illumination was applied to ensure that the entire liquid phase was captured. The sensor exposure duration was also set to 3 μs to ensure sufficient signal in the imaging plane while avoiding sensor saturation.

The recorded images were then processed using a Matlab image-processing routine to extract the boundary of the liquid phase. First, the background image was subtracted from the corresponding raw image sequence to remove the undesirable influence of scattered light from the walls of the chamber. Following Siebers [43], an intensity threshold corresponding to 3% of the maximum recorded signal in the images was then applied. The resulting image was then binarized using a built-in Matlab function to identify the spray outline. Finally, a set of morphological operations (i.e. image erosion, dilation and filling) were then performed prior to extraction of the spray outline to minimize the undesired artifacts of the image-processing. Further details of the image processing routine is discussed elsewhere [44]. The presented penetration profiles are the ensemble average of 20 injections. It was shown that the corresponding penetration profiles converged to a mean after about 10 injection events [44].

2.2.3. Diffuse back-illumination (DBI) imaging

The DBI technique [45] is based on the extinction of incident, diffuse light as it passes through the dense liquid phase [38,42,46]. As shown in Fig. 2b, two continuous tungsten light sources, similar to that used for Mie-scattering imaging, coupled with a ground glass light diffuser were used to illuminate the image background. A Phantom MiroM310 camera was used to capture the image of the spray in the direction of illumination. The camera was equipped with a 200 mm, $f/5.6$ Nikkor lens at a working distance of approximately 1.5 m, corresponding to a 37.24 × 31 mm^2 field of view at 20 kfps. A 90 mm Canon tilt-shift lens ($f/2.8$) provided a field of view of 16.3 × 16.3 mm^2, and was used at a sampling rate of 120 kfps. The sensor exposure duration