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A comparison of diffuse back-illumination (DBI) and Mie-scattering technique for measuring the liquid length of severely flashing spray

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Abstract

A quantitative measure of the liquid penetration length of a directly-injected (DI) fuel spray is one of the important parameters for engine designers and computational spray model development and validation. Spray liquid length gives an indication of important behaviour such as fuel-air mixing or liquid-phase fuel impingement on the piston bowl and cylinder walls. Multiple techniques have been developed to study liquid penetration length, however the uncertainties associated with these methods have not been exhaustively explored for multi-hole injectors with flash-boiling sprays. This work compares two measurement techniques for measuring liquid penetration length of highly flashing sprays in a constant volume chamber. The experimental setup uses the Engine Combustion Network (ECN) Spray G injector and propane injected at varying chamber pressure. The spray liquid length is measured using diffuse back-illumination (DBI) and Mie-scattering techniques. The spray structure is qualitatively similar with both measurement methods, however analysis of the liquid penetration length measured at 350 μs using DBI technique is found to be as much as 20 percent more than that measured by Mie-scattering. This deviation is thought to arise from significant beam-steering induced by the increased vaporisation from the flash-boiling propane.

Introduction

In recent years, DI technology has achieved significant market penetration due to the potential for increased fuel efficiency over port fuel injected (PFI) vehicles. DI offers attractive features including charge cooling and unthrottled, lean part-load [11]. However, realising the fuel efficiency benefits of DI requires a detailed knowledge of the in-cylinder fuel spray behaviour in order to ensure robust engine operation. Computational fluid dynamics (CFD) simulation is an important tool for understanding the governing mechanisms of DI fuel sprays in different chamber geometries and at a range of operating conditions. The accuracy, and ultimately the merit of these spray models, is strongly tied to the fidelity of the experimental data used for validation. Experimental methods for measuring parameters such as the liquid penetration length of fuel sprays have been developed [1, 2], but the uncertainties of these methods are not well understood for strongly flash-boiling fuel sprays that occurs in gasoline DI (GDI) operation. Maximum penetration of the liquid phase into the combustion chamber of an engine is an important parameter determining potential wall-impingement. An accurate measurement of this quantity not only addresses the issue of fuel impingement, but also provides a metric for partial validation of spray models. Several experimental methods have been developed for measuring liquid penetration length [1, 2]. Pickett et. al [8] compared various optical techniques widely used for liquid length measurement in diesel sprays to highlight the shortcomings and challenges associated with each technique. These experiments were primarily concerned with evaporating sprays in high density, compression-ignition (CI) relevant environments (i.e. high chamber pressures and temperatures). While gasoline DI (GDI) injection conditions are not as severe as those present in a CI engine, there are still cases where the chamber environment could introduce significant uncertainty to optical measurements. In particular, flash-boiling sprays with high rates of vaporisation introduce substantial vapour concentrations into the chamber, which may impact measurements of spray liquid penetration length. The presence of large amount of fuel vapour can potentially lead to severe beam-steering effects, particularly under conditions corresponding to throttled, part-load operation where the chamber pressure is sub-atmospheric and flash-boiling is significant. To date, there has been little study of spray liquid length uncertainty in a GDI context with flash-boiling fuel.

This issue is potentially important for characterising the liquid length of DI liquefied petroleum gas (LPG), which has recently gained interest as a viable transportation fuel [5, 6]. LPG, largely composed of propane, is highly flash-boiling throughout the GDI operating range, and therefore optical assessments of the liquid length are likely to be subject to beam-steering and experimental error due to the presence of increased fuel vapour. Due to this lack of knowledge, this work compares the measured liquid length for highly flashing propane sprays using two commonly used methods; DBI and Mie-scattering. The objective is to investigate the potential difference in liquid length measurement using DBI and Mie-scattering techniques. Finally the quantitative difference between the two methods will be discussed.

Experimental Setup and Test Method

Constant Volume Chamber

The experiment is performed in an optically accessible, quiescent constant-volume chamber (CVC). The chamber is pressurised with nitrogen creating an inert, non-reacting environment. The injector used in this experiment is an eight-hole experimental GDI injector (injector AV67-018) provided by Delphi through the ECN collaboration. The injector is fixtured in a specialized cooling jacket and mounted on one side of the chamber. Fused silica windows mounted on three sides of the chamber provide 90mm diameter optical access that is approximately the bore size of a modern, production GDI engine. The fuel rail temperature is regulated using a tape heater and the chamber wall and gas temperatures are controlled using cartridge heaters mounted in the four corners of the CVC. Prior to each injection event, the CVC is purged with nitrogen to ensure the chamber is free of fuel residuals from previous injections. Propane, a surrogate for LPG, is employed in this investigation. A detailed description and schematics of the CVC is described by Lacey et. al [3].

Optical Diagnostics

Two optical techniques are used in this experiment; Mie-scattering and DBI. For both of these methods, which were not performed simultaneously, a Phantom Miro M310, equipped with a 200 mm Nikkor lens (f/4 for Mie-scattering and f/5.6 for DBI) is used to capture the injection events. The *f-stop* has been adjusted between Mie-scattering and DBI setup to provide a good balance between optimum light level and camera exposure, while still maintaining a wide collection angle for both techniques. Figure 1 shows a schematic of the optical setup and light path for both DBI and Mie-scattering in red and blue, respectively. A continuous tungsten light source was utilised for illumination with both techniques. For DBI, the camera is operating at a frame rate of 20 kfps with a 1 μs exposure and a frame size of 384×320 pixels. This gives a viewing area that is approximately 30×35 mm (∼100 μm/pixel). The Mie-scattering images have the same pixel size and a scaling factor similar to the DBI images. The camera was operating at rate of 20 kfps with a 3 μs exposure.

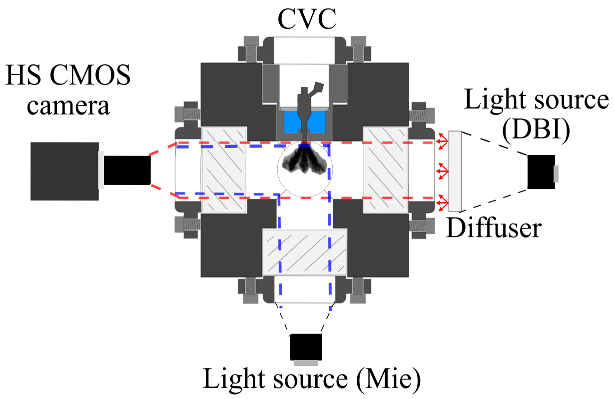

Figure 1: Schematic of the CVC and each imaging technique; note that the DBI and Mie-scattering experiments were conducted separately

Post processing

The images from the experiments are post-processed using Matlab code to extract the extent of the liquid phase in each spray image. To determine the extent of the liquid phase in the DBI images, the light intensity, I, at each pixel location is compared against the background intensity, I_o, at the same pixel location from an image with no fuel spray. In this work, the spray region is determined by using a fixed cut-off where I/I_0 = 0.9, which has been utilised in previous DBI studies [8]. While the DBI method is based on the extinction of incident light, Mie-scattering is based on the measurement of light scattered when light passes through dense particles (i.e. liquid fuel droplets) with a size comparable to the wavelength of the illumination source. The trace of the liquid phase is then determined based on a threshold of intensity that is within 3 percent of the maximum intensity, following the well-established Siebers method for Mie-scattering post-processing [9]. The spray boundary is then determined from a binary analysis of the image. The maximum penetration lengths reported are the average of the maximum axial location of the liquid fuel from the injector tip for all injection events at a given operating condition. The standard deviation (σ) of the maximum liquid penetration length is approximately ±1 mm for all the conditions tested.

Operating Conditions

Pure propane is used in this study, as it is highly flashing at chamber conditions indicative of GDI operation. Pure propane is a reasonable surrogate for LPG, as LPG is largely composed of propane [6], and using a pure fuel facilitates the fundamental analysis of fuel spray properties. The fuel temperature and pressure are set to a constant value of 309 K and 150 bar, respectively. The CVC temperature is set to be the same as fuel temperature and the chamber pressure is varied. Table 1 shows a summary of the experimental conditions that swept a range of CVC pressures. These operating points are relevant to the pressure of the combustion chamber in a GDI engine for different injection timings. The electronic injection duration is 1000 μs, but actual injection time including the closing delay is 1100 μs. The thermodynamic properties of propane are evaluated using the REFPROP software provided by National Institute of Standards and Technology (NIST) [4]. In these tests, the CVC pressures are considerably lower than the saturation pressure of pure propane inside the rail (i.e. $P_{sat}(T_{fuel} = 309K) = 12.5$ bar), thus significant flash-boiling and increased vaporisation rates are expected under these injection conditions. The severity of flash-boiling is often given by the flashing ratio [3, 10], R_p, which is the ratio of the saturation pressure of the fuel at its temperature in the rail to the back pressure into which it is injected (Equation 1). The range of R_p in this work is given in Table 1. For each operating condition, 20 injection events are recorded to perform ensemble-averaging of the processed data. Figure 2 shows the spray maximum liquid penetration length at 350 μs ASOI, averaged by number of injections. Figure 2 confirms that 20 injections are sufficient to form a statistically significant dataset, as the average penetration length of the liquid converges after 8 to 10 shots.

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

Table 1: Flashing ratio of propane at each CVC back pressure

	CVC Pressure (bar)	R_p
$T_{fuel} = T_{CVC} = 309$ K	1	12.5
$P_{sat} = 12.5$ bar	2	6.2
Injection duration = 1100 μs	6	2.1

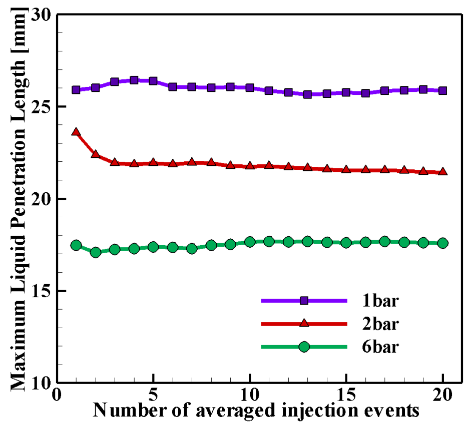

Figure 2: Ensemble-averaged liquid penetration length with a varying number of injection events used in the averaging

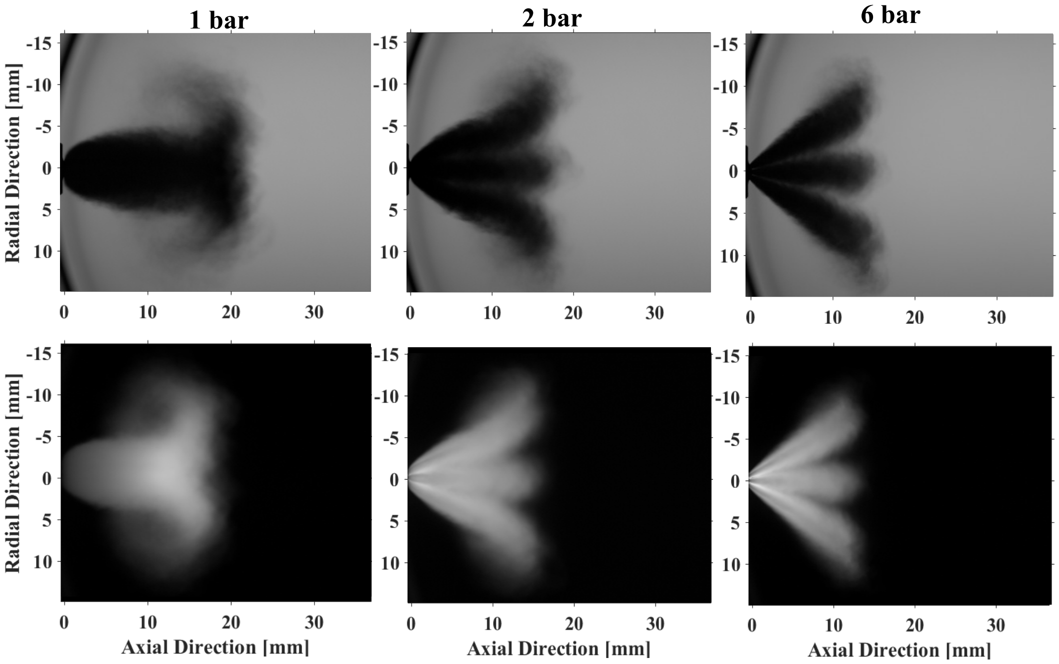

Figure 3: Ensemble averaged image of propane spray structure at 350 μs ASOI for different CVC pressures shown at the top of the figure; DBI images are shown in the top row, and Mie-scattering below. The spray liquid length is measured by taking the maximum axial length of the spray edge (dark region for DBI images or the gray region for Mie-scattering images) of individual spray images (not shown here).

Results and Discussions

Qualitative analysis of spray structure

Figure 3 shows the propane spray structure at different CVC pressures at 350 μs ASOI from DBI and Mie-scattering. The images are the ensemble-average of all injection events recorded at each operating condition. In general, the change in spray structure when varying the CVC pressure is similar for both DBI and Mie-scattered images. The spray transitions from a spray with well-defined spray plumes at high CVC pressure to a collapsed spray at low CVC pressure. While both methods appear capable of providing consistent, qualitative liquid phase spray structure at flashing conditions, there are uncertainties that must be considered when comparing quantitative data. DBI is susceptible to beam steering in the presence of vapour, as the vapour induces light extinction events that could overestimate the extent of the liquid phase. The Mie-scattering suffers from a sensitivity to light source orientation. In these experiments, the Mie-scattering light source is illuminating the head of the spray more than the fuel near the injector tip, so the intensity of light scattered through the liquid phase propane varies with axial injector distance. The next section considers some of these experimental uncertainties in the context of severely flashing propane sprays.

Impact of Flash-boiling Vaporisation

Figure 4 shows the maximum liquid length of propane sprays after the start of injection (ASOI) at different CVC pressures for both DBI and Mie-scattering. The maximum liquid penetration length is plotted up to time 500 μs after start of injection since at lower CVC pressure, the spray liquid length goes beyond the frame after this time. At small ASOI times, there is little deviation between the two measurement techniques at all CVC pressure conditions, but as the spray penetrates into the chamber and ASOI increases, the DBI and Mie-scattering liquid lengths begin to diverge at all conditions. The maximum liquid length measured from DBI images at later times in the injection process is consistently higher than that measured from Mie-scattering images. The beam-steering effect is likely the reason for higher liquid penetration length measurements using DBI at longer times ASOI and lower CVC pressure. At larger ASOI, there is more time for vaporisation in the CVC, exacerbating the beam steering effect in the DBI measurement.

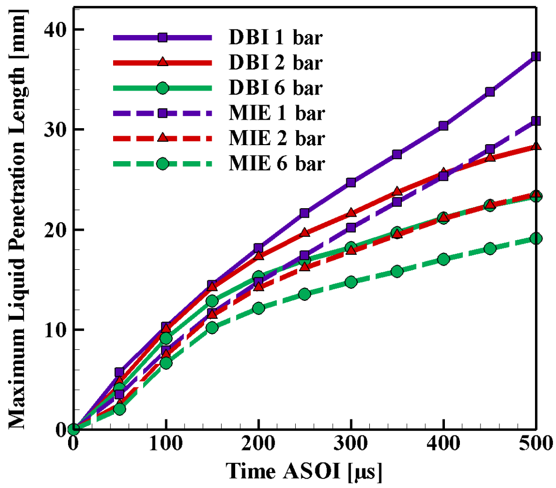

Figure 4: Comparison of maximum liquid penetration length profiles using Mie-scattering and DBI

To examine the deviation between DBI and Mie-scattering measurements, a plot of the difference between the liquid lengths between the two measurement techniques at each CVC pressure is considered in Figure 5. At smaller times ASOI, the measurement method variation across different CVC pressures is the same. At larger times ASOI, the spray maximum liquid penetration length difference between DBI and Mie-scattering increases as the flashing ratio increases (i.e. as CVC pressure decreases). This trend of increasing measurement method divergence with increasing flashing ratio appears to confirm earlier assertions regarding light extinction uncertainties. As the flashing ratio increases, the rate of vaporisation increases, which results in more fuel vapour in the chamber, exacerbating beam-steering effects and likely causing overestimations of liquid length using DBI.

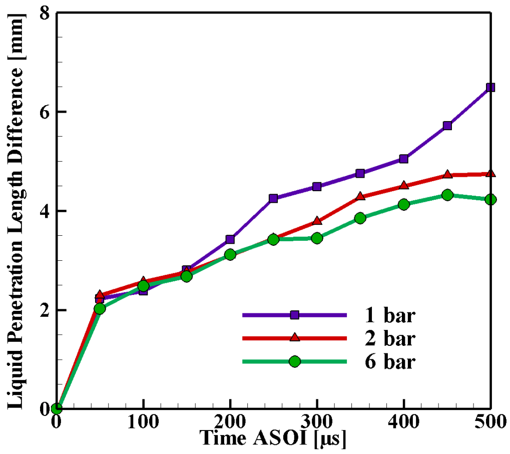

Figure 5: Liquid length measurement difference between DBI and Mie-scattering technique

The difference between DBI and Mie-scattering liquid length measurements for highly flashing sprays is significant at high flashing ratio and longer times ASOI as the spray evolves. DBI liquid length measurements are higher compared to Mie-scattering measurements. The maximum penetration length can vary by as much as 20 percent between DBI and Mie-scattering measurements at 350 μs ASOI. These DBI and Mie-scattering liquid length differences highlight a potential caveat present in the DBI methodology. DBI is the preferred liquid measurement technique of the research community due to its known reference light intensity, but quantitative measurements are highly sensitive to the intensity cut-off used in post-processing [9]. While liquid lengths measured by Mie-scattering will be influenced by the illumination setup, it is relatively insensitive to the chosen intensity threshold [7]. The fixed DBI cut-off used in this study was established by literature in previous diesel spray research, however, a more objective method to determine the DBI cut-off could potentially mitigate the differences between the DBI and Mie-scattering liquid lengths presented in this work. In practice, this could be implemented using information in the optical depth profile of the spray and will be considered further in future work.

Conclusions

A comparison of the liquid phase penetration length of severely flashing sprays using DBI and Mie-scattering techniques was performed using propane in a CVC at GDI relevant operating conditions. While qualitative assessments of the spray structure and liquid phase characterisations are consistent between DBI and Mie-scattering, the quantitative liquid length measurements are not. The difference in maximum liquid penetration length determined by the two methods can reach as much as 20 percent in some cases with severely flashing propane sprays. The difference between the two measurements increases with increased flash-boiling severity (decreasing R_p), which is attributed to higher rates of vaporisation and higher concentrations of vapour phase fuel that induces beam steering. This effect likely causes spurious light-extinction effects that most significantly impact DBI measurements, and potentially results in an overestimation of liquid length.

Acknowledgements

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