19th Australasian Fluid Mechanics Conference
Melbourne, Australia
8-11 December 2014

A Comparison of the Direct Injection of Propane and Iso-octane under Homogeneous-charge, Spark-ignition Engine Conditions

F. Poursadegh[1], D. Goldeband[1], J.S. Lacey[1], P. Petersen[2], M.J. Brear[1], R.L. Gordon[1], C. Lakey[3], B. Butcher[3], P.A. Atibeh[3] and S. Ryan[3]

[1]Department of Mechanical Engineering
University of Melbourne, Victoria 3010, Australia

[2]School of Media and Communication
RMIT University, Victoria 3000, Australia

[3]Ford Motor Company, Victoria 3214, Australia

Abstract

This paper evaluates the macroscopic characteristics of fuel sprays from a multi-hole fuel injector under simulated homogeneous-charge operation in spark-ignited (SI) internal combustion (IC) engines. Spray penetration and projected area are qualitatively investigated by employing high-speed Schlieren and diffuse back-illumination imaging techniques in a constant volume chamber (CVC). The results are then used to evaluate the impacts of ambient conditions and fuel properties on the formation of liquid and vapour phases.

Results of investigations with iso-octane and liquid propane, acting as surrogates for gasoline and liquefied petroleum gas (LPG), highlight the differences between the vaporisation behaviour of these two fuels at similar injection conditions. Whilst iso-octane undergoes conventional atomisation and evaporation, liquid propane rapidly vaporises via flash-boiling. Unlike a simple liquid fuel jet at high superheat, the individual plumes of the liquid propane spray collapse towards the axis of the injector and create a "tulip-shape" envelope, which reduces the spray width and increases the penetration length.

Introduction

Improved fuel economy and reduced emissions of greenhouse gases and other pollutants are driving the implementation of new IC engine technologies. Direct injection has several advantages over port fuel injection, including improved fuel economy, diminished CO_2 production and lower unburned hydrocarbon emissions during cold start. On the other hand, the performance of direct-injection (DI) technology is significantly influenced by the characteristics of the fuel spray, which are closely coupled to the properties of the injected fuel. While gasoline and diesel sprays have been studied extensively, those of alternative fuels such as LPG have not yet been well-characterised.

LPG is a mixture that is predominantly composed of propane and butane, and offers several benefits relative to conventional fuels. LPG has lower energy specific carbon dioxide emissions and a higher octane number than gasoline, both of which make it an attractive alternative fuel for SI engines [1, 2]. Further, LPG has a higher saturation pressure relative to that of conventional gasoline, suggesting that its rapid evaporation through flash boiling may promote lower levels of particulates and other emissions due to greater premixing prior to combustion in engine [3].

Flash-boiling is generally characterised as an explosively rapid phase change due to a sudden depressurisation. At relatively low liquid preheat temperatures, the abrupt jet breakup begins some distance downstream of the nozzle from rapid bubble growth inside the jet. For higher liquid temperatures, however, the jet starts flashing inside the nozzle. This flow expands rapidly upon leaving the nozzle exit, leading to large spray cone angles and reduced penetration [4, 5]. Previous studies have revealed that flashing fuel sprays consist of finer droplets with an improved evaporation behaviour compared to conventional sprays. However, the complex physics of flashing multi-plume sprays present in production gasoline DI (GDI) engines over a wide range of superheat levels still requires further investigation [6, 7].

The current study therefore aims to provide further insights into the structure and vaporisation of multi-plume fuel sprays at homogeneous-charge engine operating conditions, i.e. start of injection timing early in the intake stroke. The objective is to investigate the impact of fuel properties at in-cylinder conditions relevant to homogeneous-charge GDI engine operation using iso-octane and liquid propane, representative of conventional liquid gasoline and the LPG respectively.

Experimental Apparatus

The experiments were conducted in an optically accessible, constant-volume chamber under quiescent and non-reactive SI engine-like conditions. Injecting fuel into a quiescent and non-reactive environment permits isolation of critical spray phenomena from complex, turbulent in-cylinder flows due to combustion and piston motion.

The enclosed volume of the chamber was comprised of three intersecting cylinders providing 90 *mm* optical access on three sides of the cubical vessel. A sectional view of the vessel is depicted in Figure 1. As shown in the sectional view, the fuel injector is mounted on the top face of the chamber such that the fuel spray is directed into the centre of the vessel. Fused silica windows placed in three sides of the chamber allow line-of-sight and orthogonal optical access to the fuel spray. A combination of fluorocarbon o-rings and copper gaskets were also employed to seal the chamber under both high pressure and vacuum conditions (o-rings for quartz-to-metal and copper gaskets for the metal-to-metal interfaces). In-cylinder conditions are simulated by using heated nitrogen. Two K-type thermocouples and a piezoelectric pressure transducer were employed to monitor chamber temperature and pressure, respectively.

In the current study, an experimental eight-hole, high-pressure, solenoid actuated, stepped-hole valve covered Delphi injector with a nominal included spray angle of 80 degrees was employed. The interior of the injector fixture contained space for a 50/50 mixture of water and ethylene glycol that was designed to surround the injector and maintain a constant injector body temperature throughout operation. A length of heat trace was also affixed to the fuel line immediately before its connection to the injector to control the temperature of the liquid fuel and match it to that of the coolant jacket and injector body. The temperature of the liquid fuel was regulated in the range of 293 to 363 *K*.

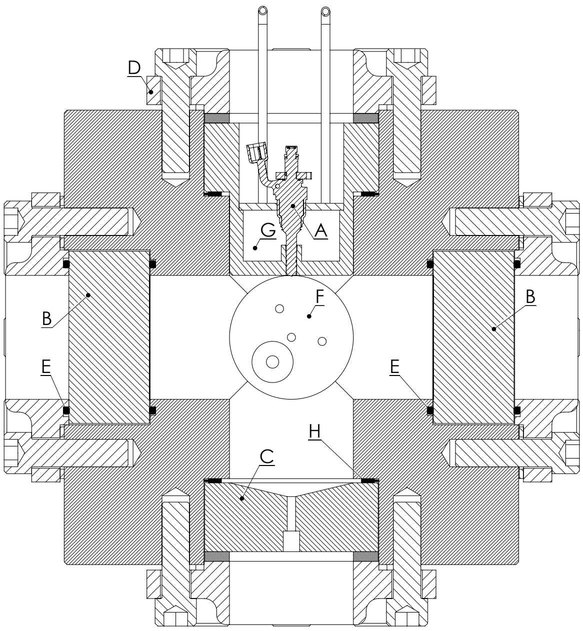

Figure 1: A sectional view of the CVC: (A) the fuel injector, (B) fused silica windows, (C) vessel discharge port, (D) flange, (E) fluorocarbon o-rings, (F) instrumentation and incoming gas port, (G) coolant jacket, (H) copper gasket.

Optical Diagnostic Techniques

In this study, high-speed Schlieren imaging and diffuse back-illumination (DBI) techniques were utilised to fully characterise fuel spray phenomena. A high-speed imaging system was employed to investigate both liquid and vapour envelopes of the sprays. Acquiring images at high-speed permits both a sufficient spatial and temporal resolution of individual injection events.

Schlieren imaging is a well-established and relatively simple technique of high sensitivity that is capable of capturing density gradients in flow fields [8]. This allows for the production of both qualitative images of different fuel sprays, and quantitative data such as penetration length and spray area. Although rather straightforward in many ways, Schlieren imaging is not free from difficulties. The chief disadvantage of this visualisation technique is that it is difficult to separately resolve the liquid and vapour phases because Schlieren imaging is sensitive to small variations in density.

A continuous high-power Xenon light equipped with an endoscope was utilised as light source for Schlieren imaging. Passing through a narrow vertical slit, light was collimated through the chamber by a 6 *inch* parabolic mirror of 60 *inch* focal length and received by an identical parabolic mirror placed in a z-type configuration. A vertical knife edge was used as a cut-off at the focal point of the Schlieren head. The images were acquired using Phantom Miro M310 camera operating at a framing rate of 19 kfps with 1 μs camera exposure time at a spatial resolution of 384×384 pixels, which spanned 90 by 90 *mm* and gave a resolution of 0.23 *mm* per pixel.

DBI is an optical diagnostic technique used to investigate the liquid phase development in evaporating gasoline sprays [9, 10]. DBI has several advantages over Mie-scattering, including the simplicity of the optical setup and its reference light intensity for measurement purposes. With DBI, the incident illumination is utilised as the reference light intensity to extract the global extinction map of light being attenuated by the presence of spray [11]. The extinction map is then used to evaluate the macroscopic parameters of the liquid core, e.g. liquid penetration length. In spite of these benefits, beam steering, caused by the refraction of light through the vapour surrounding the liquid core, has been found to impact DBI images.

In order to provide a uniformly illuminated background for the DBI technique, a back-lightning system consisting of a directional high-power diffuse light source and a light diffuser was employed. Images of the spray event were collected in the direction of illumination using the same CMOS high-speed camera used for Schlieren imaging equipped with a 135 *mm* $f/2.5$ lens. In an effort to reduce the visual impact of beam steering, the smallest *f-stop* value was selected for this imaging technique [11]. The camera was also operating at a frame rate of 27 kfps with 7 μs camera exposure time at a spatial resolution of 320×320 pixels to capture the most important dynamics of the liquid core with a reasonable spatial resolution, i.e. 3.2 pixels per *mm*.

Operating Conditions

The operating conditions in the experiments emulate DI engine conditions during the intake stroke (i.e. operation for well-mixed fuel/air charges). Two parameter sweeps were used to assess the differences between the spray of a liquid fuel (iso-octane) and propane. Varying the fuel temperature was performed to study the impact of engine temperature upon the fuel spray (cold-start versus warmed-up) and changing the chamber pressure allowed for insight as to the effects of both atmospheric and boosted intake conditions.

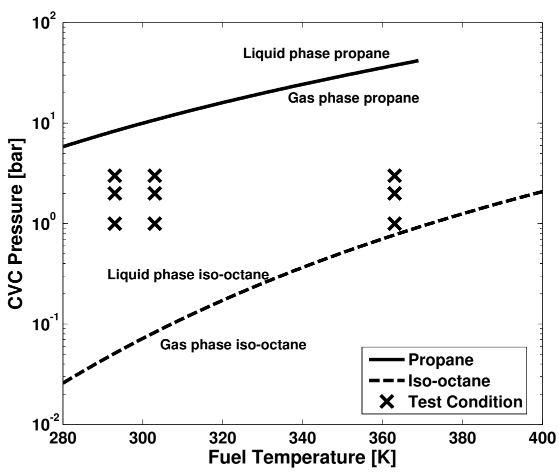

Figure 2: Saturation lines for propane (solid) and iso-octane (dashed) plotted against the CVC pressure and fuel temperature conditions used in the experiments

A summary of the experimental conditions for the CVC and fuels is shown in Figure 2 and Table 1. In contrast to iso-octane, propane is well-below its saturation pressure at all the fuel temperatures tested. For these same engine-like conditions, the two fuels are therefore operating in different regimes, as propane tends to flash-boiling (below its saturation line), whereas iso-octane is a liquid (above its saturation line). Injection pressure was maintained at 200 *bar* by a high-pressure nitrogen bottle feeding a stainless steel tank storing the liquid fuel. The corresponding injection pulse width with the prescribed injection pressure was set to 680 μs. The rail pressure and pulse width were utilised because the injector had been extensively tested at this condition, and the key phenomena of spray evolution at the chamber conditions of interest are spanned by these injection specifications [10].

Injection Duration	680 μs
Fuel Rail Pressure	200 bar
Fuel Temperature Range	293-363 K
CVC Temperature	303 K
CVC Pressure Range	1-3 bar
CVC Exhaust Time	2.5 ms

Table 1: Summary of Experimental Operating Conditions

Results and Discussion

In the first part of the study, the influence of fuel properties on spray atomisation and evaporation behaviour at early injection timings were investigated qualitatively. Figure 3 compares the spray evolution of these two fuels for chamber pressures ranging from 1 to 3 *bar* at 303 *K* chamber temperature and a fuel temperature of 363 *K*. This set of conditions was employed to approximate fuel injection for a fully warmed-up engine at three common intake boost levels for modern GDI engines in the absence of throttling effects.

At 363 *K*, the vapour pressure for iso-octane and propane are 0.78 and 37.6 *bar* respectively. Because of the low saturation pressure of iso-octane, at the chamber conditions of interest, the spray is conventional. Increasing the chamber pressure imposes more aerodynamic resistance on the spray; and therefore, both liquid and vapour envelopes of iso-octane sprays penetrate less into the chamber.

Considering the high saturation pressure of propane, its spray development under the conditions in Figure 3 falls into the flash-boiling regime. Spray formation in this regime is influenced by the ratio of ambient to saturation pressure (flashing-ratio) and the difference between the actual and boiling-point temperatures of the fuel [6]. Increasing the degree of fuel superheat by reducing the chamber pressure pushes the spray into a regime in which individual plumes collapse inwards toward the injector axis and eventually form a single plume spray.

In order to further investigate the flashing and consequent plume-to-plume interaction of propane sprays, another set of experiments was designed to investigate the spray behaviour of liquid propane in the course of engine warm up at different intake boost pressures. Figure 4 illustrates the evolution of a liquid-propane spray under the aforementioned experimental matrix. Increasing the degree of superheat by reducing the chamber pressure or increasing the fuel temperature, individual spray plumes interact and form a "tulip-shape" spray [7], similar to what is observed for propane at 293 *K* and 303 *K* at 1 *bar* CVC pressure. At this level of superheat, vortex structures are also formed mainly on the outer surface of the spray. Further increasing the degree of superheat of the fuel, all plumes merge together and form a single stream with increased penetration, as seen for 363 *K* propane at 1 and 2 *bar* chamber pressure.

Although several studies have been recently devoted to investigate this complex phenomenon for multi-plume flashing sprays, its physics are not as well-understood as those of flash-boiling liquid jets. It is worthwhile to note that this same multi-plume phenomenon has been observed for pure ethanol [6] and RON-95 gasoline [7] at sub-atmospheric pressures (indicative of fuel injection events during engine throttling). While the absolute conditions for these fuels was different from those of Figure 4, the degree of superheat of the fuels was similar to propane, suggesting that there may be a parameter to describe a "normalised" fuel behaviour under flashing conditions in multi-hole injectors. Future efforts will be required to ascertain this quantity, and it could prove to be significant in the design of DI engines with alternative fuels.

Conclusions

The structure and vaporisation of multi-plume fuel sprays under simulated homogeneous-charge GDI engine operation conditions were qualitatively investigated employing high-speed Schlieren and DBI techniques. The effect of fuel properties was examined using iso-octane and liquid propane. While the overall spray structure and evaporation behaviour of iso-octane remained almost the same under the conditions of interest, liquid propane underwent a drastic transition within the flash-boiling regime. For an increasing degree of superheat for propane, the

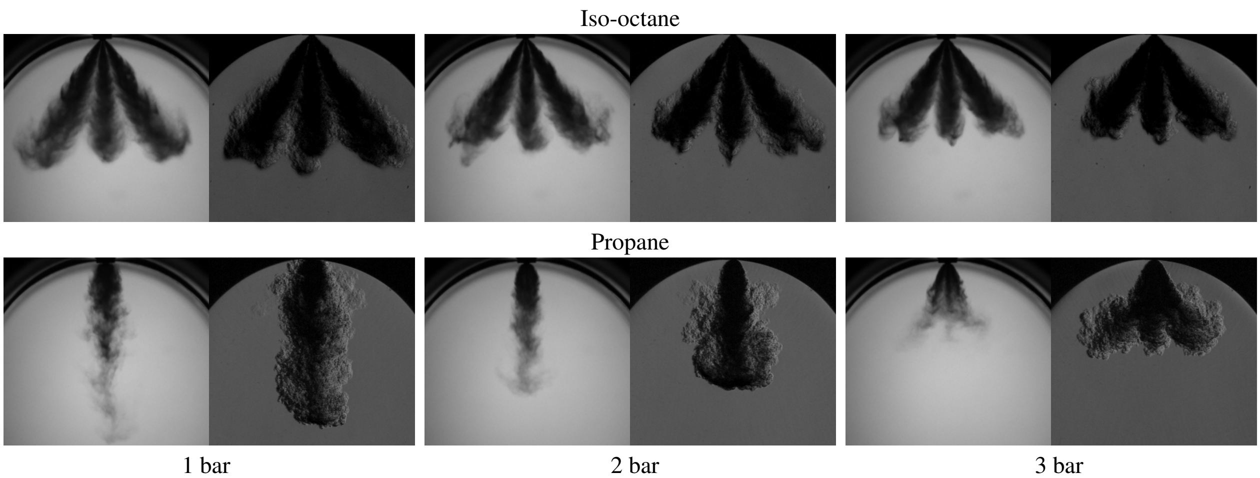

Figure 3: Iso-octane (top) and Propane (bottom) sprays 680 μs ASOI with a fuel and chamber temperature of 363 *K* and 303 *K*, respectively; chamber pressure is noted below the images, and for each pair of images, DBI is on the left and Schlieren is on the right, where lower chamber pressures result in a higher degree of superheat and more severe flashing

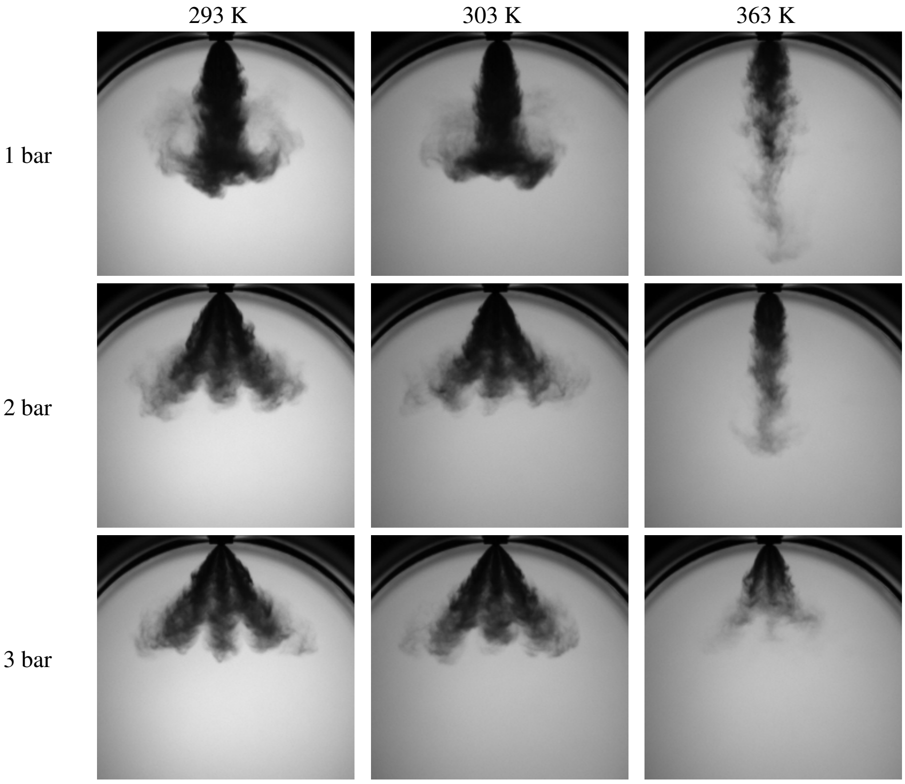

Figure 4: DBI images (680 μs ASOI) highlighting the flashing of propane by varying the fuel temperature (top) and chamber pressure (left side) at a constant chamber temperature of 303 K; increasing fuel temperature or decreasing chamber pressure increases the degree of superheat for the fuel, increasing the severity of flashing

multi-plume structure of the spray at 293 K and 3 *bar* transformed into a single-plume jet with an increased penetration length and more rapid vaporisation behaviour at 363 K fuel temperature and 1 *bar* chamber pressure. This phenomenon has been observed in previous multi-hole injector experiments using conventional liquid fuels, implying there could be a normalised parameter to describe some attributes of any fuel undergoing flash-boiling, though more investigation will be required to confirm this.

Acknowledgements

This research was supported by the Advanced Centre for Automotive Research and Testing (ACART, `http://www.acart.com.au`) and the Australian Research Council. The authors also gratefully acknowledge Ford Motor Company for their support.

References

[1] Mesman, P. and Veenhuizen, B., The Spray Behavior of Liquid LPG at Different Back Pressures During Injection in a Constant Volume Chamber, *SAE Technical Paper*, 2009-01-1834, 2009.

[2] Morganti, K.J., Foong, T.M, Brear, M.J., Gabriel da Silva, Yang, Y. and Dryer, F.L, The research and motor octane numbers of liquefied petroleum gas (LPG), *Fuel*, 108, 2013, 797–811.

[3] Reitz, R.D., A Photographic Study of Flash-Boiling Atomisation, *Aerosol Science and Technology*, **12**, 1990, 561–569.

[4] Oza, R.D. and Sinnamon, J.F., An experimental and analytical study of flash-boiling fuel injection, *SAE Technical Paper*, 830590, 1983.

[5] Sher, E., Bar-Kohany, T. and Rashkovan, A., Flash-boiling atomization, *Progress in Energy and Combustion Science*, **34**, 417–439, 2008.

[6] Zeng, W., Xu, M., Zhang, G., Zhang, Y. and Cleary, D.J., Atomization and vaporization for flash-boiling multi-hole sprays with alcohol fuels, *Fuel*, **95**, 287–297, 2012.

[7] Mojtabi, M., Chadwick, N., Wigley, G., Helie, J. and Continental, A., The Effect of Flash Boiling on Breakup and Atomisation in GDI Sprays, *Proceedings of the 22nd European Conference on Liquid Atomization and Spray Systems*, Italy, 2008.

[8] Settles, G.S., *Schlieren and Shadowgraph Techniques: Visualizing Phenomena in Transparent Media*, Springer, 2001.

[9] SAE Standard J2715. *Gasoline fuel injector spray measurement and characterisation*, SAE, 2007.

[10] Engine Combustion Network, `http://www.sandia.gov/ecn`.

[11] Desantes, J.M., Pastor, J., Payri, R. and Pastor, J.M., Experimental characterization of internal nozzle flow and diesel spray behavior. Part II: Evaporative conditions, *Atomization and sprays*, **15**, 2005, 517–544.