

Spray Formation from Spark-Eroded and Laser-Drilled Injectors for DISI Engines with Gasoline and Alcohol Fuels

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ABSTRACT

One of the latest advancements in injector technology is laser drilling of the nozzle holes. In this context, the spray formation and atomisation characteristics of gasoline, ethanol and 1-butanol were investigated for a 7-hole spark eroded (SE) injector and its 'direct replacement' Laser-drilled (LD) injector using optical techniques. In the first step of the optical investigation, high-speed spray imaging was performed in a quiescent injection chamber with global illumination using diffused Laser light. The images were statistically analyzed to obtain spray penetration, spray tip velocity and spray 'cone' angles. Furthermore, droplet sizing was undertaken using Phase Doppler Anemometry (PDA). A single spray plume was isolated for this analysis and measurements were obtained across the plume at a fixed distance from the nozzle exit. The droplet measurements were grouped into bins and maps were created showing droplet sizes and velocities against time and position during and post injection. All tests were performed at 120 bar fuel pressure, two injection chamber 'back' pressures (0.5 bar and 1 bar) and two injector temperatures (20 °C and 80 °C), to examine effects relevant to typical engine operating conditions with early intake stroke injection strategies, including fuel flash boiling.

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INTRODUCTION

Background

The design of new direct injection systems for spark-ignition engines is very important for improved atomisation and mixture formation with different fuels, as well as low exhaust emissions, including particulates that are central to EU6 regulations. It is preferable to meet the proposed targets by means of engine internal measures rather than separate treatment in the exhaust system that can be associated with a CO₂ penalty. Latest injector manufacturing methods by Laser-drilling have shown some promising results. Specifically, Whitaker et al. [1] showed a significant reduction in particulates using a Laser-drilled in comparison to a spark-eroded multi hole injector; however, in their study the exact nozzle design was not specified. As particulates are generally attributed to poor atomization, wall wetting and incomplete air-fuel mixing, it is important to understand the differences in fuel spray formation between spark-eroded and Laser-drilled injectors. The challenge is further complicated by the predicted fuel stock that may contain significant amounts of biofuels. To overcome ethical issues, it is also important to ensure that any new fuels will not compete with food chains, hence alternative ways of their large scale production such as, amongst others,

e.g. cellulosic or hemicellulosic feedstock are being established. Ethanol is to date still one of the preferred renewable additives or substitutes to gasoline; amongst its favorable properties is the fuel octane number enhancing capability. Butanol is also believed to be suitable to play a strong role. The use of butanol may not require major modifications to the current infrastructure and is also more compatible with some materials used in injection system technologies. Butanol is also less hygroscopic, has a lower vapor pressure and its heating value is higher than ethanol's. Butanol production processes are already established and have the potential to be widened to have similar capabilities to ethanol production [2].

Present Contribution

The manufacturing process of Laser drilling generally allows for the implementation of complex geometrical aids to promote or suppress turbulence and cavitation as needed [3] but to the best of the authors' knowledge, there are no other major publications that have compared the atomization characteristics from spark-eroded and Laser-drilled injectors. In this context, the work in this paper characterized the mechanism of spray formation from two injectors, one spark-

eroded and its 'like-for-like' replacement Laser-drilled injector in order to understand associated effects. The main objectives of the work are summarized below:

- Visual analysis of the sprays produced by the two injectors using high-speed imaging.
- Quantification of the sprays' geometrical features, including penetration, as well as overall outer envelope 'cone' angles at 5 mm and 25 mm from the nozzle.
- Droplet sizing by Phase Doppler Anemometry (PDA).
- Study of the effect of fuel type, primarily gasoline, ethanol and butanol, with both injectors. Some measurements and analysis was also performed with *iso*-octane, as the latter is a common fuel used for research purposes and can be useful in the research community for direct comparisons with previous work on injectors.

INJECTORS AND FUELS

Fuels

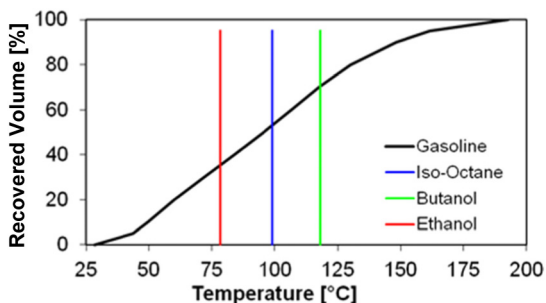


Figure 1. Distillation curve of gasoline (measured) and boiling points of single components [12].

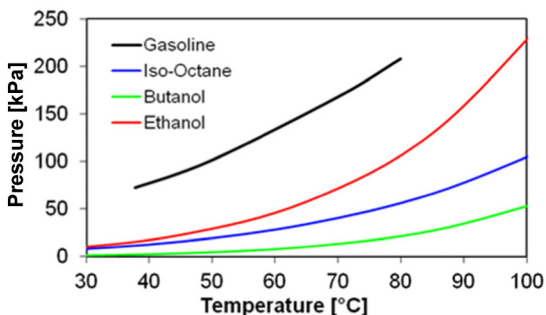


Figure 2. Vapour pressure against fuel temperature of gasoline (measured) and boiling points of single components [12].

The fuels used to compare the two injectors were selected to be significantly different in terms of fuel properties. Regular gasoline (RON95) with its wide range of low to high volatility fractions was used alongside the single components ethanol and 1-butanol (also denoted E100 and B100 respectively). Some measurements were also conducted with *iso*-octane which is a popular single-component research surrogate for gasoline. Differences in viscosity, surface tension, latent heat, boiling point and vapor pressure are all important in terms of spray formation; a summary of the fuel properties is given in Table 1. Figures 1 and 2 show the distillation curve and vapor

pressure against fuel temperature. The refractive index of the fuels was also measured (from 20 - 70 °C and extrapolated; at 514 nm) as shown in Figure 3.

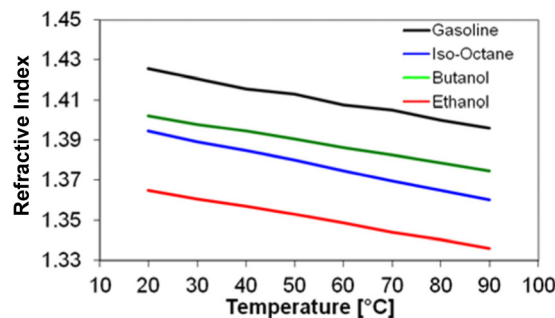


Figure 3. Refractive index (measured).

Table 1. Basic fuel properties.

	Ethanol	1-Butanol	Gasoline	Iso-Oct.
Chemical formula	C ₂ H ₅ OH	C ₄ H ₉ OH	~C ₄ -C ₁₂	C ₈ H ₁₈
Molar mass [g/mol] ^a	46.07	74.12	100-105	114.3
Density 20 °C [g/cm ³]	0.79	0.81	0.72	0.69
Density 80 °C [g/cm ³]	0.73	0.76	0.66	0.64
Solub. in water (20 °C) [g/l]	miscible	79	partially	not
Boiling point [°C]	78.3	118	30 to 210	99
Flash point [°C]	12	30	-43	-12
Ignition temp. [°C]	425	340	>350	410
DVPE at 20 °C [kPa]	6.4 ^d	0.8 ^d	35 ⁱ	5.7 ^d
DVPE at 37.8 °C (~RVP) [kPa]	16.1 ^d	2.2 ^d	72.4 ⁱ	11.8 ^d
DVPE at 80 °C [kPa]	100 ^d	16.4 ^d	208 ⁱ	50 ^d
Bubble Point (0.5 bar) [°C]	62.6	108.8	29.8	80
Kin. viscosity (23 °C) [cSt]	1.33 ⁱ	3.22 ⁱ	0.47 ⁱ	0.62 ⁱ
Kin. viscosity (80 °C) [cSt]	0.60 ⁱ	0.99 ⁱ	0.25 ^j	0.40 ⁱ
Surface tension (23 °C) [mN/m]	23.01 ⁱ	25.50 ⁱ	21.80 ⁱ	18.78 ⁱ
Surface tension (80 °C) [mN/m]	16.4 ^d	19.3 ^d	–	13.6 ^d
Expl. limit (upper) [Vol%]	15	11.3	7.6	6
Expl. limit (lower) [Vol%]	3.5	1.4	1.4	1
Latent heat (at <i>T</i> _{boil}) [kJ/kg]	855 ^d	584 ^d	364	272 ^d
Latent heat (25 °C) [kJ/kg]	874 ^d	669 ^d	380-500	300 ^d
Stoichiometric AFR	9	11.1	14.6	15.1
Heating value [MJ/kg], [MJ/l]	26.9, 21.3 ^d	33.9, 27.5 ^d	42.7, 32 ^c	44.6, 30.8 ^d
Specific heat cp (25 °C) [kJ/kgK]	2.46 ^d	2.30 ^d	2.22 ^c	2.09 ^d
Specific energy [MJ/kg air]	2.99	3.01	2.92	2.94
laminar burning velocity [m/s]				
(stoich, lean at 373 K, 10 bar)	27.5, 17.5 ^e	28, 18 ^e	28, 21 ^e	25, 17 ^e
RON	129 ^f	96 ^f	95	100
H/C, O/C	3, 0.5	2.5, 0.25	1.92, 0	2.25, 0

a) If not specified, data taken from product data sheets.

b) Calculated [10].

c) Calculated [11].

d) Calculated [12].

e) Taken from [13, 14].

f) Taken from [15].

i) Measured values.

j) Estimated values based on measurements.

Injector Nozzles

Two 7-hole solenoid injectors designed for side mounting in the combustion chambers of a 4 cylinder 2.0 engine were the focus of the investigation. The first injector had a standard

spark-eroded nozzle (MH7-SE) while the second was its 'direct replacement' manufactured using Laser drilling (MH7-LD). Despite being 'like-for-like direct replacements', first visual inspection under a microscope revealed similar stepped hole pattern but different hole diameters, as shown in Figure 4. Specifically, the outer hole diameter of the SE injector was measured 0.39 mm and the inner step 0.21 mm. The respective dimensions of the LD injector were 0.43 and 0.24 mm.

Considering that the manufacturing process of Laser drilling generally allows for the implementation of complex geometrical aids to promote or suppress turbulence and cavitation [3], silicone castings were used to obtain more detailed information about the inner nozzle shape and surface quality according to [4] and [5]. The obtained castings are shown schematically in Figure 5.

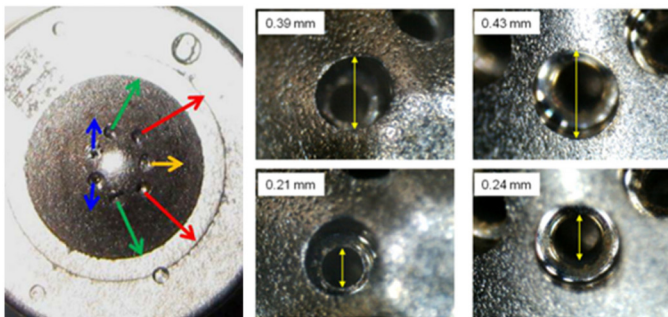


Figure 4. Injector hole layout (left) and stepped hole outer and inner dimensions (middle SE, right LD injector).

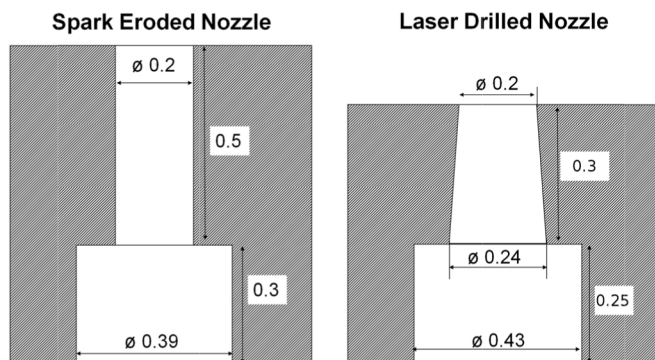


Figure 5. Sketch of SE (left) and LD (right) nozzle hole design; nozzle outlet is at the bottom, inlet at the top.

The spark eroded injector featured an inner, spark-eroded, cylindrical bore with a diameter of 0.2 mm and a length of ~0.5 mm, before opening up into a drilled hole with a diameter of 0.39 mm and a depth of ~0.3 mm. This diameter step is commonly associated with benefits regarding reduction of deposit formation. This injector-hole design is believed to feature two regions of flow separation. The first one is located at the entrance of the inner bore, where a vena contracta is formed that reduces the effective diameter (generally by a factor of ~0.6). A low pressure recirculation area is hence formed at the inlet edge, promoting cavitation. When exiting the

inner hole and the flow enters the larger outer hole, a similar phenomenon is to be expected but this now leads to the onset of atomisation. In contrast, for the Laser-drilled injector, it was found that the outer hole remained conventionally drilled and it was cylindrical with a diameter of ~0.43 mm and ~0.3 mm length, while the inner, Laser drilled, hole was of a conical shape with a start diameter of 0.2 mm, opening up to 0.24 mm over a distance of 0.3 mm. Such design differences further highlighted the necessity for behavioural analysis for engine developers and calibrators with a view of incorporating suitable adjustments for optimised engine performance when injector types are replaced.

For example, the increased surface smoothness of the laser drilling, that was distinctly visible in electron microscope imaging, can reduce the friction factor of the nozzle, in addition to reduced losses by the shorter conically shaped nozzle. Furthermore, the conical hole creates a more acute angle at the entrance (by ~4°) and the incoming liquid will experience a stronger flow separation in the zone past the entry corner. The separation region may not only be wider but can also be maintained for longer downstream, or never really reattach due to the ever increasing hole diameter. This is believed to induce and maintain cavitation more readily. Regarding turbulence, the effect of the nozzle cone is not necessarily clear in practice, especially over a range of operating conditions. As the entry into the flow channel is of identical size between the two injectors, the respective Reynolds (Re) and Ohnesorge (Oh) numbers can easily be estimated by using 'average' flow velocities derived from mass flow measurements. However, the vena contracta can reduce the effective hole diameter, hence flow velocities and associated Re numbers can be much larger than such basic estimated values. The conical shape of the LD nozzle can also lead to flow relaxation with lower Re number as the hole area increases, but the short length and flow momentum may not allow for immediate flow adaption as the residence time in the nozzle is very short; therefore, the difference in inferred turbulence may not be as large as expected when using the outer hole diameter for Re number estimations.

The maximum initial droplet sizes and associated Weber numbers when the liquid leaves the nozzle are often based on the nozzle-hole dimensions (or at least of the same order). However, the actual hole diameter influence may not play a significant role in the presence of strong cavitation when the process of exiting is accompanied by violent disruption. In contrast, in absence of cavitation, fuels with low vapour pressure, high viscosity and therefore low Re (e.g. cold butanol as the extreme of the current experiment) could be affected by the larger opening of the LD injector compared to the SE nozzle; hence larger initial droplet sizes could follow. In fact, as will be shown later, the LD nozzle did actually produce larger droplets for ethanol and butanol, but not for the 'more cavitating' gasoline or E25.

Mass Flow Analysis

Experiments were first carried out to establish the injectors' flow rates with 120 bar injection pressure. Injected fuel quantities were measured for gasoline, *iso*-octane, ethanol and butanol fuels. The injected fuel was collected over 200 injection events at an injector body temperature of 20 °C and 80 °C and 1 bar ambient air pressure (the injector was heated using a sleeve heater around the injector's mounting block). Figure 5 shows the injected fuel mass for gasoline using a range of injection durations up to 1.5 ms (20 °C, 1 bar). Both injectors showed no injected fuel with injection trigger pulse durations lower than 0.25 ms. With durations longer than this, the flow rate of the Laser-drilled injector was always larger than the spark-eroded injector's, typically in the region of 10%. This is much less than what one would expect from continuity calculations on the basis of the differences in nozzle hole diameters between the two injectors and can be attributed to further differences in the inner shape of the hole geometry that could influence in-nozzle two-phase flow effects.

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Figures 6 and 7 show the mass flow for all fuels at 20 °C and 80 °C injector conditions for a pulse duration of 1.26 ms. The latter represented the injection pulse duration to obtain close to stoichiometric conditions overall at an operating point of 0.5 bar intake plenum pressure, 1500 RPM, inside the cylinder of an optical research engine of 0.5 l capacity.

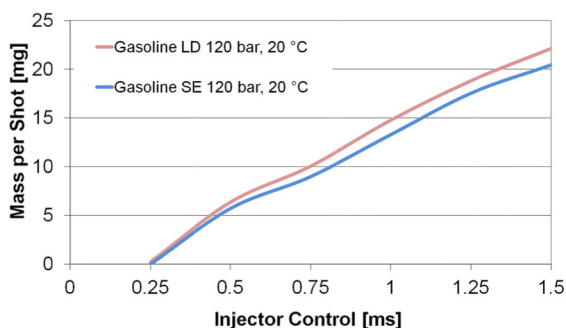


Figure 5. Injection quantity vs. pulse time at 20 °C injector temperature, 120 bar fuel pressure, 1 bar back pressure.

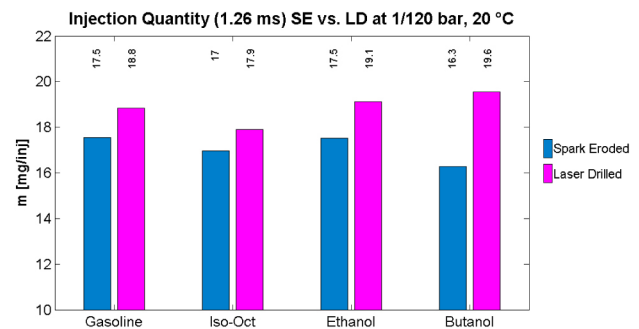


Figure 6. Injection quantity at 20 °C injector temperature, 120 bar fuel pressure, 1 bar back pressure (1.26 ms pulse).

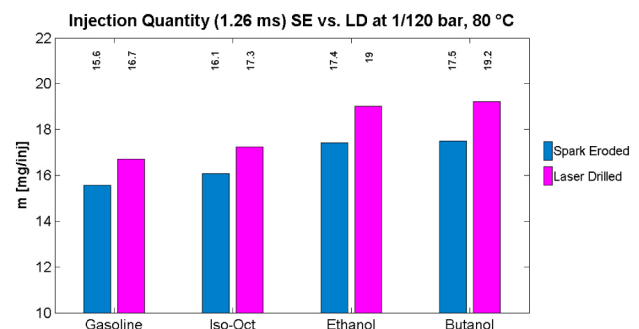


Figure 7. Injection quantity at 80 °C injector temperature, 120 bar fuel pressure, 1 bar back pressure (1.26 ms pulse).

Those values were used to derive equivalent fuel flow velocities and then Reynolds and Ohnesorge numbers using fuel properties, as shown in Figure 8. This analysis showed that the breakup was within the atomisation regime for all fuels with the exception of cold butanol, where the SE injector was on the border to the 2nd wind induced regime (regimes according to Reitz and Bracco [6]). Higher temperatures increased the flow for butanol inside the SE injector, while all other fuels showed a decrease in injection quantity. The decrease was strongest for gasoline. Cavitation and flash boiling effects are believed to be the main underlying cause for the reduced flow rates, as the reduced fuel viscosity on its own should have increased the flow at higher temperature. The latter may be dominant though for butanol whose flow rate increased.

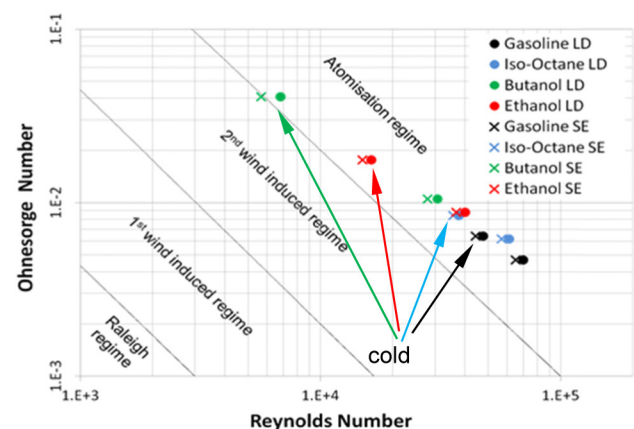


Figure 8. Ohnesorge diagram as from mass flow analysis.

SETUP AND METHODOLOGY

Spray Imaging Setup

The inner diameter of the quiescent injection chamber, shown in full setup in Figure 9, was 180 mm and the height 300 mm. The top cover, where the injectors were placed, was protruding into the inside of the chamber giving a final chamber volume of ~7 liters. Four optically polished UV grade fused silica windows with a diameter of 95 mm and a thickness of 32 mm allowed optical access. For spray imaging, a Photron APX-RS high-speed CMOS camera was used to take 60 images per injection event at a set to a frame rate of 9 kHz (this corresponded to 1° crank angle resolution for an engine operating at 1500 RPM). The camera's internal memory allowed acquisition of 113 injection events at 640×480 pixels. The injection duration was fixed to 1.26 ms.

The spray was illuminated at a 90° angle by pulsed light of a 527 nm Pegasus-PIV New Wave Nd:YLF high speed Laser, allowing for a light exposure of the camera chip of < 180 ns. The Laser's energy stability of <1 % promised low shot-to-shot variation, critical for the image analysis. The high repetition rate diode pumped Laser was capable providing 10 mJ per cavity. It was synchronized with the high speed camera and the injector driver using a AVL 427 timing unit. A Nikon Nikkor 28 mm macro lens was used for the experiments. The resulting resolution was 122 μm per pixel with the camera focus set to the chamber centre at an object distance of 230 mm. The f-stop was f/5.6 resulting in a depth of field of ~14 mm. The nominally 1.5 mm Laser beam was diffused using a lens of short focal length and frosted glass for evenly distributed illumination of the spray to obtain consistent Mie scattering. Speckles created by the Laser were greatly reduced by the use of multiple diffusers.

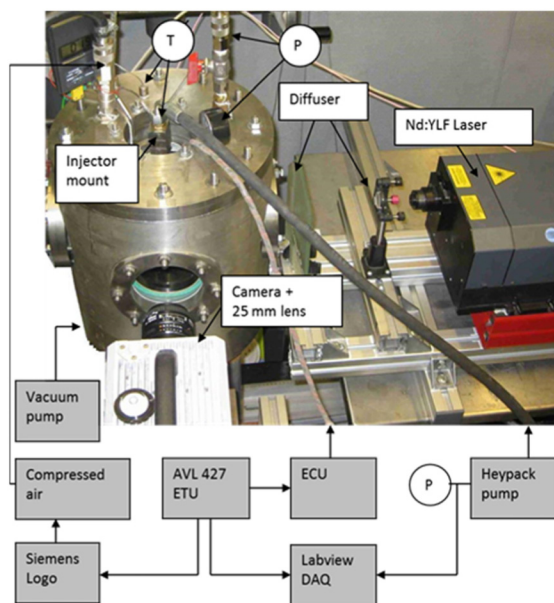


Figure 9. Spray image setup in quiescent chamber.

The injector was rotated so that the symmetry axis was in the focal plane and images were taken mainly in the spray's side view. Additionally, a 45° mirror was placed inside the chamber to obtain the injector footprint, using the Laser with and without sheet optics. Images were taken for 100 injection events, while footprint measurements were limited to 10 injections for cold gasoline only. The chamber was automatically purged (controlled by a Siemens LOGO PLC) of residual fuel with compressed air after each injection for a duration of 1.5 s. Sufficient time was included to stabilize the air-flow in the chamber after purging before the next injection was triggered with a frequency of 0.2 Hz. The chamber was attached to a vacuum pump for sub-atmospheric measurements at 0.5 bar air pressure, while it was open to ambient for 1 bar air pressure, representing full load in a naturally aspirated engine. The chamber and air temperature was at 20 °C. The fuel injector was brought to temperatures of 20 °C or 80 °C using a heating sleeve around the injector mounting block. The fuel was supplied by a Heypack pump and regulator system.

Spray Imaging Processing

Primary target of the processing was to obtain various angles describing the spray shape and to find the point of maximum penetration for each image. MATLAB code was developed to process automatically the large number of images. The definition of a suitable threshold was important to reduce ambiguity and ensure comparability between different fuels. The images obtained had a very high signal to noise ratio and included a distinct step change in image intensity in the presence of spray. The threshold of the spray was defined using the image histogram when no spray was present (*i.e.* during the time of spray delay). The histogram of the empty images showed a single peak at an intensity level of 6 (of 255) and, with the exception of the nozzle tip, no values above 10 were found. The spray border was hence defined above a threshold of 15, which gave sufficient margin to the background noise.

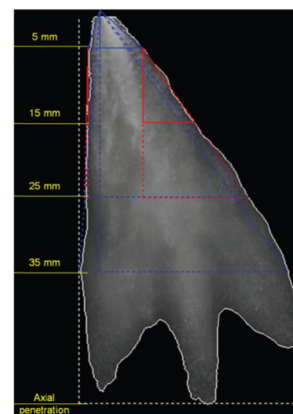


Figure 10. Spray image analysis locations.

Analysis of the images with spray showed that the pixel values at the defined spray border were mainly in the region of 18-30, with a steep increase from outside to inside the border, depending on the fuel. This gave confidence that little spray was lost due to the chosen threshold level. Reflections and

glaring was reduced by covering the inner chamber walls with matt black foam mats. No further reflections were caused, with the exception of the nozzle tip itself. The general image processing consisted of:

- Raw image import into MATLAB as a matrix consisting of 8-bit values (0-255).
- Background removal to reduce reflections.
- Threshold definition to distinguish spray and background.
- Binarisation of image to create background values of zero and spray values of 1.
- Trace of the outline of the spray.
- Definition of the nozzle position.
- Finding the position of spray the furthest from the nozzle.
- Converting pixels into mm.
- Calculation of the left and right hand side spray angles at the required distance from the nozzle.
- Addition of left and right hand side angles (overall angle).
- Superimposition of angles and outlining onto raw image for visualization, as shown in [Figure 10](#).

Only the axial spray penetration, as well as the angle from the nozzle tip to 5 mm and to 25 mm past the nozzle are included in the presented work.

Phase Doppler Anemometry (PDA) Setup

The PDA system (TSI 5W Coherent Argon ion Laser with FSA4000 signal processor and TLN05-250 fiber probes) was arranged for 30° off-axis forward scatter angle between transmitter and receiver as shown in [Figure 11](#). The setup of channel 1 (514.5 nm) of the PDA system was used for the size measurements and vertical velocity measurements. It was set to ~200 mW, which was close to the maximum achievable Laser power.

The photo-multiplier voltage (PMT) was initially chosen using the D10 stabilization method. For this, the droplet size D10 of the gasoline spray was measured for increasing PMT voltages at maximum beam power to increase the signal to noise ratio. D10 was then plotted against PMT voltage, and the PMT selected for which the D10 began to stabilize. It was found that the D10 variation was very low in the interval between 350 V to 700 V and a value of 400 V was subsequently chosen. The TSI software's intensity validation, *i.e.* the check for invalid size measurements by signals from multiple particles, reflection, phase wrap and particles outside the 1/e2 beam waist diameter was activated. Channel 2 (488 nm) was used to measure the horizontal droplet velocity. The maximum achievable Laser output power of ~125 mW was used with a PMT voltage setting of 450 V, selected to achieve maximum data rates. [Table 2](#) summarizes the hardware and [Table 3](#) important software settings.

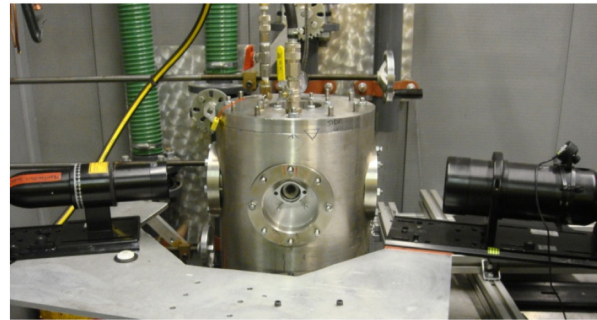


Figure 11. PDA transmitter and receiver setup.

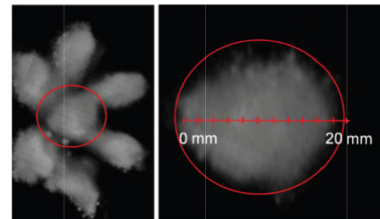


Figure 12. Footprint and single plume extraction for PDA.

Table 1. PDA system parameters.

	Channel 1	Channel 2
Wavelength [nm]	514.5	488
Beam Diameter [mm]	1.77	1.77
Beam Waist [μm]	92.5	87.8
Beam Separation [mm]	20	20
Transmitter Focal Length [mm]	250	250
Beam Half Angle [°]	2.3	2.3
Receiver Focal Length Front lens [mm]	300	300
Receiver Focal Length Back lens [mm]	250	250
Slit Aperture [μm]	150 or 25	150 or 25
Fringe Spacing [μm]	6.43	6.1
Number of Fringes	14	14
Measurement Volume diameter [μm]	93	88
Measurement Volume length [mm]	2.3	2.2
Bragg Cell Frequency [MHz]	40	40

A single spray plume was isolated to avoid the merging of the plumes that resulted in a very dense spray, particularly during hot collapsing conditions. To maintain the flow rate, the remaining six plumes were redirected using a metal funnel plate. Care had to be taken with the positioning of the funnel not to obstruct part of the bore but keeping the edges near to the nozzle hole and efficiently shielding the target region from neighboring plumes. For reasons of accessibility and easy setup, the most central plume was selected and the sheet metal funnel was carefully attached to the injector tip to redirect the remaining plumes. [Figure 12](#) illustrates the overall spray cross section (left) and the extracted plume including the measurement locations (right). The measurements were taken at a vertical distance of 25 mm from the nozzle, along a straight horizontal line in intervals of 2 mm, beginning in the chamber centre moving through the spray until signal drop out indicates the spray's border. Droplets were measured for 3.3 ms from the start of injection to obtain the droplets during the