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A New High Pressure Diesel Spray Research Facility

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ABSTRACT

The application of high pressure advanced fuel injection equipment allows for better control of spray mixing, which ultimately can lead to a more favourable trade-off in noise, soot and NOx formation across the engine operating map. The new Diesel research facility at the University of Brighton has been specifically designed to enable the study of Diesel sprays at realistic automotive in-cylinder conditions while simultaneously providing excellent optical access for both qualitative and quantitative measurements of the combusting/non-combusting spray. The rig is constructed around a single cylinder two-stroke Diesel engine with a specially designed optical chamber incorporated between the cylinder and head. Spray cone angle and penetration data extracted from photographic and high-speed video studies undertaken in the test rig are presented. Injection pressures of 160 MPa and in-cylinder pressures of 10 MPa were achieved.

1. INTRODUCTION

Within the last decade the high-speed direct injection Diesel engine has become a realistic alternative to the gasoline engine for modern passenger car applications. Good drivability and durability together with high economy has led to its increasing popularity in the market place. At present cars powered by DI Diesel engines enjoy approximately 23% of the total market share in Europe. European legislation is set to impose further restriction on the level of emissions that are permitted from Diesel engines together with targets for fuel efficiency. The Diesel engine manufacturer has therefore the task to design suitable power train systems that meet or exceed these directives.

There are several avenues open to the engine designer in the attempt to reduce emissions and improve efficiency, some of which tend towards further sophistication of engine technology and control, and others towards the addition of after treatment of the exhaust gases. The fuel injection system itself is a key element in the bid to control emissions; it has a direct influence on the combustion processes that take place within the engine. Several authors [2,3] have reported on varying the injection parameters of pressure and timing and the effects of multiple injections on the emissions spectrum. Common rail injection systems (CR) and electronic unit injectors (EUI) offer a greater control over the injection process than previously afforded by mechanical systems. The trend towards higher injection pressures to achieve better in-cylinder mixing and reduce soot emissions is set to continue [4]. The spray characteristics of systems employing high injection pressure (160 MPa) and small nozzle diameters (200 µm) injecting into high-pressure environments are not fully understood, however it is known that the temporal and spatial distribution of the fuel droplets and their inter-reaction with the surrounding air are significant factors in the combustion process. The quality of the spray would appear to be different from that visualised in previous systems operating at lower pressures. Some previous work has been undertaken into visualising high-pressure sprays into high temperature and pressure atmospheres, at best approaching the conditions found in-cylinder. This type of work has been typically undertaken using two different experimental approaches: high-pressure vessels "bombs" [5] and rapid cycling machines [6,7,8]. In the case of combustion "bombs" the test are limited to a single shot of fuel before the chamber has to be purged and recharged. The reciprocating machines although having the advantage of being multiple shot devices have been limited to maximum in-cylinder pressures in the region of 60 bars, well below the in-cylinder peak pressures expected in the next generation of Diesel engines.

A need is therefore identified to study firstly the temporal and spatial development of Diesel sprays under realistic injection and in-cylinder conditions, and secondly to study the effects of different injection regimes on the combustion process. Data obtained can be used to establish a link between the injection and combustion processes, and indirectly be used in the development of models to be incorporated in CFD codes.

This paper reports on the new high-pressure Diesel experimental test facility installed at the University of Brighton.This facility has been designed specifically to enable the gaps in the current literature (spray and combustion analysis after injection into environments above 6Mpa) to be addressed in addition to providing a facility to test sprays in conditions anticipated for the next generation of Diesel engines. The Diesel test facility is based around a Ricardo Proteus test engine [9] with a modified cylinder head design incorporating a "top hat" structure into which Diesel spray is injected. The top hat section provides a near quiescent high pressure environment with realistic in-cylinder conditions being achieved by conditioning of the intake air. Excellent optical access is provided to the chamber by four removable quartz glass windows. The design has been optimised so that many state of the art optical techniques may be applied to enable both qualitative and quantitative measurements of fuel, air and combustion products. An outline of the experimental facility is given in the following text together with some preliminary results from high-speed video and stills photography of fuel sprays.

2. DESCRIPTION OF THE FACILITY

The engine is based on a Ricardo single cylinder Proteus engine. The Proteus was converted to two-stroke cycle operation by the addition of inlet and exhaust ports in the cylinder liner. This approach significantly increased the room available in the cylinder head for optical access by the removal of inlet and exhaust valves, this approach also reduced mechanical overheads reducing engine build times. A long optical chamber 80mm in length and 50mm in diameter was fitted into the cylinder head to enable the full length of the developed fuel spray to be visualised. The compression ratio of the engine was reduced to further increase the volume available for the optical chamber.

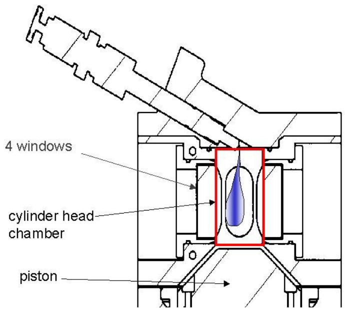

Figure 1. Optical Proteus cylinder head and extended barrel cross-section

Temperatures and pressures representative of a modern engine were maintained by increasing the boost pressure and temperature to 0.6 MPa and 130 °C. A cross-section through the engine is shown in Figure 1.

The air motion was designed to follow the loop scavenge two stroke cycle. The design of the ports and piston were optimised using the Ricardo WAVE gas exchange programme and then further using the Ricardo VECTIS CFD [10] code. WAVE was first used to optimise the port areas. CFD was then used to optimise the air motion to achieve efficient scavenging and near quiescent air in the optical chamber. Good scavenging efficiency and quiescent air motion at TDC were achieved with the optimised design.

The cylinder head is heated by a water jacket (90°C) and the sump oil (85°C) by emersion heaters, this enables the engine to be heated to realistic operating temperatures prior to motoring operations. The engine is motored at 500 rpm for the present non-combusting spray work. The dynamo is coupled to the engine via a reduction gearbox of 6:1 ratio: this reduces the torque through the dynamo. The boost air pressure and temperature are PID controlled; engine operating conditions are controlled and monitored by a centrally dedicated control computer using in house software. A Kistler 6121 transducer attached to a storage scope monitors in-cylinder pressure.

A high pressure Bosch common rail FIE system was selected partly due to the high flexibility of common rail systems and the decreased design complications compared to the implementation of unit injector systems. In the present configuration this allows injection pressures of 160 MPa to be achieved, a schematic of the injection system is given in Figure 2. A five-hole VCO nozzle, with a 0.2 mm diameter orifice was used. Four of the holes were blocked to allow a single fuel spray to be introduced into the optical chamber. The injector was inclined at an angle of 65 degrees so the fuel spray from the single orifice was orientated down into the chamber. Previous work on large-scale models has highlighted differences between single and multi hole VCO nozzles. These differences have not been confirmed on a conventional sized injector under the rapid transience encountered during a fuel injection pulse. However, differences between the spray structures from different nozzle geometries have been reported [11]. Further work is required to clarify the effect of nozzle geometry on the fuel spray structure.

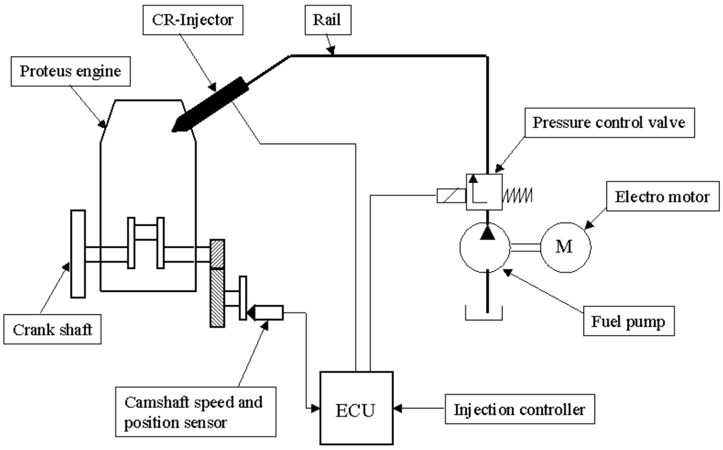

Figure 2. Schematic view of the fuel injection system

Four windows provide optical access to the chamber in the current build configuration; specially designed holders hold these in the top hat section. The windows can be removed easily for cleaning or replacement. The windows holders are sealed into the casting by 'o' rings and an annealed copper gasket, the gasket also seals the glass section against the casting. The windows are potted in the holder by a silicon-based resin, this arrangement has performed adequately for the conditions obtained in the cylinder. A two-window top hat section has been designed for forward scatter PDA experimentation; the modular nature of the engine build allows quick change over of engine configuration allowing a range of experimental configurations for different optical techniques and injector types.

3. DESCRIPTION OF THE SPRAY IMAGING SYSTEMS

As the air-fuel mixing process is a key parameter in diesel combustion, a good knowledge of the formation of the spray is essential to improve mixing efficiency. By simply visualizing the diesel jet, a number of characteristics of the spray, such as its penetration, cone angle, liquid core length and fuel break-up can be easily obtained.
Two different acquisition strategies can be adopted:

- high-speed visualisation
- single-frame acquisition

In the high-speed case several photographs of a single spray are acquired consecutively, with an exposure time low enough to avoid blurring due to spray movement. This technique can be applied either with a high-speed video camera using light-sensitive film, or with a charge-coupled device (CCD) camera. The former has the major inconvenience of requiring the processing of thousands of photographs for every injection. Therefore, the analysis of such a large quantity of stills is not easily achieved, and the use of post-processing software is made tedious by the need to digitise every single photograph.

CCD cameras offer the opportunity to observe a complete injection at high recording speed, but the resolution of the images is significantly lower than with standard film. Because the output is readily available in digital format and can be observed instantly, this technique is preferred to standard film recording.

After analysis of the high-speed recordings, the most critical phases of the diesel injection were then photographed using a 35mm still camera and a high-speed flashgun. This allowed the acquisition of a set of high resolution photographs, thus giving better-detailed images at important timings (e.g. spray break-up).

This section describes the imaging systems used for high-speed video and 35mm stills on the Proteus engine.

3.1 High-speed spray visualization

The CCD video camera used in this series of experiments was a Kodak Ektapro HS Motion Analyzer (Model 4540), with a recording rate adjustable from 30 to 4500 frames per second at full resolution (256×256 pixels × 256 grey levels), and from 9000 to 40500 frames per second at progressively reduced resolution. The best compromise between acquisition rate and image resolution was obtained with a frame rate of 18000 pictures per second, with a corresponding resolution of 256×64 pixels × 256 levels of grey. The camera was used in intensified gain mode, with a gamma correction factor of 1.0 in order to maximize the intensity of the recorded images.

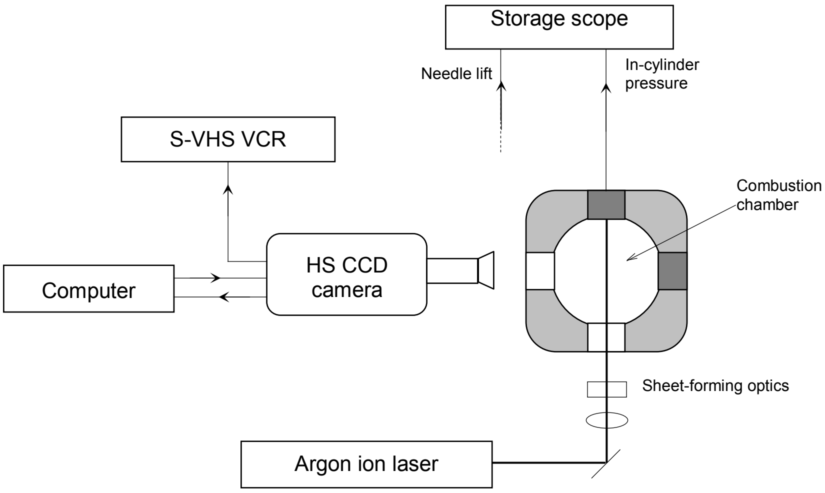

Figure 3. Experimental set-up for high-speed video recording of spray formation. The combustion chamber is shown from the top.

The injection timing was controlled by means of a custom made fuel injection equipment system (FIE), denoted the RW78 FIE unit. This unit essentially consists of a microprocessor dedicated to the task of triggering an injector and a secondary device (such as a pulsed laser or a CCD camera). Before each series of experiments, a personal computer was used to upload to the FIE unit the key injection parameters (e.g. injection angle, injection duration, rail pressure, delay of secondary trigger, etc.). This enabled high timing accuracy with a fully customisable injection system.

The non-combusting spray was illuminated by means of a continuous-wave low-power Argon ion laser tuned to 514.5 nm, whose output beam was converted into a vertical sheet crossing the spray through its central axis, propagating from the right-hand side on the photographs. The laser sheet was cropped to the height of the optical accesses to the combustion chamber (55 mm), and had a thickness of about 1 mm.

Because the CCD camera had enough memory to acquire two consecutive injections, its synchronization with the injection event was unnecessary and thus the acquisition process was triggered manually. All the injections observed were then recorded on S-VHS videotape, and the most representative sprays were downloaded on computer directly from the CCD camera.

The injector needle lift and in-cylinder pressure were acquired by a digital storage oscilloscope for each recorded injection, and then downloaded onto computer.
Figure 4 shows the evolution of a diesel spray injected at a pressure of 135 MPa, with an in-cylinder pressure of 6 MPa.

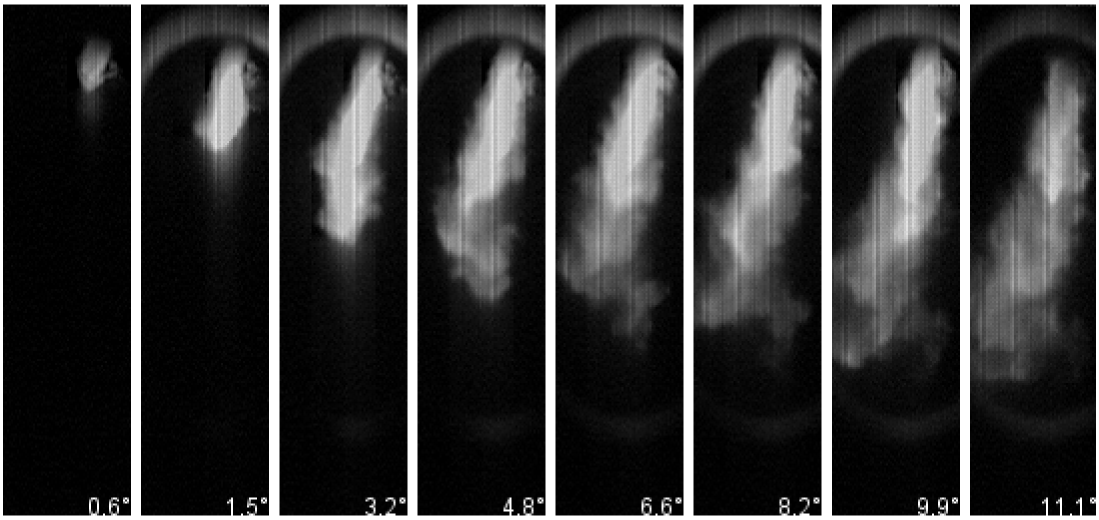

Figure 4. Evolution of a spray captured with high-speed CCD video camera at 18000 frames per second. Injection pressure: 135 MPa; in-cylinder pressure: 6 MPa; engine speed: 500 rpm. Crank angles are relative to start of injection.

3.2 Spray photography

A fully manual Pentax still camera was used with a telephoto lens (125 mm, f:1/4-1/22) and two extension tubes (1+3 cm). This combination was found to give the best compromise between magnification and focal distance. During the tests, a high-speed argon flash lamp was synchronised with the engine and delayed relative to TDC by means of the RW78 FIE system. For each photograph, the shutter of the camera was kept open until an injection occurred. A diffused backlighting was preferred to side-lighting for a more homogeneous illumination of the spray background. The duration of the flash was about 3 μs.

Kodak 400 ISO films were used and the camera aperture was set to f:1/8. These settings were found to give a good compromise between sensitivity of the film, quality of the prints and depth of field (measured to be about 4 mm at f:1/8). Even though a smaller lens aperture would have provided a much larger depth of field (i.e. better focusing of the whole spray), the amount of light available with the argon flashgun was not sufficient to give correct exposure.

For each one of the three different fuelling rates tested, two photographs were taken at different timings: one around the maximum liquid length and one showing the break up of the spray. Because the tip of the nozzle was not visually accessible through the windows, the beginning of the injection could not be observed.

As the tests were done under backlighting, the shape of the back window can clearly be seen on each photograph. The dimensions of those optical accesses on the Proteus were measured to be 25×55 mm. After correction for the optical distortion due to the imaging system, the scaling factor for the plane of the spray were found to be about 1:0.28 (i.e. 1 cm on a photograph is equivalent to 0.28 cm in reality), which corresponds to a magnification factor of 3.6.

As opposed to the high-speed video experiments, laser sheet illumination was not used. Therefore these photographs show the overall shape of the spray, integrated along the line of sight.

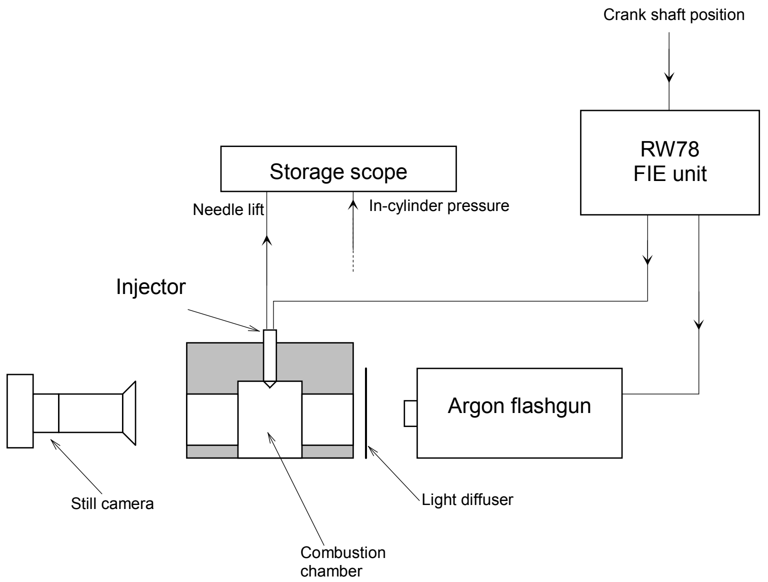

Figure 5. Experimental set-up for backlit spray photography. The combustion chamber is viewed from the side.

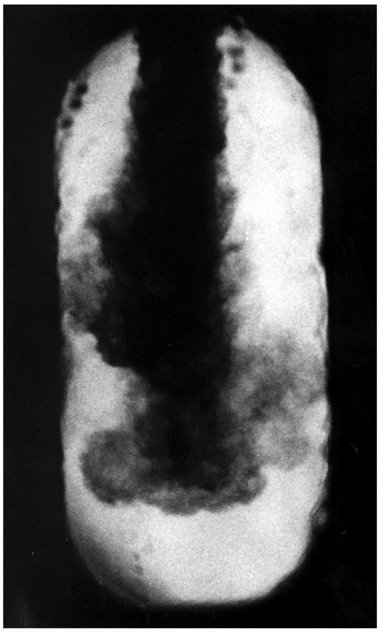

Figure 6. Injection at 160 MPa; photograph taken 4.95°CA after start of injection; pressure at TDC: 8 MPa; spray penetration about 4.5 cm.

4. PRELIMINARY RESULTS AND DISCUSSION

4.1 In-cylinder conditions

Preliminary tests using the facility were undertaken to commission the rig and to establish whether the in-cylinder design conditions could be realised. In-cylinder pressures of 12 MPa have been measured with the engine motored at 500 rpm and in-cylinder temperatures of 760 K calculated. The optical access windows that were fitted during these test conditions were inspected after the trial and showed no signs of degradation or wear.

4.2 Preliminary spray results and discussion

Individual frames from the high-speed video images (figure 4) were identified at key points in the spray development, these particular frames were enhanced using a commercial image processing package thus enabling the salient features of liquid length, cone angle and break-up length to be quantified. In figure 8 the results for spray penetration with time for various injection and in-cylinder conditions are presented. At lower ambient in-cylinder density (lower pressure) the spray is seen to achieve greater penetration, a similar weaker effect is observed with increasing injection pressure. These trends in penetration are in agreement with other work undertaken in lower density conditions [12,13] where the penetration of spray was found to be dependent on both air density and injection pressure with a stronger dependence on the former.

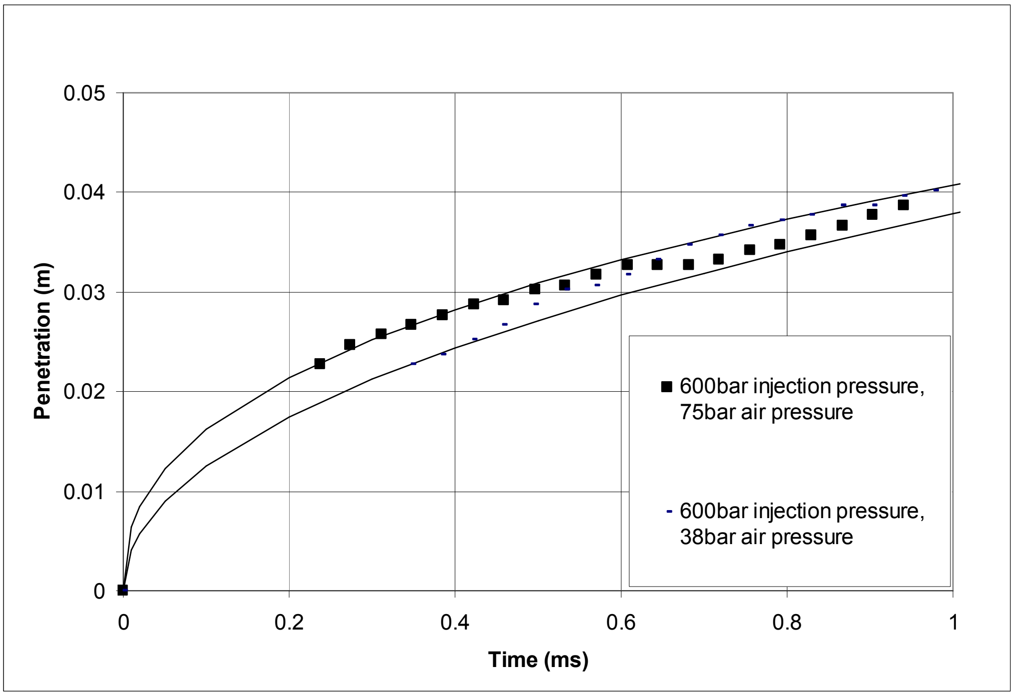

Figure 7. Spray penetration results (3ms pulse width).

It was interesting to note the shot to shot variability in spray development when employing shorter injection pulse widths, although this is probably due to needle instability further investigation is required into injector behaviour at these conditions. The penetration of the spray jet at two different operating conditions for a 0.9ms pulse width is shown in Figure 8, the trend observed for penetration with larger needle pulse width is clearly not conserved.

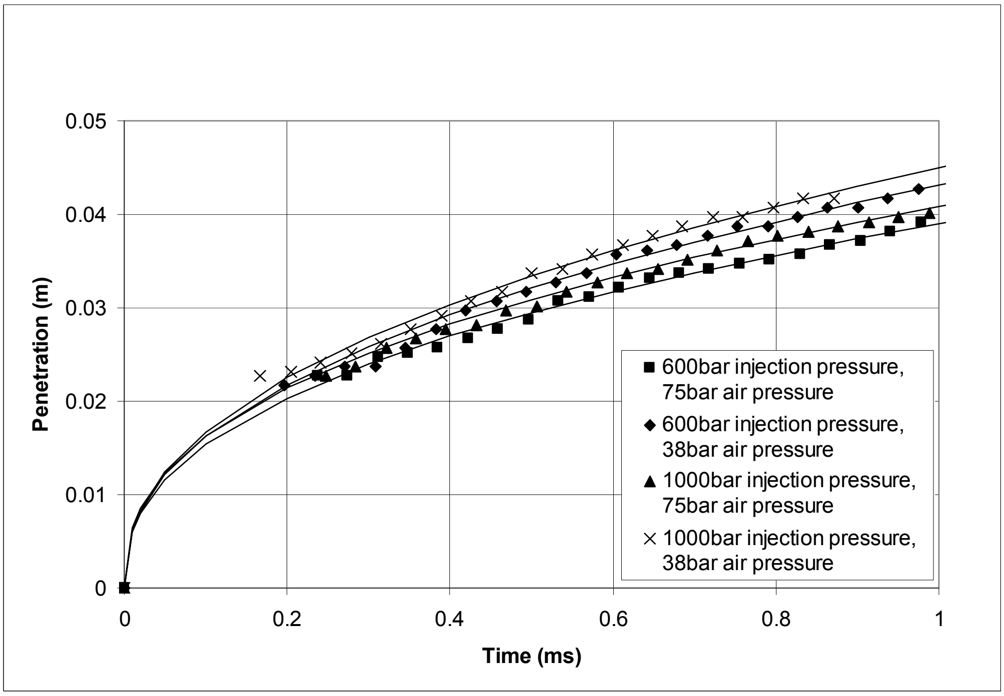

Figure 8. Spray penetration results (0.9ms pulse width).

5. Conclusions

A new high pressure Diesel test facility has been designed and commissioned at the University of Brighton with industrial partnership from Ricardo Consulting Engineers. Initial tests on the rig have shown that it is able to simulate both current and anticipated in-cylinder conditions, while at the same time allowing good optical access of the Diesel spray. Preliminary experiments have utilised high-speed video and stills photography to enable image capture of a single transient Diesel spray at injection and in-cylinder pressures previously unachieved in an optical access engine. Initial analysis of results show that trends in penetration length reported by previous workers are observed, however some shot to shot variation in spray development is noted for smaller injection pulse widths. These variations are thought to be caused by instability of the injector at low needle lift additional work on different nozzle designs and configurations is planned in to investigate this further. Further work using optical techniques such as PLIF, LII and PDA is planned in the near future.

6. References

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