SPRAY DEVELOPMENT AND COMBUSTION CHARACTERISTICS FOR COMMON RAIL DIESEL INJECTION SYSTEMS

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ABSTRACT

An attempt to understand, further, the processes of auto-ignition, combustion and ultimately emission formation for a common rail diesel injection system, has lead to an investigation into the effects in-cylinder density and fuel injection pressure have on liquid penetration, vapour formation and auto-ignition delay. Although several correlations for diesel spray penetration at different operating conditions have been presented in the literature, to date the findings are inconclusive with only limited investigation into the operating envelope expected in present and future high speed direct injection diesel engines.

The present paper describes how two high-speed video cameras were utilised to achieved pseudo 3-dimensional imaging of the spray (backlit) and of auto-ignition sites (flame luminescence). It also describes how Schlieren imaging enabled vapour phase analysis. Data have been gathered for in-cylinder densities in the range 10 to 50 $kg.m^{-3}$ and injection pressures between 60 and 160 MPa. New correlations have been established for the penetration of both the liquid and vapour phases of a high-pressure diesel spray injected from a modern VCO nozzle common rail system. By increasing injection pressures and using small injector orifice sizes, it is thought that the injected diesel droplets reduce in size and penetrate further, hence increasing air utilisation, thus leading to faster evaporation rates and reduced ignition delay. An experimental correlation for auto-ignition delay against in-cylinder density has been presented, suggesting that as the charge density increases, penetration is reduced but auto-ignition delay is reduced, indicating more favourable conditions for ignition.

1 INTRODUCTION

In order to improve fuel economy and reduce emissions, the engineer has to develop new techniques and processes that can be integrated within existing engine sub-systems. Recently there have been many advances in fuel injection technology with the introduction of common rail which provides increased controllability. The common rail system injects the fuel into the cylinder at very high pressure with the fuelling quantity being controlled by an electronic control unit which determines the fuelling level. This was not possible with mechanical fuel systems. The higher injection pressures of the common rail system give rise to different characteristics of the fuel spray in the engine. Vaporisation and the degree of air utilisation of the spray are largely determined by the injection pressure, nozzle design and geometry as well as the in-cylinder conditions (air motion, density and temperature). Ultimately, the combustion process is determined by the quality of this distribution and of this mixing, which itself impacts on the subsequent spray development [1].

Traditionally, parameters such as penetration with time, fuel dispersion angle and droplet size enable the assessment of the injection system performance under different operating conditions. The merits of high or low penetration are largely dependent on engine size and design, but ultimately the aim of any injection system is to achieve as much utilisation of the air as possible leading to a clean burn [2]. A review of early correlations by Hay and Jones [3] found that most investigators agreed that penetration was dependent on ambient density and injection pressure. Many of the initial investigations of spray performance were focused on low-pressure sprays injected into ambient or low-density conditions [4]. More recent investigations by Hiroyasu and Arai [5], Naber and Siebers [6] have also confirmed this dependency at both higher fuel injection pressure and higher in-cylinder pressures. Under realistic engine conditions the effects of vaporisation are important as reported in the authors' previous work [7]. Dent [8] suggested the inclusion of a term to compensate for these temperature effects in his correlation for spray penetration. Some investigations into the spray behaviour of fuels injected through a common rail system have been reported in the literature [6,7]. Although the influence of injection parameters has been widely investigated, information on the effects of in-cylinder density and fuel rail pressure on spray and fuel vapour distribution, when using modern fuel injection systems, is far from conclusive.

Injection and in-cylinder conditions are not the sole drivers of the penetration and distribution of the fuel spray, nozzle geometry and injection rate profiles have also been found to impact on spray performance [9,10,11,12,13]. The variation in the behaviour of different types of nozzle may go some way to explaining the disagreement in correlations for spray performance found in the literature. Bae & Kang [13] and Campanella et al. [14] investigated the performance of individual holes of multi-hole injection nozzles and reported respectively little and more significant hole to hole variations.

The mixture of air and fuel vapour at the required chemical ratio provides suitable conditions for auto-ignition. Despite the significant amount of research that has been carried on diesel combustion in order to gain the thorough understanding of diesel combustion required to reduce engine emissions, critical events such as auto-ignition are still not fully understood. The influence on the timing of auto-ignition is far reaching and has been shown to effect engine efficiency, emission formation and noise levels. Self-ignition of diesel sprays is usually described in terms of ignition delay and ignition sites location. It has been suggested that auto-ignition may be a continuous process [15] and therefore that a definite time at which ignition begins may not exist. However it is widely considered that auto-ignition is the beginning of the thermal explosion that follows both an initial physical and chemical delay. The start of ignition is defined in different ways by a number of researchers, and this has lead to large variation in ignition times for a range of engine conditions. The start of ignition has traditionally been identified in two ways, the time at which a flame is first visualised, or the time at which a pressure or temperature rise is recorded within the cylinder. In many of the experiments reported the visual onset of combustion is recorded using a single camera and the exact location of the auto-ignition sites is ambiguous. Auto-ignition was reported to occur at the tip of the spreading vapour phase [16], occurring at locations further from the nozzle as injection pressure increased.

In summary, the engine efficiency and emissions relate to the combustion which is triggered by the auto-ignition process, itself influenced by the vaporisation and the air utilisation, which in-turn is dependent on the injection equipment used, the fuel injection pressure, quantity and rate and the in-cylinder conditions of temperature and pressure (density). Although the literature concerning auto-ignition and spray development is extensive, the effect of the interactions of many of these processes is still not fully understood.

The current work is part of an ongoing investigation into liquid spray and vapour penetration, auto-ignition and emission formation processes. Details of experiments undertaken to quantify both the liquid and vapour distribution of a diesel fuel injected through modern common rail fuel injection system into realistic engine environments (high-temperature charge experiments) and into in-cylinder conditions at lower temperatures than expected in a working engine (low-temperature charge) are given in this paper. In addition a study of the auto-ignition of the diesel spray is undertaken using two high-speed video cameras. Two video cameras were used so that the ambiguity of the ignition sites could be removed. Injection using a range of fuel rail pressures and a number of in-cylinder density conditions are presented. The results are compared with other experimental observation.

2 EXPERIMENTAL APPARATUS

2.1 Spray rig

The Ricardo high-pressure spray rig facility at the University of Brighton allows the testing of a wide range of common rail diesel nozzles at different fuelling rates and pressures under extensive ambient conditions (figure 3). The facility provides the ability to view the development of diesel sprays in high temperature and pressure environments: for specific details about the experimental rig the reader is referred to previous publications [17,18]. In the present tests, the spray was studied using two different injector locations in the rig, this was to allow both close up and far field studies of the spray (figures 1a and 1b respectively).

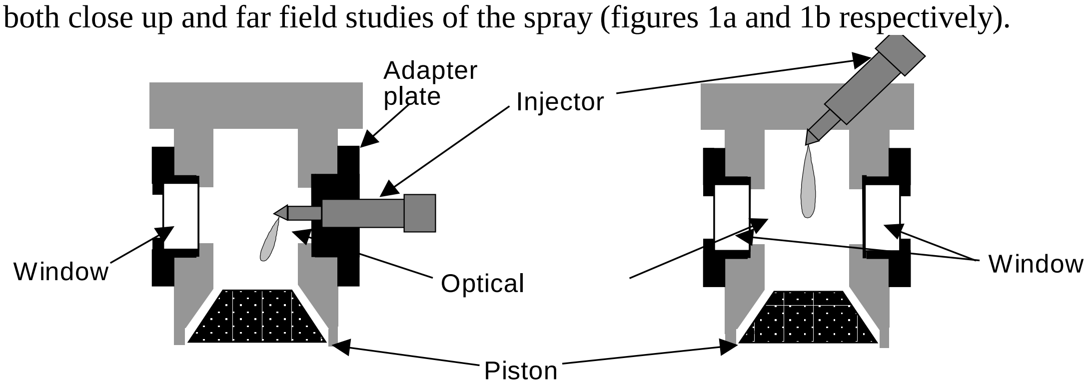


Fig 1a. Early stages of the nozzle exit view (close up penetration data).

Fig 1b. Plume development, evaporation and combustion view (full length data).

Although a number of interchangeable nozzles have been studied on the injection facility, tests described and analysed within the paper were evaluated using a single nozzle type, being a single-hole, 0.2 mm diameter, single-guided, Valve Covers Orifice (VCO) nozzle (l/d=5.0).

2.2 Image acquisition

Backlit and Schlieren imaging where the two techniques employed for, respectively, the analysis liquid core and vapour phase visualisation during this study. A third technique was used for the auto-ignition study, directly capturing the flame luminosity.

For the liquid phase imaging, illumination of the spray was provided by halogen photoflood lamps fitted with a diffuser. Images of the spray produced over a range of injection and in-cylinder conditions were captured using a Kodak Ektapro high-speed image Analyser (Model 4540) triggered by the injection pulse. Details of the image acquisition and data processing are given in a previous publication [19]. For the recording of the auto-ignition process, two high-speed CCD video cameras with synchronised recording at 27,000 frames per second were placed orthogonal to each other as shown in figure 2. No additional lighting was required since this technique is based on the flame luminosity. This setup offered a pseudo three-dimensional analysis of flame location and structure.

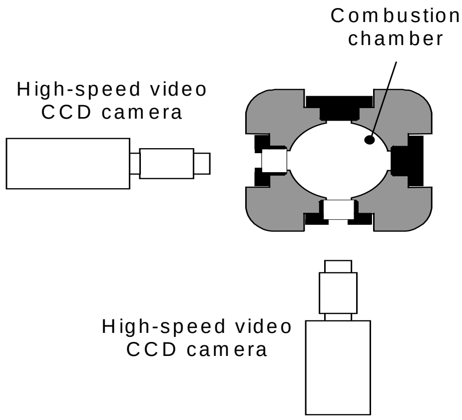


Fig 2. Experimental set-up for pseudo three-dimensional auto-ignition study. Both video cameras operate at a recording rate of 27,000 frames per second.

The progressive visualisation offered by the high-speed video approach was invaluable in the assessment of the spray development, auto-ignition event and subsequent combustion. Since this was a high speed camera, a fixed exposure setting had to be used during the acquisition process, however this had the disadvantage of overloading the cameras during the main combustion event soon after the auto-ignition. In order to supplement the ignition delay data obtained through video recordings, in-cylinder pressure traces were acquired with a high-speed data logger while the engine's inlet pressure was being varied. Further work will incorporate varying exposure settings through the combustion process for a more detailed analysis.

2.3 Test Conditions

The test rig was designed to reflect modern and future diesel engine in-cylinder conditions. Stable motored peak pressures of up to 120 bar can be achieved in the rig, while using a maximum of 9 bar intake boost (Cr = 9), in conjunction with a maximum heated intake condition of 170°C. In the current tests peak in-cylinder pressures (pre-injection) of up to 100bar were used, with a maximum of 100°C in the heated boosted intake. These in-cylinder conditions correspond to those of a modern or future 2.0L engine (compression ratio in the range of 17 and 18.5 with an absolute intake pressure in the range 2 and 2.5 bar, figure 3).

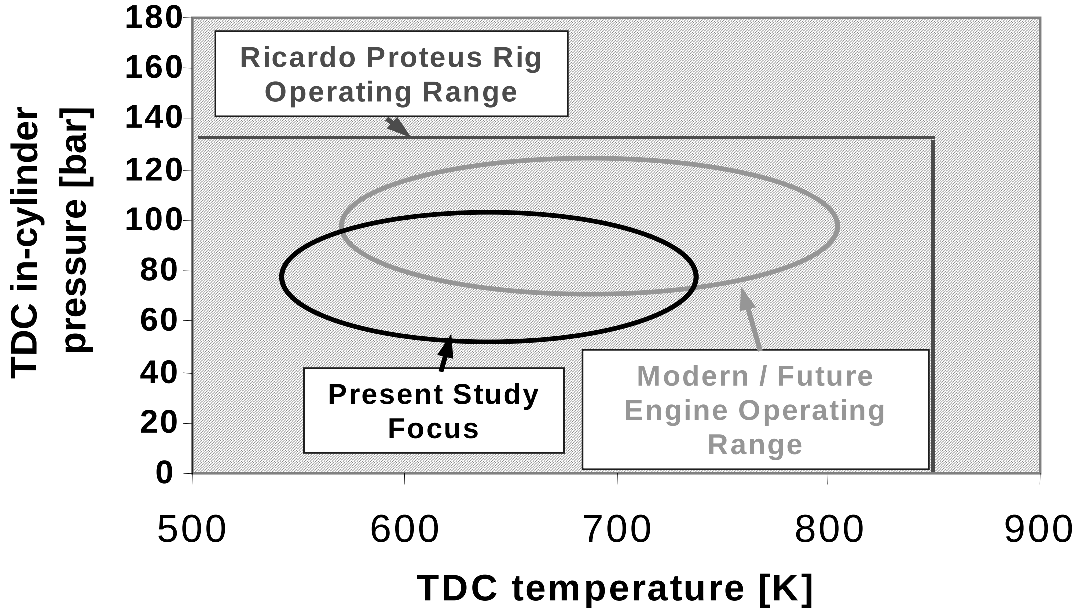


Fig 3. TDC pressures and temperatures expected from modern and future engines versus the present study range.

The operating conditions tested in the current work are detailed in table 1. The in-cylinder peak charge temperatures in Table 1 have been calculated from data acquired during the experimentation. Charge temperature peaks at top dead centre and is reduced on the expansion stroke. For a 60 MPa injection pressure and a 30 mm^3 fuelling (12° of crank) injected into a high-temperature charge with density 42 $kg.m^{-3}$, the in-cylinder charge temperature was estimated to drop by a calculated 37 K (due to expansion alone) over the injection period. The fuel used was pump grade low sulphur diesel with a density of 840 $kg.m^{-3}$ and was maintained within the limits 20°C to 25°C. Additional experiments were performed with 0.2 mm mini-sac and 0.15 mm VCO nozzles for comparison purposes.

Liquid penetration	
In-cylinder densities ($kg.m^{-3}$)	10 – 50
In-cylinder temperatures (K)	Low temperature 550 & High temperature 700
Injection quantities (mm^3)	10, 30, 50
Injection pressure (MPa)	60, 100, 140, 160
Injection pulse width for 30 mm^3 0.2 VCO (ms)	4.2, 3.1, 2.6, 2.4
Vapour penetration and auto-ignition sites	
In-cylinder densities ($kg.m^{-3}$)	10 – 50 (from 31 for auto-ignition)
In-cylinder temperatures (K)	High temperature 700
Injection quantities (mm^3)	30
Injection pressure (MPa)	60, 100, 140, 160 (not 60 for auto-ignition)
Injection pulse width for 30 mm^3 0.2 VCO (ms)	4.2, 3.1, 2.6, 2.4
Combustion injection angle	15º BTDC

Table 1. Experimental in-cylinder and injection conditions.

3. RESULTS AND DISCUSSION

3.1 Data analysis process

The results from the liquid and vapour spray and auto-ignition sites investigations were captured with the motion analyser. The video frames were downloaded onto a PC for post-processing. These frames were combined to construct a number of movies so that liquid and vapour spray and combustion behaviour could be compared under identical injection and in-cylinder conditions. The results presented in this paper have been derived from these comparative studies. For brevity and clarity, the figures presented are limited to a few examples. Figure 4 shows the information extracted from video images and the association with the injector operation (0 ms represents the injection signal time).

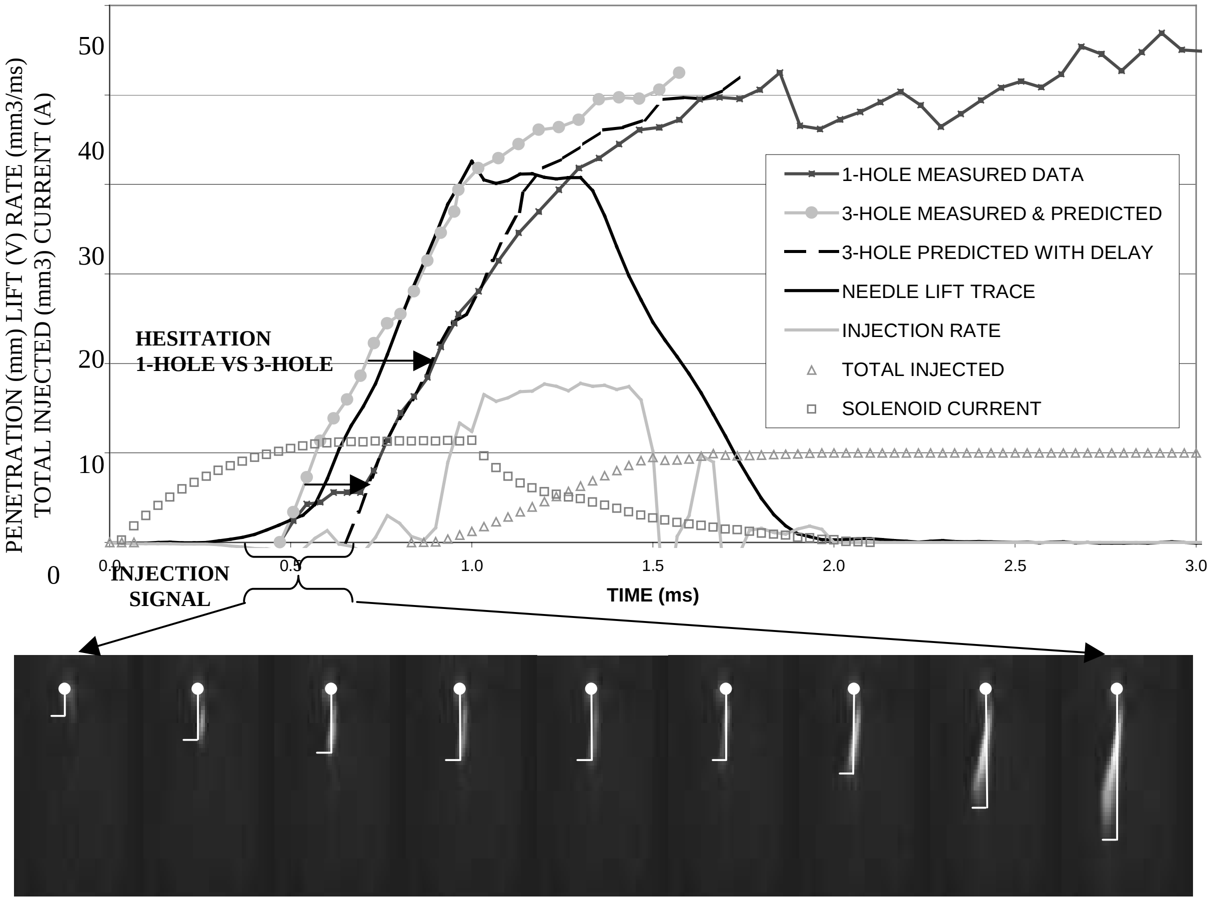


Fig 4. Information extracted from video images and linked to a typical injector operation (0 ms is the injection signal time). Single-guided single-hole 0.2 mm VCO nozzle, 10 mm^3 fuelling injected at 160 MPa into a chamber density of 40 kg.m^{-3}.

The first observation is the apparent discrepancy between the measured needle lift and injection rate. This can be explained by the finite time required for the fuel to travel passed the needle, and through the nozzle hole(s); the needle starting to lift ~0.25ms prior to the rate tube measured fuel exit. The video observed time delay between the injection signal and the first sight of fuel leaving the nozzle was studied for different injection pressures and nozzle types (figure 5). This injection delay proved to be independent of the in-cylinder charge density and nozzle type but closely related to the injection pressure. This indicates downstream in-cylinder conditions have a negligible effect within the nozzle region during the opening phase and can be ignored when considering injection delay. The time dependent liquid and vapour penetration data presented in this paper are referenced from the time spray is first visualised exiting the nozzle. The auto-ignition data however, is presented relative to start of injection pulse signal.

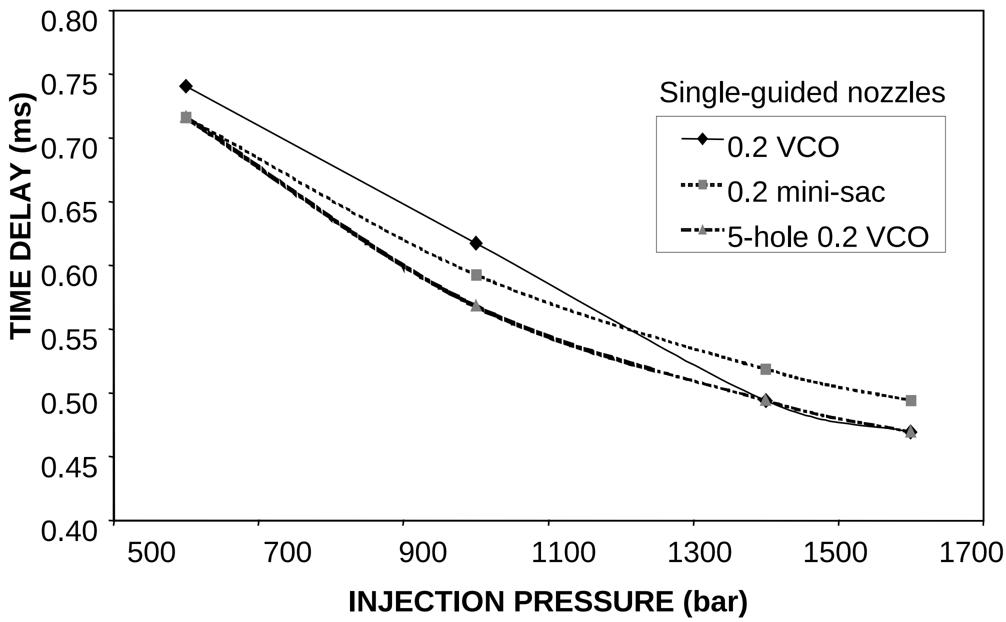


Fig 5. Time delay between injection signal and first sight of fuel for different injection pressures and nozzles at 60 bar ICP, 10 mm^3 fuelling.

3.2 Initial spray hesitation

The example given in figure 4 shows an initial ‘hesitation’ period of flow at the beginning of the visible injection, despite the needle continuing to rise. This phenomenon was also noted on the injection rate profile measured on the Lucas rate gauge. Similar in-cylinder (and rate tests) tests were conducted for a 0.2 mm VCO nozzle with a double-guided needle and a 0.15 mm single-hole VCO nozzle. Similar hesitation phenomena were observed with both of these nozzle designs, but they were of a reduced magnitude when compared to the single guided 0.2mm VCO nozzle. This behaviour was not observed when multi-hole VCO, 0.10 mm single-hole VCO and the mini-sac nozzle tested.

Spray structure and hole-to-hole variations have previously been observed in multi-hole VCO nozzle injections by Gupta et al. [20] and were linked to the needle oscillations and cavitation. Prior to lifting, pressures around the needle are balanced, however once the lift starts, pressures can become temporarily unbalanced, especially if the holes are not uniformly spaced around the nozzle, this being the case with a single-hole, leading to the pulsed closure of the orifice. Due to the internal geometry the physical closure of the nozzle hole by the needle is not possible with a sac volume nozzle design. Figure 6 shows a graphical representation and video image capture of the effect of the closure on the flow. Decreasing the nozzle hole section reduced this pressure balance effect to a point where the hesitation disappeared, reinforcing the hypothesis. The subsequent penetration rates were shown to be comparable between the single and multi-hole designs, hence when comparing single-hole nozzle data with penetration correlations in the literature this behaviour must be taken into account, i.e. a time offset must and can be applied to adjust for this hesitation period.

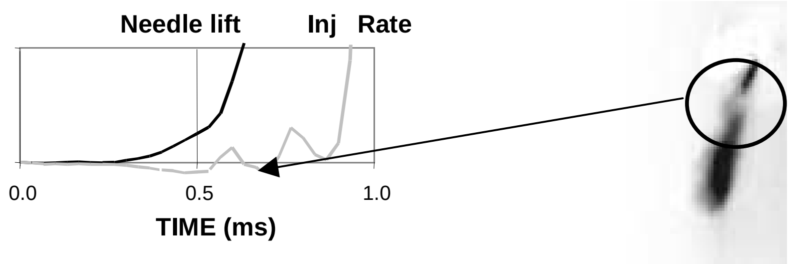


Fig 6. Video image showing an interruption in the fuel flow corresponding to the hesitation of the needle. Single-guided single-hole 0.2 mm VCO nozzle, 10 mm^3 fuelling at 160 MPa injection pressure into 8 MPa in-cylinder pressure.

3.3 Far field spray studies

3.3.1 Low-temperature charge liquid dispersion

A complete study of the liquid penetration was accomplished by inhibiting the combustion. This was achieved by maintaining a low intake air temperature and hence keeping the in-cylinder peak gas temperature below the combustion threshold. The full development of a non-combusting spray was then captured by high speed video as previously described. Recordings were performed for 20°C intake air, three different injection pressures (60, 100 and 160 MPa) and several in-cylinder densities (14, 28, 34, 42 and 49 kg.m^{-3}).

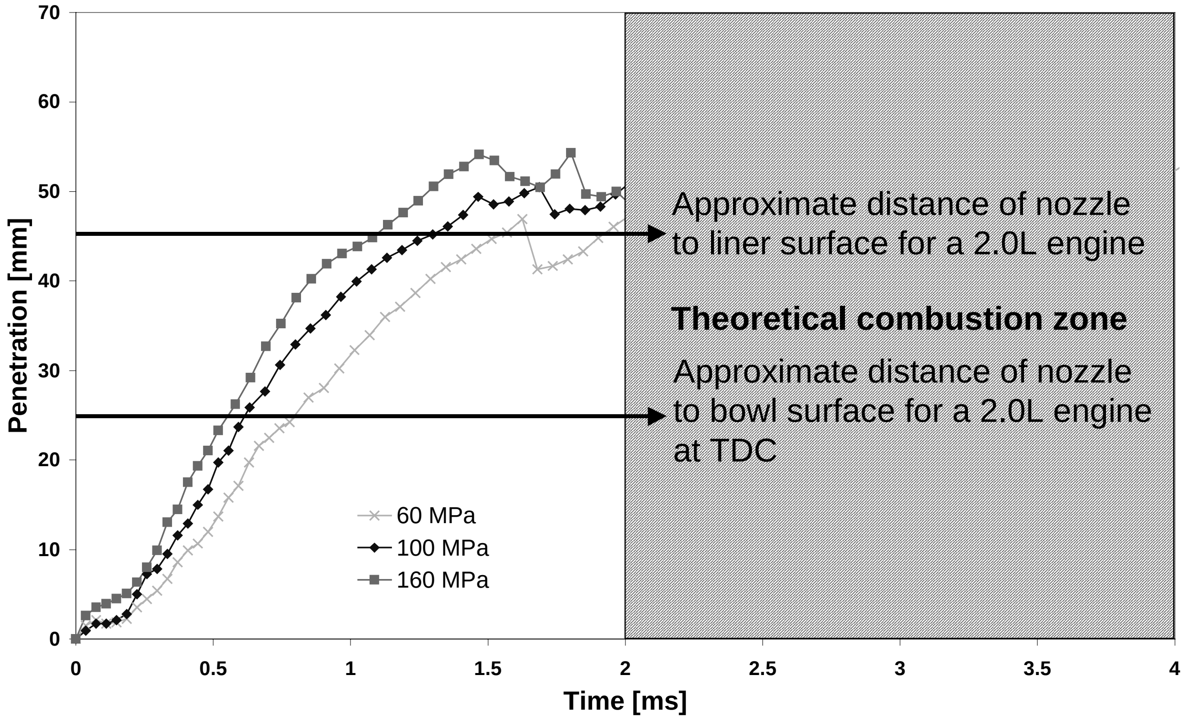


Fig 7. Influence of injection pressure on liquid penetration for low-temperature charge. Single-guided single-hole 0.2 mm VCO nozzle, 30 mm^3 fuelling at different fuel injection pressures into chamber density of 49 kg.m^{-3}.

Figure 7 gives typical liquid penetrations for different injection pressures. After the initial hesitation, the liquid penetration profiles for low-temperature charge showed a phase of almost linear increase in penetration followed by a rapid transition to fluctuations around a stabilised penetration length. Investigations proved these fluctuations were a result of portions of liquid breaking off the main core due to spray instability.

In these tests, higher injection pressures increased the liquid core penetration rates and also produced fully developed sprays in a shorter time (1 ms at 160 MPa injection and 1.5 ms at 60 MPa for 49 kg.m^{-3} in-cylinder density). This is in agreement with the findings of Wigley et al. [21] where increased rail pressure equated to smaller size droplets with faster velocities. These reduced droplet sizes for higher injection pressures improved the evaporation rate due to a higher surface-to-volume ratio. However, injection pressure had little effect on the ultimate penetration length (less than 10 mm difference in penetration for the 60 and 160 MPa injection pressure cases). The relationship between the injection pressure and the cone angle was investigated and proved negligible; a stable dispersion full cone angle of 11° was reached in all cases.

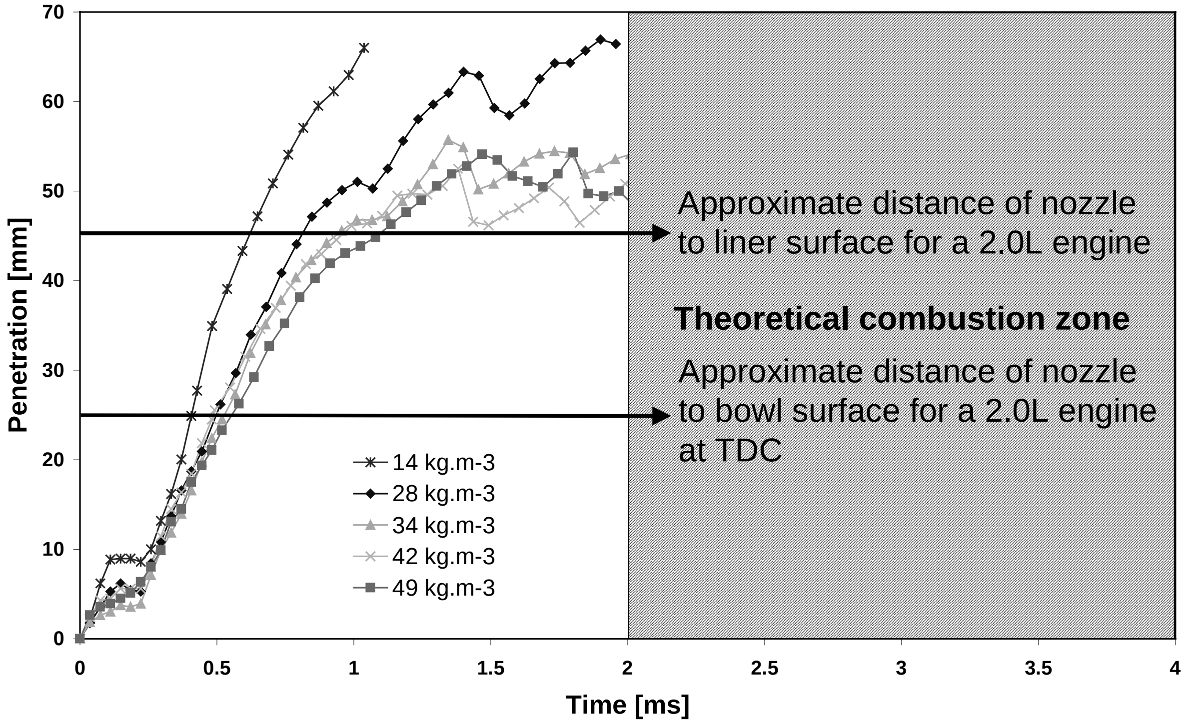


Fig 8. Influence of ambient density on spray penetration for low-temperature charge. Single-guided single-hole 0.2 mm VCO nozzle, 30 mm^3 fuelling at 160 MPa injection pressure into different chamber densities.

Figure 8 shows the effect of in-cylinder densities on liquid core penetration. The penetration profiles were similar to the previous data with an initial hesitation period, a linear phase lasting approximately 1 ms and a stabilised final phase. Detailed investigations showed that increasing density had a reducing influence on the rate of the main penetration phase. Additional experiments are planned to confirm this trend by extending the test range. Increasing the density beyond 34 kg.m^{-3} has no measurable impact on the ultimate penetration length, which stabilised around an average of 50 mm.

The low-temperature charge results indicated that the liquid core penetration was influenced by injection pressure and charge air density. A high-density gas phase gives greater resistance to the motion of the liquid phase trying to travel through it. The resultant higher shear forces cause an increase in the level of spray break-up and momentum transfer from the liquid spray.

3.2.2 High-temperature charge liquid and vapour dispersion

Both liquid and vapour phase penetrations were investigated in a high-temperature charge environment. The preconditioned air intake facilitated comparable in-cylinder operating conditions to those found in a modern common rail diesel engine, at high load with an efficient charge air cooler. Data was acquired at three different injection pressures (60, 100 and 160 MPa) and several in-cylinder densities (14, 28, 30, 36 and 37 $kg.m^{-3}$). These tests were undertaken with a boosted intake temperature of 100°C, relating to a calculated in-cylinder TDC temperature of 700 K. Repeatability studies for key conditions were conducted during the experimental work, typically a penetration variation of less than 10% was observed for the Schlieren tests.

The observed liquid spray development followed a similar pattern to the low-temperature charge tests, however, the ultimate liquid length achieved for the higher charge temperature was lower than for the cold charge temperature. This is a direct result of increased evaporation rates. The vapour cloud visualised by the Schlieren technique developed alongside the liquid core, widening with the penetration and continuing to develop beyond the point of ultimate liquid length. The vapour penetration rate was comparable to the liquid penetration rate in the low-temperature charge as shown in figure 9. Since the injection event continues during the measurement period, the penetration of the leading edge liquid or vapour is driven forward by the momentum of the newly injected droplets.

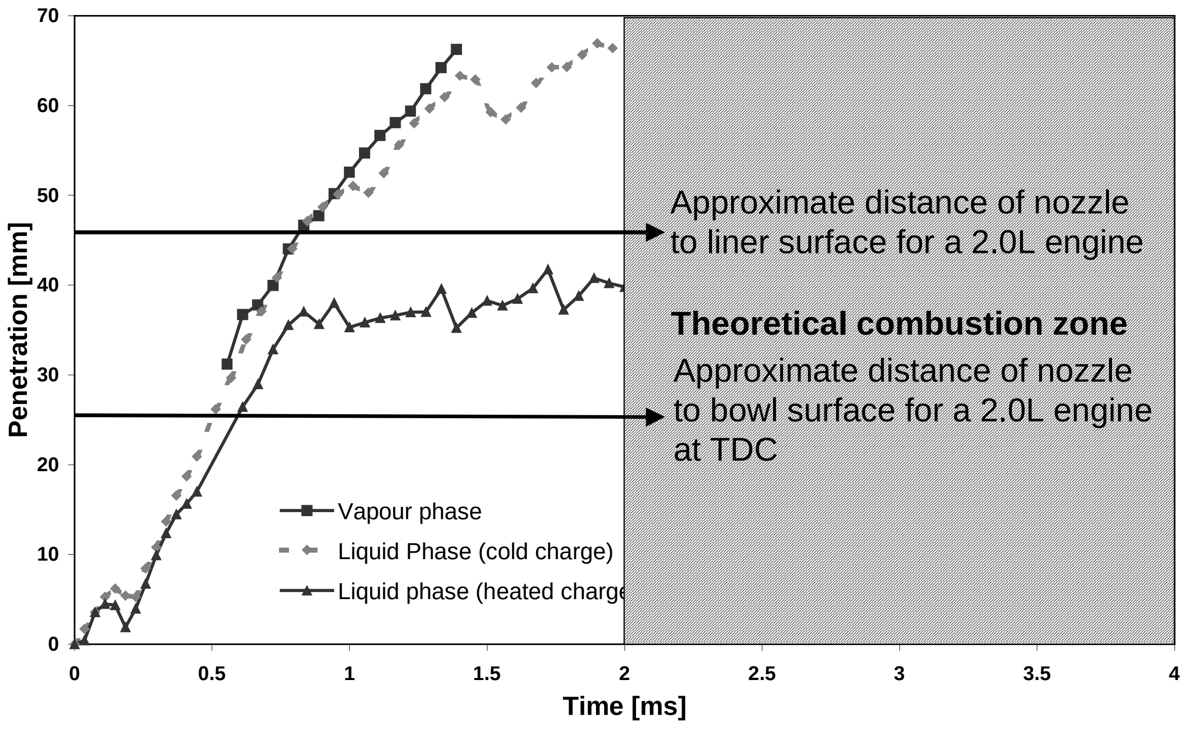


Fig 9. Liquid and vapour penetration compared to a liquid penetration at a low-temperature charge. Single-guided single-hole 0.2 mm VCO nozzle, 30 mm^3 fuelling at 160 MPa injection pressure into chamber density of 28 $kg.m^{-3}$.

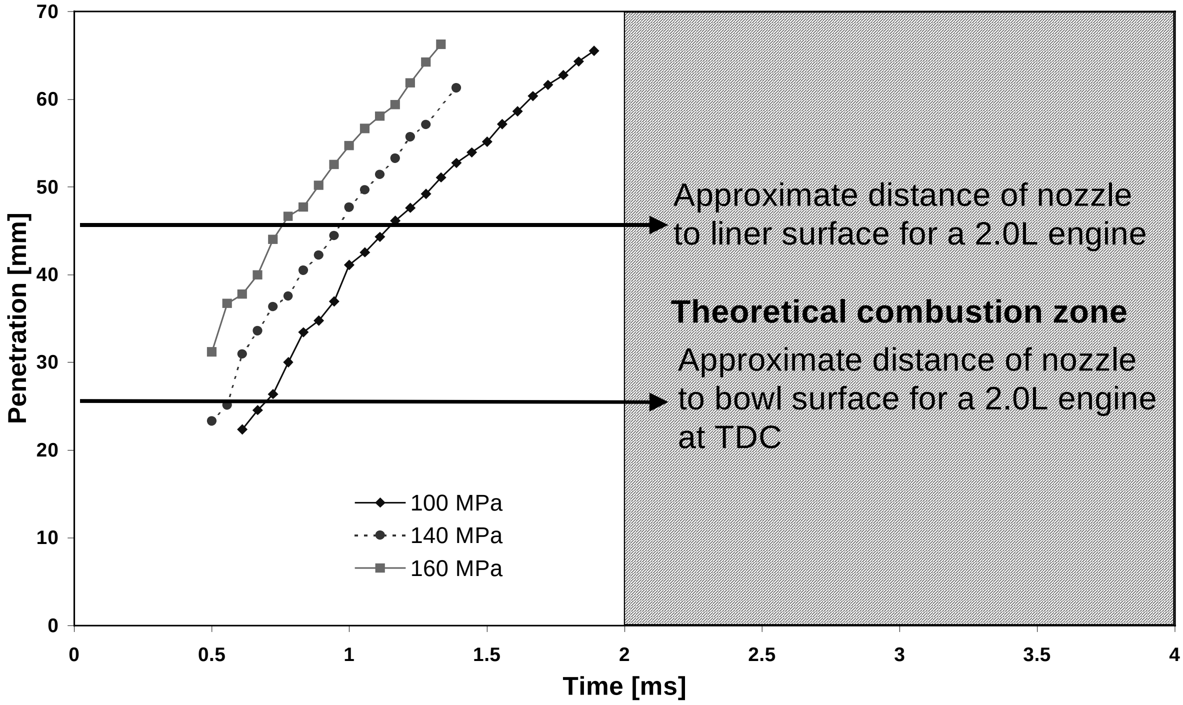


Fig 10. Schlieren results of vapour penetration for a high-temperature charge. Single-guided single-hole 0.2 mm VCO nozzle, 30 mm^3 fuelling at different injection pressures into chamber density of 30 kg.m^{-3}.

The injection pressure effect on liquid phase development for the higher temperature charge was comparable to the earlier findings for the lower temperature charge. Higher injection pressures promote faster vapour propagation at the early stage of the injection (figure 10), in concurrence with the previous cold intake liquid tests. The expected smaller droplets for higher injection pressures will present an increased surface-to-volume ratio resulting in an increase in evaporation rate, hence the shorter ultimate liquid penetration length observed. This supports the trend of increasing injection pressure in diesel engines since it would result in greater mixing and lower liquid impingement.

The effect of in-cylinder density had a similar impact on the ultimate liquid penetration lengths as for the low-temperature charge tests, with higher densities resulting in shorter liquid penetrations (from about 55 mm at 14 kg.m^{-3} to 30 mm at 40 kg.m^{-3}). Experiments indicated a reducing influence on the rate of the main vapour penetration phase for increasing density (figure 11) in a similar way to the cold liquid penetration tests. Additional experiments are planned to confirm this trend by extending the test range. As mentioned earlier, the increase in density seems to correspond to an increase in shear forces. Shear forces would have two effects, firstly to increase the level of break up of the droplet and thus increasing their surface area to volume ratio, and secondly to increase the level of mixing between the hot gases and the liquid phase. Both of these effects would contribute to increased evaporation of the liquid phase and decrease in penetration for liquid and vapour. This observation agrees with those of Siebers [22] who suggested that the fuel vaporisation process in a diesel spray is controlled by the air entrainment and mixing processes.

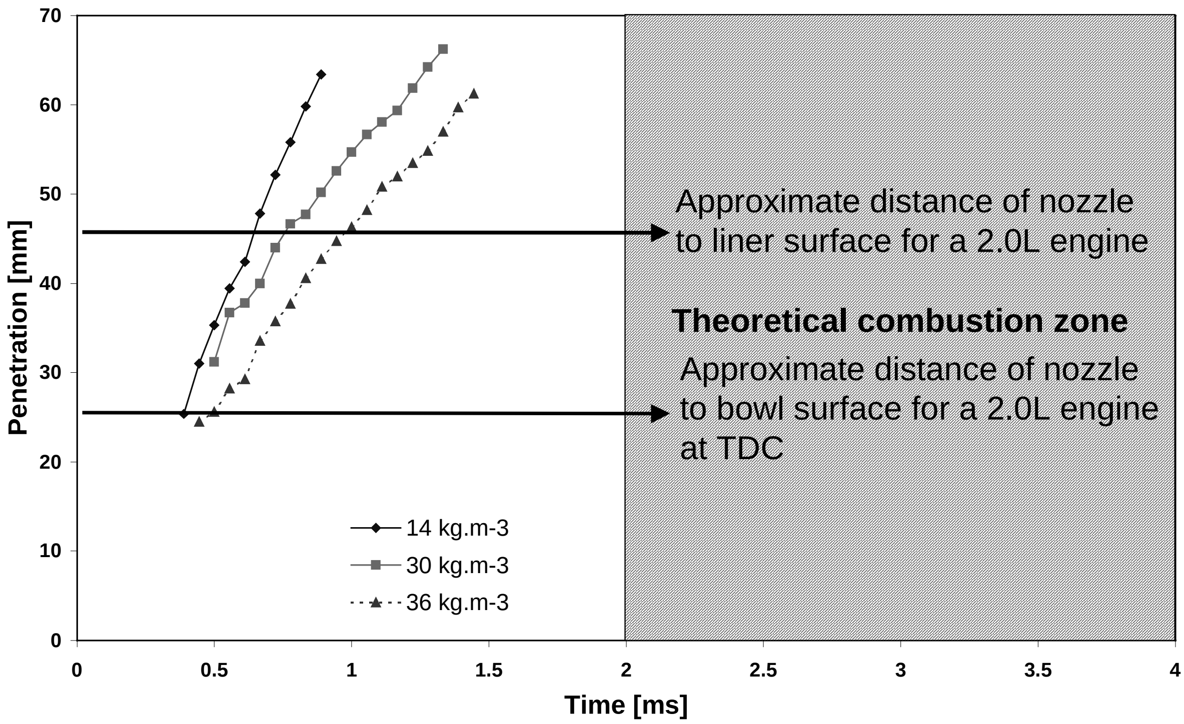
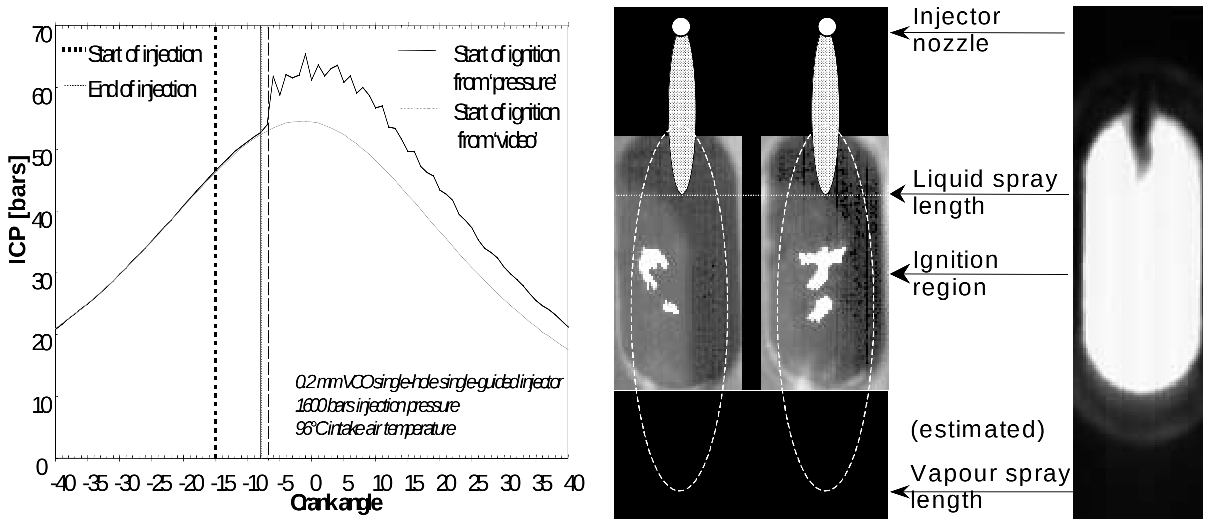


Fig 11. Schlieren results of vapour penetration for a high-temperature charge. Single-guided single-hole 0.2 mm VCO nozzle, 30 mm^3 fuelling at 160MPa injection pressure into different chamber densities.

The results presented here agreed with those of other workers [23] where the vapour was observed to linearly penetrate with time across the combustion chamber. The highest rate of vapour propagation was found to occur with the highest injection pressures into the lowest densities. The spray development was dictated by the droplet surface area to volume ratio, which varies the evaporation rate, and the shear forces acting on the plume. For hotter in-cylinder conditions, it was visible that impingement would be less of an issue than for cold intake conditions.

3.3 Auto-ignition studies

Combustion studies were carried out by using a high-temperature charge and adjusting the start of injection timing to 15° before TDC. Two techniques were used to determine the start of combustion. The first was by analysis of the in-cylinder pressure trace, ignition was judged to occur at the beginning of the pressure deviation from a motored trace as shown in figure 12(a). The second used the first instance of in-cylinder luminosity to detect the onset of combustion, the experimental set-up was described earlier in figure 2. The twin camera arrangement provides a pseudo three-dimensional image of the combustion process, removing some of the spatial ambiguity that a single camera angle provides. Figure 12(b) illustrates auto-ignition in multiple sites, from which both temporal and spatial information can be obtained. For clarity, vapour and liquid penetration taken from the authors' previous experiments for the same conditions have been overlaid in the images.



(a) (b)

Fig 12. Measurement of auto-ignition delay measured by (a) in-cylinder pressure and (b) simultaneous high speed cameras. Single-guided single-hole 0.2 mm VCO nozzle, 30 mm^3 fuelling at 160 MPa injection pressure into chamber density of 33 kg.m^{-3}.

Results obtained using both techniques were in agreement. A distinct trend was that in-cylinder pressure (at constant intake temperature) has a pronounced effect on the auto-ignition delay and hence the combustion preparation process, conversely the fuel injection pressure has no visible influence (figure 13). The ignition delay tends to stabilise at a minimum value of around 2 ms, a consequence of the finite time required for the mixing process prior to chemical reaction and combustion. There was evidence of a marginal reduction in auto-ignition time delay for the luminosity technique compared to the pressure derived method, which is in agreement with Higgins and Siebers [1].

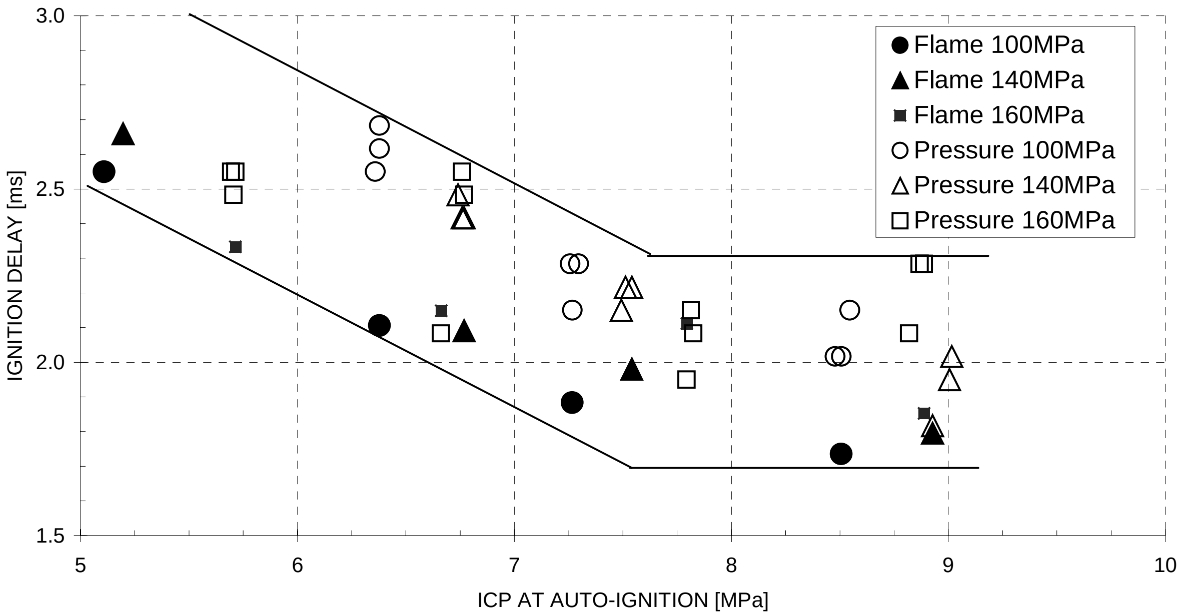


Fig 13. Ignition delay calculated from luminosity and pressure trace. Single-guided single-hole 0.2 mm VCO nozzle, 30 mm^3 fuelling at different injection pressures and in-cylinder pressures with similar intake temperatures.

Increased in-cylinder pressure (or density since intake temperature is fixed) is believed to give rise to greater shear on the penetrating liquid. This results in smaller droplet sizes because of increased primary and secondary break up, with these smaller droplets surrounding the spray plume in a boundary layer between bulk liquid and gas phase. This boundary offers increased evaporating rates which, when combined with the local air entrainment [22], provide favourable conditions for the formation of the combustible mixture within the penetrating vapour region. This results in shorter preparation time and hence auto-ignition delay.

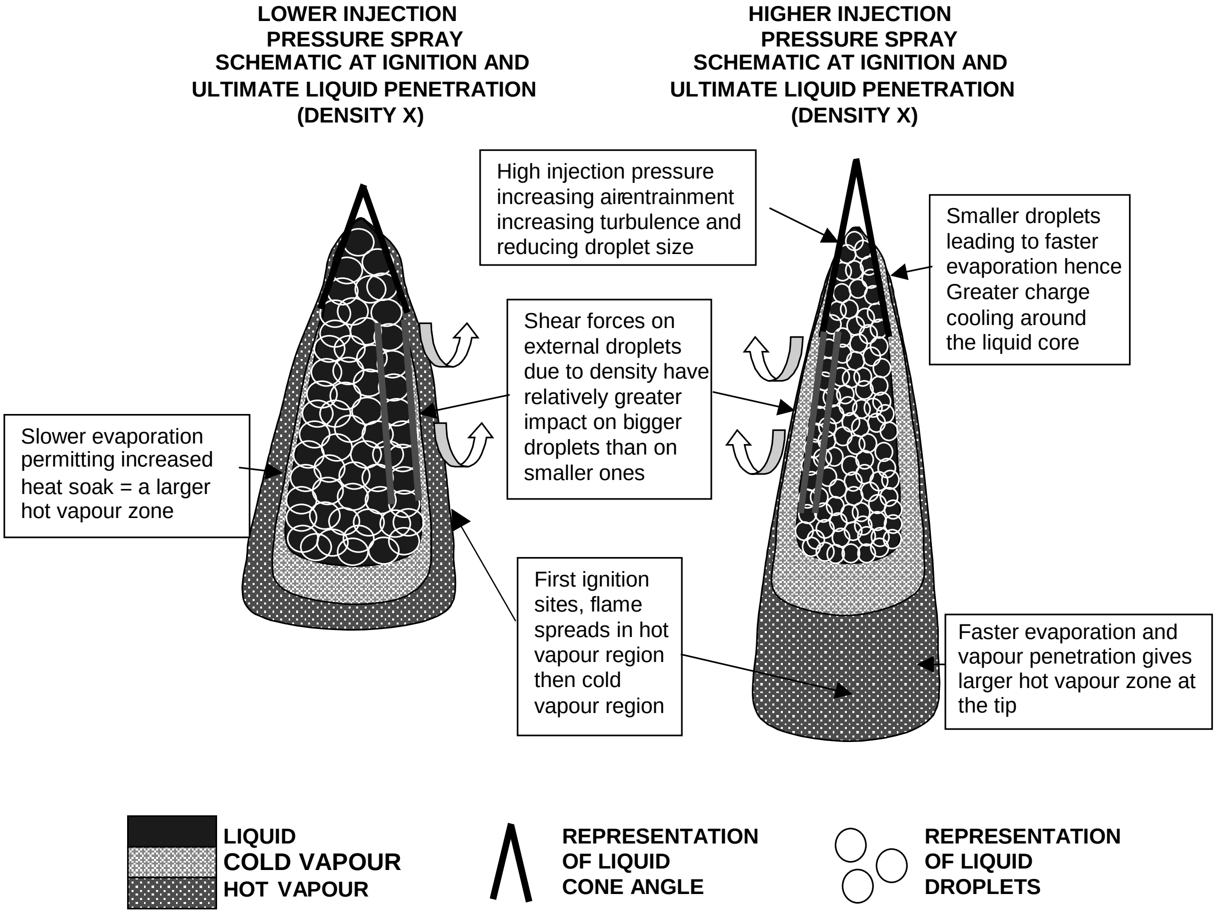


Fig 14. Summary schematics of two spray developments in similar in-cylinder densities for different injection pressures based on the different results seen in this study.

Analysis of the initial stages of ignition were undertaken using the luminosity video data. At the lower injection pressure of 100 MPa, the combustion process began in the vapour region in the periphery of the liquid phase region and subsequently spread around the liquid plume. For the same fuelling quantity, the injection pressure was increased from 100 MPa to 160 MPa. The initial luminosity (ignition) sites were again found in the vapour region but further away from the liquid tip and closer to the leading edge of the vapour region. The flame then developed around the liquid plume separated by a layer of vapour referred to here as "cold vapour". After a short period corresponding to the premix burn, the flame would engulf this cold vapour in a diffusion combustion process.

Higher injection pressures increase the rate of fuel delivery and generate smaller droplets, together these affect the rate of evaporation and heat transfer thus reducing local temperature along the liquid core. It is believed this surrounding colder vapour region is too dense and below the ignition temperature to ignite, hence auto-ignition initiates in the leading penetrating hot vapour zone. Conversely, lower injection pressure result in the formation of a hot vapour region around the liquid core, a result of larger droplets with a lower evaporating rate. Both mixing approaches achieve auto-ignition within a similar time-scale, however further fundamental analyses are required to investigate combustion duration and emission formation. This hypothesised phenomena is schematically represented in figure 14 involved during the liquid and spray development leading to combustion.

4.CONCLUSIONS

High temporal resolution images of injection events from a common rail injection system have been acquired. The present study examined the effects of fuel injection pressure and in-cylinder conditions on the spray and vapour development and the auto-ignition delay for a single nozzle design. This study is part of a continuing step-by-step programme to understand the diesel injection combustion and emissions in conditions similar to those in modern and futuristic diesel engines.

- Pressure fluctuations in the injector nozzle deflected the needle and resulted in different early stage injection behaviour for the single-hole VCO nozzle when compared to a multi-hole nozzle of the same diameter with equal fuelling per hole. The hesitation was found to produce a predictable delay in the injection process. Correlations could be determined between the injection delay and both the injection pressure and nozzle hole size.

- Higher injection pressures for cold intake air conditions led to higher penetration rates but did not impact on the ultimate penetration length. Increasing in-cylinder density, hence the reaction force on the spray, reduced the liquid penetration rate and the ultimate penetration length.

- Greater evaporation was observed for hot intake air conditions. This effect was more prevalent for higher injection pressures believed to be a consequence of the higher surface to volume ratio of the smaller droplets. This also led to shorter stable liquid penetration lengths.

- The leading edge of the hot test vapour phase penetrated at a similar rate to the cold test liquid core. This vapour penetration rate is sustained beyond the hot liquid stabilised penetration time, penetrating deeper into the chamber, because the injection event is continuing.

- The vapour penetration profiles were shown to be dependent upon both injection pressure and in-cylinder density. In the same way as for cold tests, vapour penetration was proportional to injection pressure and inversely proportional to in-cylinder density.

- Both photographic and in-cylinder pressure data showed that the timing of auto-ignition was dependent on in-cylinder density and independent of injection pressure. This was attributed to the increase shear and droplet break-up in conjunction with increased air entrainment.

- Video data revealed that despite temporal independence of injection pressure, the spatial position of the ignition sites followed distinctive separate trends dependant on injection pressure. Higher injection pressures resulted in ignition in the leading vapour zone while ignition occurred in the periphery of the liquid core for lower pressures. Further analyses to link this with heat release and emissions are required.

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