Fuel spray vapour distribution for high pressure diesel fuel spray cases for different injector nozzle geometries.

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Abstract

The evolution of diesel fuel injection technology, to facilitate strong correlations of in-cylinder spray propagation with injection conditions and injector geometry, is crucial in facing emission challenges. More observations of spray propagation are, therefore, required to provide valuable information on how to ensure that all the injected fuel has maximum contact with the available air, to promote complete combustion and reduce emissions. In this study, high pressure diesel fuel sprays are injected into a constant-volume chamber at injection and ambient pressure values typical of current diesel engines. For these types of sprays the maximum fuel liquid phase penetration is different and reached sooner than the maximum fuel vapour phase penetration. Thus, the vapour fuel could reach the combustion chamber wall and could be convected and deflected by swirling air. In hot combustion chambers this impingement can be acceptable but this might be less so in larger combustion chambers with cold walls. The fuel-ambient mixture in vapourized fuel spray jets is essential to the efficient performance of these engines. For this work, the fuel vapour penetration values are presented for fuel injectors of different k-factors. The results indicate that the geometry of fuel injectors based on the k-factors appear to affect the vapour phase penetration more than the liquid phase penetration. This is a consequence of the effects of the injector types on the exit velocity of the fuel droplets.

Keyword

Vapour, spray, k-factor, shadowgraph.

Introduction

Spray formation occurs with the introduction of liquid into a gaseous environment through an orifice such that the liquid breaks-up into droplets by interacting with the surrounding gases and causing its own unsteadiness [3]. For diesel engines, spray characteristics (liquid/vapour penetration and distribution) significantly affect the combustion and emission processes. By optimizing these characteristics, the tailpipe emissions, mainly oxides of Nitrogen (NO_x) and partciculate matter (PM), can be minimized [2]. Spray penetration, which is usually analysed macroscopically, considers the development of the liquid and vapour components. It is desirable to achieve optimal travel of these spray components to avoid the adverse effects of impingement caused by under/over-penetration of liquid spray [19, 20]. Advances in fuel injection system, with the introduction of the common rail technology, have provided increased controllability of the injection event.

The analyses of injection system development have been presented from several viewpoints. Nozzle geometry has been studied for the influence on the internal flow and spray characteristics with respect to: atomization [4,5], mixing processes [6,7], emission [9,10] and cavitation [8, 13]. Different injection strategies have been investigated to show the effect on pollutant emissions [2,3]. Specific studies have also been conducted with conical and cylindrical nozzles [11, 12], and to develop more understanding on the effects of nozzle holes [14-16] on spray characteristics. Many works in the literature also focused on parameters that affected spray penetration, whilst developing useful correlations [21, 22]. From these studies, it appears that the influence of nozzle geometry on spray characteristics has been established [7, 28]. Despite the comprehensive nature of these investigations, conducted using experimental/numerical methods under evaporative/non-evaporative conditions and often with the aid of optical techniques, the understanding is by no means complete and challenges not dismissed. The physics of the effects of nozzle geometry on in-cylinder spray development and combustion is still of interest to the research community and the auto-industry. For example, the survey in this work [7, 28], supported by other investigations [23, 24], clearly showed the significant effects of nozzle flow characteristics on spray development. This contrasts with other works [25, 26] which suggested negligible influence of nozzle flow characteristics over spray formation. Clearly, the true extent of the effect of nozzle geometry over a wide range of operating conditions and response variables need to be fully understood. Part of this uncertainty derives from unclear details about vaporisation, which is crucial for the injection process [27]. Since the vapor fuel continues to penetrate downstream while the liquid-phase fuel penetration stays at the liquid length, there is a correlation between the vapour penetration rate, total air entrainment rate and fuel–air mixing. Thus, depending on the injector geometry and the in-cylinder conditions, a higher vapour penetration may cause better air utilization,

which affects the combustion process.

It is common to specify injector geometry based on the k-factor, this places emphasis on the hole diameter and its profound effect on fuel injection. Most injection characteristics change with the hole diameter. The k-factor can have a negative, zero or positive value. Spray hole (or orifice) with a negative conical shape factor exhibit an orifice with increasing diameter towards the nozzle exit. With a positive value of the conical shape factor, the orifice diameter decreases towards the exit (Figure 1). These two configurations implement a conical (or tapering) profile. A zero value for k (i.e. no conicity) indicates a cylindrical orifice since the diameters are equal. In this study, optical technique is applied to visualize in-cylinder spray penetration in the absence of a piston bowl, by implementing: high speed liquid spray visualization (Mie scattering technique) and vapour spray visualization using high-speed laser shadowgraph. Two injectors with different k-factors are utilized via a standard common rail system, and a low sulphur automotive diesel as the test fuel. It is expected that the result will be useful for vapour phase penetration modeling and for use in the validation of spray models.

$$K = \frac{(D_{inlet} - D_{outlet})}{10} \qquad\qquad (1)$$

Where K is the k-factor, a measure of conicity; D_{inlet} and D_{outlet} are inlet and outlet orifice diameters in micrometres (µm), respectively.
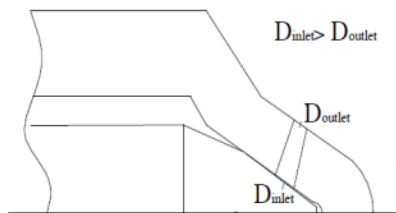

Figure 1: Nozzle configuration (Inlet/outlet diameter)

Material and methods

The liquid and vapour spray measurement systems were based on an optical engine, the Ricardo Proteus rig, installed at the University of Brighton, UK, where the tests were conducted under thermodynamic conditions similar to those found in a direct injection (DI) diesel engine. Optical diagnostics using high speed image acquisition equipment were developed and optimised around the Proteus, to visualise in-cylinder spray penetration. The Proteus is a 2-stroke, liner ported, single cylinder reciprocating rapid compression machine (RCM), with a specially designed head (top-hat shape and optical chamber with windows) for optical access. For the current study, steady in-cylinder (non-combusting) conditions were maintained all through the tests.

The injection system for this study was based on the high pressure (HP) common-rail system (CRS) fuel injection equipment on the Proteus rig using different injectors with key specifications summarised in Table 1. The Injectors have same hole diameters but different k-factors. Both injector types are classified by the k-factor parameter defined in equation (1). Only one, out of the four common rail injector outlets, was used at any given time, so the other unused three were fitted with plugs.

Table 1: Injector specifications

	Flow (cc/min)	Holes	Hole size (mm)	Cone angle (deg.)	k-factor
Injector C (Bosch 3601)	960	8	0.137	155	1.3
Injector D (Bosch 3603)	960	8	0.137	155	3.5

The optical arrangements were varied slightly between the liquid and vapour spray experiments, but similar steps were applied in setting-up. Engine logs were recorded with AVL Indiset high speed data acquisition system for fast logs (crank angle resolved), and EmTronics data logger for slow logs. For each regime of test, a minimum of fifty (50) videos were acquired with the laser/camera combination. The videos were post-processed with a Matlab software and analysed. In addition, the engine was stopped at intervals, during the tests, to clean the optical windows.

The liquid spray was visualised using the Mie scattering technique as shown in Figure 2. Here, the laser beam

was aligned to pass through the vertical plane of the fuel spray and cause elastic scattering of the laser light by the liquid fuel droplets as soon as fuel was injected into the chamber. The high-speed camera was positioned perpendicular to the laser illumination to collect the scattered light. This visualised the liquid fuel distribution and showed the liquid spray penetration within the spray. The laser light was collimated before entering the optical engine, at reduced intensity via neutral density filters, by carefully placing the filter between the laser and a collimating lens. A slightly varied optical arrangement in Figure 3 implemented the shadowgraph technique for vapour spray visualisation
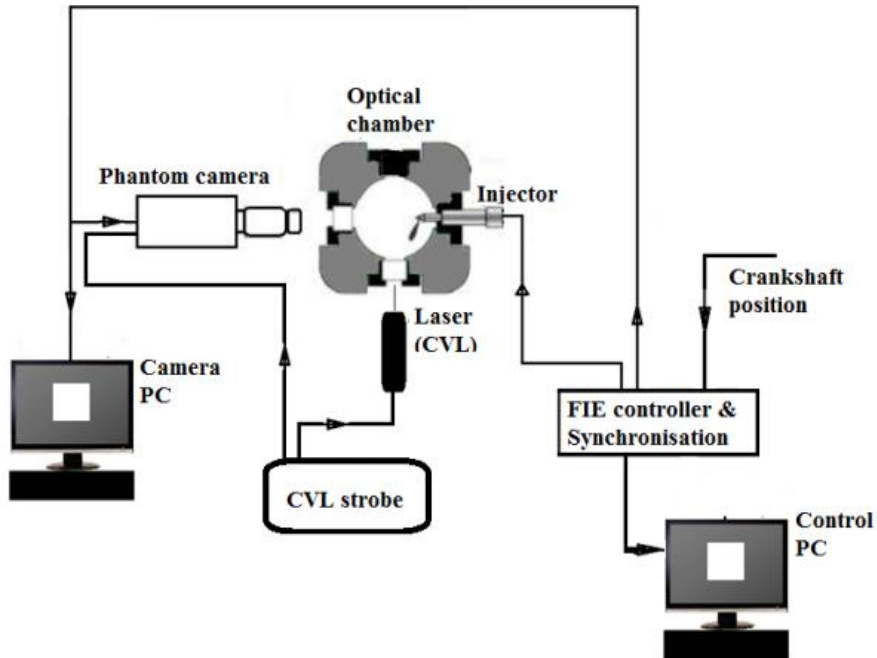
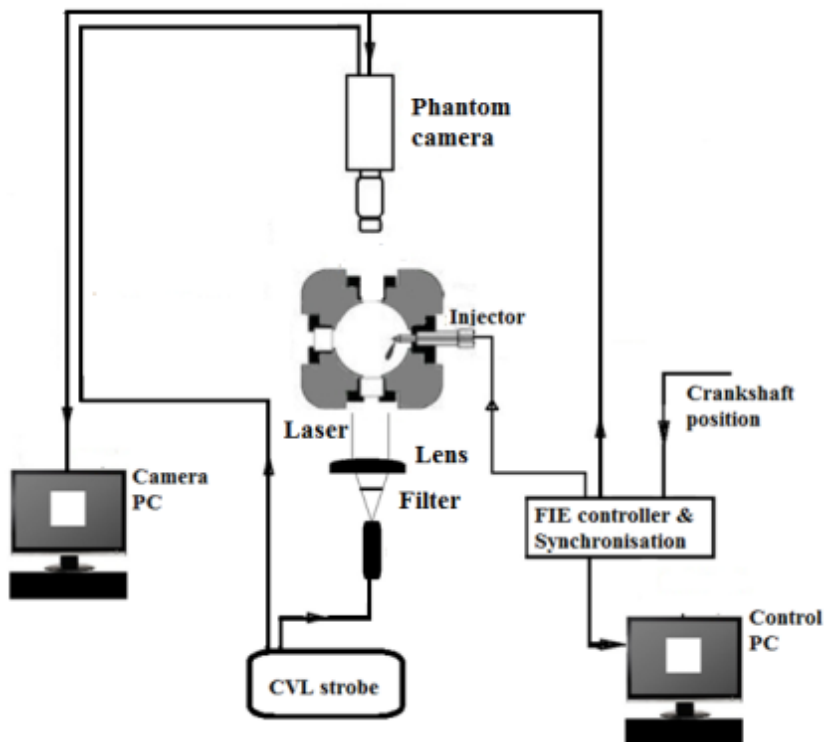

Figure 2: Schematic for Liquid spray visualisation

Figure 3: Set-up for vapour visualisation

Liquid and vapour spray penetrations were investigated with Injectors C and D respectively. The test conditions

were selected from the matrix in Table 2, for investigations across injection pressure ranges (high, medium and low). While the test fuel used was Carcal RF06-08-B5 (density; 833.2 kg/m^3). Normal injection was timed at top dead centre (TDC). The actual intake air temperature was determined by the intake manifold temperature (TMAN), and hence varied significantly (less than 100 ^{o}C). Spray parameters were quantified with respect to time after start of injection (ASOI) for every spray plume.

Table 2: Test Matrix

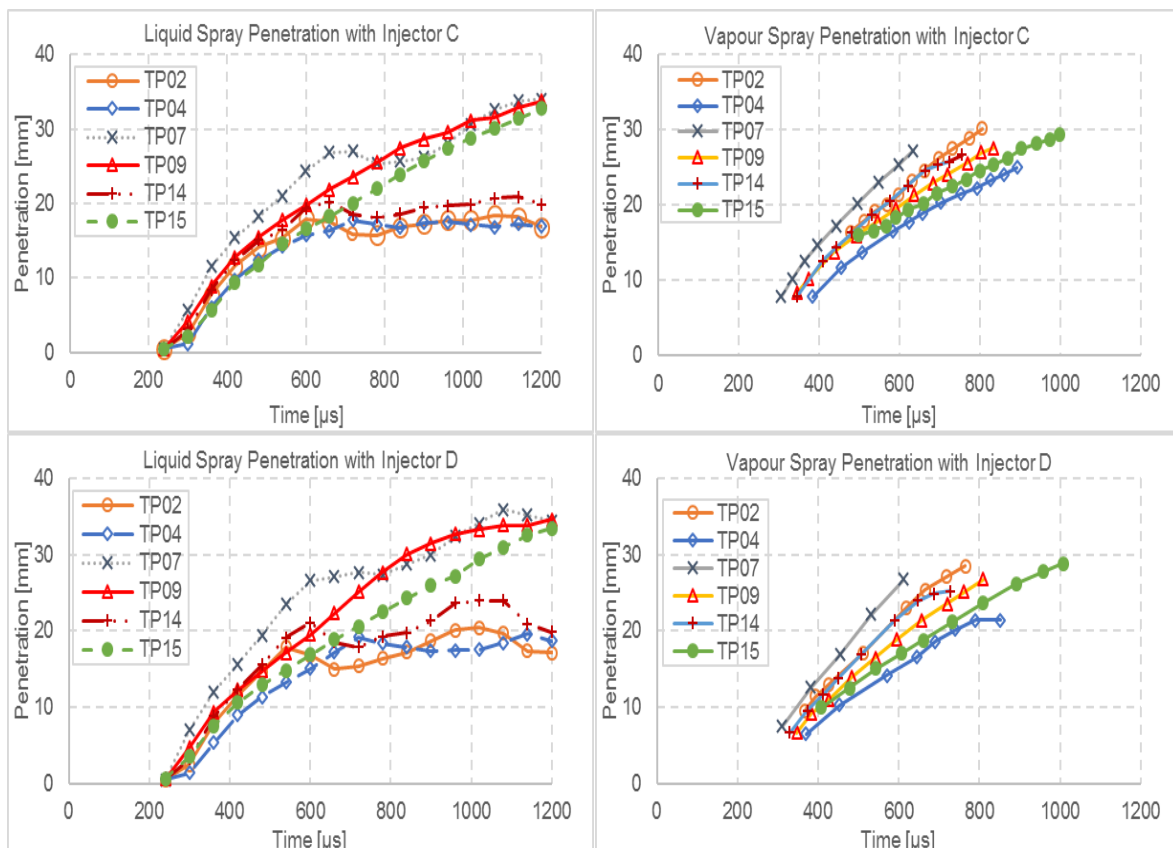| Test point (TP)	Intake air temperature TMAN (°C)	Peak in-cylinder pressure ICP (bar)	Fuel pressure P (bar)	Injection quantity (mm³) @ 38 °C
1	100	84	2000	65
2	100	84	1600	36.31
3	100	84	1400	36.71
4	100	84	1000	35.31
5	100	84	600	34.86
6	100	50	2000	45
7	100	50	1600	45
8	100	50	1400	45
9	100	50	1000	25
10	100	66	2000	65
11	100	66	1400	45
12	100	66	1000	45
13	100	79	1800	60
14	100	73	1600	50
15	100	40	600	20

Result and discussion

Figure 4: Comparison between injectors C and D spray (liquid and vapour) penetration measurements
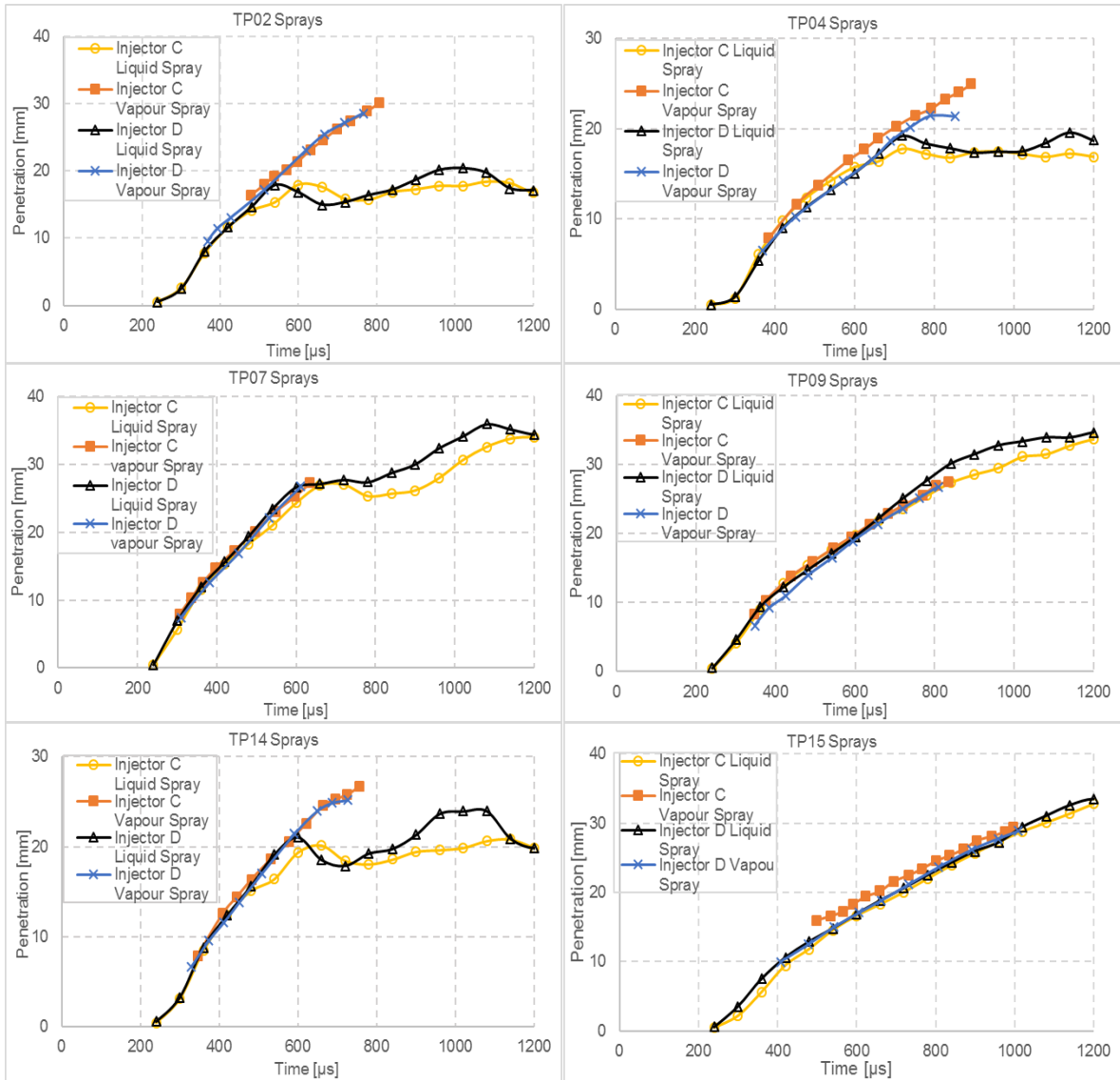
Figure 5: Comparison between injectors C and D spray (liquid and vapour) penetration measurements
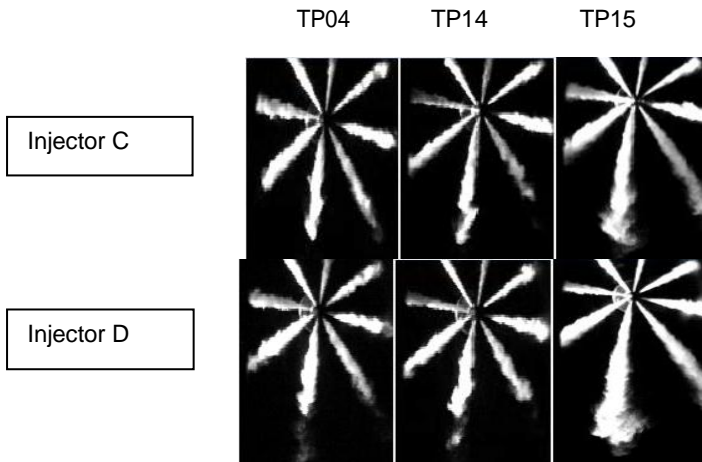

Figure 6: Image sequence for selected liquid spray penetration from all the injectors

Figures 4 and 5 show the results for the spray (liquid and vapour) penetration tests conducted with injectors C and D at Test Points selected from the matrix, for different injection pressures (low to high). Excerpt from the

image sequence of liquid spray penetration from the injectors are presented in Figure 6.

In Table 1, the k-factor for injectors C and D were specified as: 1.3 and 3.5 respectively. Results from the plots and observations of the image sequence, which agree with literature, showed that nozzles with higher k-factor caused higher spray (liquid and vapour) penetration. It was also observed that the nozzle exit velocity and density increased with increase in conicity [29, 30] The results also showed that these behaviours were more evident under high (injection) pressures, as shown in Figures 4 and 5 for all the test points, except TP15 (with low pressures).

From the results, the effects of in-cylinder pressure on liquid spray penetration agree with previous investigations [21]. Increasing the ambient pressure increases the ambient temperature which causes the spray to evaporate faster and travel less. This trend is manifest even with increased injection pressure, especially for liquid spray penetration across the injectors. From the point of view of fluid dynamics, the evaporation of droplets involves simultaneous heat and mass transfer processes. The heat of evaporation is transferred from surrounding hot gases to the drop surface by conduction and convection, while vapour is transferred to the surrounding by convection and diffusion. The evaporation rate is dependent on the thermo-physical properties of the fuel and the surrounding air. For very high in-cylinder pressure and temperature, evaporation is quick since the latent heat drastically decreases for high temperatures. As the hot entrained air initiates evaporation of the spray, the fuel cools and contracts. These processes significantly reduce droplet dispersion and hence liquid spray penetration [1, 31]. The effect of increased injection pressure, which increased spray velocity/momentum [21], is more noticeable in the transient part of the liquid spray penetration than the quasi steady stage. The slight positive slope observed at the steady period in some of the liquid penetration curves in Figures 4 and 5 can be attributed to two factors [8,17]. Firstly, the temperature of the fuel at the beginning of the injection is higher because the injector sac is always in direct contact with the high temperature gas of the combustion chamber; during the injection, the fuel flowing from upstream of the sac cools down the injector tip. This causes the temperature of the fuel at the orifice outlet to decrease during the injection, which impacts on liquid length [8]. Secondly, for long injections, low temperature fuel–air mix is re-entrained in the spray causing a decrease in the effective ambient temperature and an increment in liquid length. Taking the large size of the chamber into account as well as the tendency of the slope to decrease at the end of the injection, the first fact was generally considered to be responsible for the observed phenomenon.

The effect of increased injection pressure is clearer in the vapour penetration, which is further than the liquid spray travel [21]. Vapour penetration profiles have been shown to depend on both injection pressure and in-cylinder density [18]. It was further suggested that the mechanism for the vapour transport was the gas motion induced by the liquid phase momentum exchange, from the droplets to the gas phase. To support these facts, increased penetration of the vapour was observed at higher injection pressures and lower gas densities, which was when the liquid phase had a higher momentum. The momentum effect is felt more, across the injectors as the k-factor increases. The vapour spray penetrated more, at higher injection pressures (and higher ambient pressure), because the consequent level of turbulence was such that increased the hydrodynamic interaction of the spray. This process was facilitated by smaller nozzle exit as the k-factor increased. Primary breakup was accelerated leading to smaller droplets and reduced liquid spray penetration. The resulting increase in dispersion increases the vaporization rate and fuel air mixing.

Knowing that the k-factor could significantly affect vapour spray penetration is important for high speed direct injection (HSDI) diesel engine. Increase in vapour penetration improves mixing, results in greater premix burning and faster combustion, which may cause NO_x emission to increase, but reduce PM emissions.

Conclusion

The liquid and vapour phases of diesel fuel spray were characterised in this work, using optical techniques based on visualization. Mie-Scaterred and shadowgraph images were continuously recorded to expose liquid and vapour penetrations respectively, under real engine conditions. The injectors used were essentially different in terms of the k-factors. From the results, the significant influence of injector design (k-factor) on HSDI diesel engine spray development was confirmed. It was observed that the geometry of fuel injectors based on the k-factors affected the vapour phase penetration more than the liquid phase penetration. This was a consequence of the effects of the injector types on the exit velocity of the fuel droplets.

Further work could be done by replicating the characterisation experiments with piston bowl for impingement studies. The understanding from the present work will provide the necessary guidance and basis for comparison. The comparison of the data with commonly used correlations would provide further confidence on its use for spray model validations

Nomenclature

ASOI   After start of injection
CRS   Common-rail system
CVL   Copper vapour laser
D   Nozzle diameter [µm]
DI   Direct injection
HP   High pressure
HSDI   High speed direct injection
k   k-factor
NO_x Oxides of Nitrogen
PC   Personal computer (Dedicated desktop)
PM   Particulate matter
RCM   Rapid compression machine
TDC   Top dead centre
TMAN   Intake manifold temperature
TP   Test point

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