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A Macro-Microscopic Investigation of High-Pressure Sprays Injected by a Common Rail System.

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Abstract

The main purpose of this research is to investigate high-pressure diesel oil sprays generated by a common-rail system through small nozzle holes. High-speed photography, phase Doppler particle analyzer (PDPA), and a combination of data obtained with high-speed photography and PDPA, based on the light extinction principle within sprays are used to deal with the objective. The sprays are characterised in an environment, which simulates in-cylinder air density of the actual diesel engine when the injection starts. However, it must be pointed out that isothermal condition at room temperature is considered and no-evaporation of drops occurs. A wide parametric study has generated evidence needed to quantify the influence of the common-rail pressure, nozzle hole diameter and environment gas density on the macroscopic evolution of sprays (spray tip penetration, and spray cone angle) as well as microscopic behaviour (spatial and temporal evolution of drop size, drop velocity and drop concentration distributions).

Keywords: High-pressure diesel oil spray; Single-hole nozzle; Intermittent spray characteristics; Spray macroscopic characteristics; Spray microscopic characteristics; Spray visualisation; PDPA (Phase Doppler Particle Analyzer)

1. Introduction

The efficiency of the combustion process of D.I. diesel engine from the scope of either the engine efficiency itself or pollutant emissions depends on numerous factors, but principally on the injection process characteristics as it is the main responsible, further more than in the case of IDI diesel engines, of the fuel/air mixture formation. This process is influenced by both spray behaviour and air movement in the combustion chamber. The spray characteristics are clearly influenced by several parameters, which can be classified into two groups: (a) parameters of the diesel-oil injection system and (b) parameters of the environment where the spray is injected.

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Experimental data about the spray behaviour and the combustion development are needed to understand better the processes, to isolate the controlling parameters, and to provide initial data and comparative values for compute models for the actual spray. Diesel sprays have been studied during decades with different techniques for different injection conditions, but usually very far from engine-like conditions, either because the injection conditions, themselves, were not a continuous-unsteady process or because the atmosphere in which the fuel was injected was very different from that of the actual engine. The atomisation process is known to be very different at atmospheric density and at high density (Reitz and Bracco, 1982; Hiroyasu and Arai, 1989). On the other hand, the behaviour and experimental results of single shot injections are known to be different from the case of continuous diesel-oil injection Hiroyasu et al.(1989).

This paper deals with the problem of quantifying and predicting the spray behaviour as a function of the parameters governing the injection process. For this purpose, a test rig was designed and conducted that allows continuous diesel-oil injection at room temperature (non-vaporization presence), with a common-rail injection system, against gas densities up to 30 kg/m^3, usual value at Top-Dead-Centre (TDC) for diesel engines. Parameters studied were the environment gas density as a representative parameter external to the system, and nozzle hole diameter and injection pressure as influential system parameter. Results obtained are divided into two groups: (i) global spray (macroscopic) features: spray tip penetration and cone angle, and (ii) internal dynamics of the spray (microscopic features): distributions of velocities, diameters and concentrations.

2. Experimental facilities

The high-pressure diesel-oil sprays are characterised in an environment, which simulates incylinder air density existing in the actual diesel engine when the injection starts. However, it must be pointed out that isothermal condition is considered and non-evaporation is present.

2.1 High-density injection rig

The test rig was developed by attempting to achieve three main objectives: To reproduce the same air density, existing in the actual diesel engine at the end of compression, to allow the observation and optical accesses compatible with PDPA measurement technique, and to permit the use of diesel-oil injection systems.

Among the different gases available, Sulphur hexafluoride (SF_6) was chosen because of its high molecular weight and its viscosity, very similar to that of the air. At room temperature, SF_6 allows experiments at a density up to 30 kg/m^3 with a relatively low pressure of less than 0.5 MPa. In addition, SF_6 is an inert gas, avoiding corrosive effects on the rig, and its optical properties are very similar to those of air.

Figure 1(a) shows a drawing of the experimental facility. The injection chamber has three optical accesses for visualization and PDPA measurements [Fig. 1(b)]. Two opposite windows allow shadowgraph visualization while a third one placed at 90° allows PDPA measurements (110° between emitting and receiving optics). A <1 m/s laminar flow of pressurised gas, moving in parallel to the spray axis, ensures the scavenging of the fuel between two consecutive injection-shots, without disturbing the spray behaviour. Details on the high-density gas rig can be found in references Desantes et al. (1997; 1998) and payri et al. (1996).

2.2 Injection system

A non-conventional common-rail system was used to generate high-pressure diesel-oil sprays. It consists of a research system conceived to work in the high-density injection rig and includes a high-pressure volumetric pump driven by a motor, whose electronic system is ordered by an appropriate software. The nozzle used is of the DLLA mini-sac type by Bosh with a wall thickness of 1 mm, but which has only 1-hole in the same position as one of the orifices in the standard 5-hole nozzle [Fig. 1(c)].

2.3 Image acquisition system

For the acquisition of spray images, the "AVL 513D Engine Videoscope" system has been used. It consists of a colour CCD camera (PULNIX TMC-9700), a digital acquisition card, a stroboscopic Xe-flash lamp illumination system, and control hardware and software. The flash is located in front of the camera with a set of diffusers to ensure homogeneous illumination. The system is synchronised with the common-rail by means of a TTL external signal.

2.4 PDPA system

The emitting optics of the PDPA system is a modular 1-component TSI system with 40 MHz Bragg cell and a fibre optics LDA (laser Doppler anemometer) probe, operating with a 4W water-cooled Ar+ laser source. Collecting optics and electronics are those of a standard Dantec 1-component system. PDPA measurements were performed without temporal gating. Similarly, to the image acquisition system, an electronic pulse generated by the common-rail system was used as a trigger for the system. The PDPA optics was mounted vertically on an 3D-table, which permits measurement at any point in the

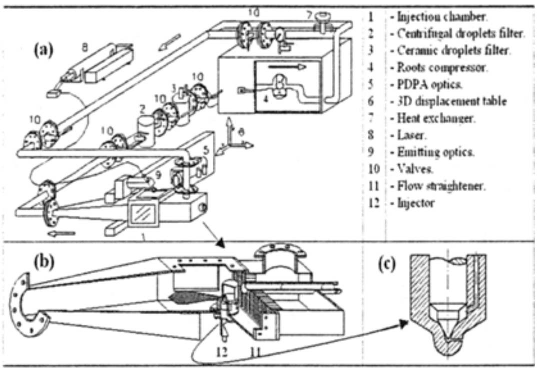

Fig. 1. High-density gas injection rig. (a) Layout of the experimental facility, (b) Injection chamber and (c) Schematic drawing (non-scale model) of nozzles tested.

spray.

For each case, PDPA measurements were performed at different points on the spray axis. Figure 2 shows an outline of the PDPA measurement location points within the spray.

Validation rate of the measurements is very dependent on the measurement point position within the spray, but lies always between 15 and 60 %.

3. Analysis of results

The important parameter controlling the combustion process is the fuel-air mixture formation. In DI diesel engines, most of this mixture is ensured by the air entrainment, which depends directly on penetration and cone angle of the spray. A study of the influence of the main parameters, controlling the spray behaviour (injection pressure, size and geometry of the hole and air density), has been performed in the high-density gas rig. To cover the whole range of the injection system operation, the principal parameters such as the hole diameter, the injection pressure and the gas density were varied from 0,11 to 0,27 mm, 30 to 110 MPa, and 10 to 30 kg/m^3 respectively.

3.1 Injection rate

In theory, the injection rate is assumed to have a rectangular form. Actually, the process of needle lifting is not instantaneous, consequently the injection rate is non-rectangular; and its shape changes with the modification of the injection conditions. This can be due to two different causes:

- *The dependence of the dynamic behaviour of the common-rail system on the injection pressure.*

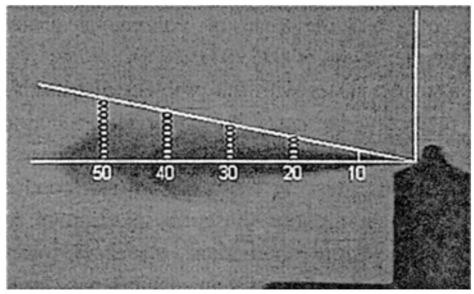

Fig. 2. PDA measurement points on the.

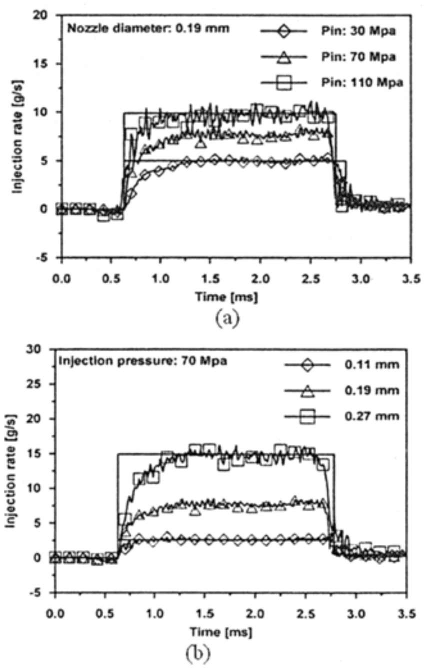

Fig. 3. Effects of the hydrodynamics and geometry systems on the injection rate.

The dependence of the effective section variation within the injector hole diameter on the needle lift.

Figure 4 shows the rate of injection measured together with a theoretical rectangular curve. It can be noted that the increase in the injection pressure for a given hole diameter of the injector involves higher slopes during the lifting of the needle [Fig. 3(a)]. Figure 3(b) shows that the injection rate is closer to the rectangular shape for the smaller hole diameters, in other words the plateau is reached by the curve earlier.

The two effects, as one will see later, should influence the spray tip penetration at the beginning of the injection because the injection rate has a non rectangular form what makes the instantaneous momentum flux through the hole weaker than the theoretical one.

3.2 Macroscopic behaviour

Spray tip penetration and cone angle – In Fig. 4, a sample of the results obtained shows the influences of the injection pressure, the nozzle hole diameter and the gas density on the spray tip penetration and the cone angle.

The gas density effects are shown on the Figs. 4(a1) and 4(b1). The dots represent experimental measurements and the solid lines are statistical fits to the experimental data, obtained with all the test cases. The expression, mentioned below, is obtained by assuming a rectangular form for the injection rate. Despite the differences in the injection rate shape for the different injection conditions, the R^2 value suggests high confidence on the correlation results from the statistical viewpoint. The gas density increase reduces the spray cone angle and slows down the spray tip penetration. However the effects of the increase in hole diameter are contrary [Figs. 4(a2) and 4(b2)]. Large hole diameters increase the spray cone angle and accelerate the spray tip penetration. In Fig. 4b2 for the injection pressure of 70 MPa, the spray tip penetration matches perfectly the statistical fit for the hole diameter of 0.11 mm, whilst discrepancies at the injection beginning are high for 0.19 and 0.27 mm hole diameters, as could be waited from the injection rate shape curve which was not perfectly rectangular [Fig 3(a)]. The same behaviour of the spray tip penetration could be observed at the injection beginning on the Fig. 4b3 for the hole diameter and injection pressure of 0.19 mm and 30 MPa respectively. However, where the injection rate was quasi-rectangular, the agreement between instantaneous data and fitted results for spray tip penetration is good even at the injection beginning [see 70 and 110 MPa on Fig. 4(b3)]. However, the injection pressure does not produce any affect on the spray cone angle [Fig. 4(a3)]. The spray cone angle is the same for the two represented pressures. Thereby, the spray cone angle remains depending only of the hole diameter and the gas density.

The penetration of high pressure sprays, without counting the parameters studied above (injection pressure, hole diameter and gas density), depends directly of the instantaneous injection conditions, i.e. particularly of the liquid core momentum, and also of the geometry of both the nozzle and the needle.

For the common-rail system and the used nozzles, the influence of the three parameters mentioned above on the spray cone angle and the spray tip penetration is given by the following expressions:

$$\tan\left(\frac{\div}{2}\right) \propto d_0^{0.5}\Im_a^{0.3} \tag{1}$$

$$S(t) \propto \tan\left(\frac{\div}{2}\right)^{0,5} d_0^{0.5}P_{cr}^{0.25}\Im_a^{-0.25}t^{0.5} \tag{2}$$

where: d_0: nozzle diameter
P_{cr}: injection pressure
ρ_a: gas density
T: time from the injection start
θ: spray cone angle
$S(t)$: spray tip penetration

So, the main difficulties in the prediction of the spray tip penetration lie on the consideration of the cone angle of the spray, which is a function of the hole diameter and gas density.

3.3 Microscopic behaviour

In addition to the macroscopic behaviour study of high-pressure diesel-oil sprays with the shadowgraph technique, the investigation has been carried out on its microscopic behaviour by the PDPA technique. The droplet evaporation is neglected by maintaining the injection rig at room temperature, despite its great importance in the actual diesel engine.

However, the information on the evolution of the spray droplets size in cold rig helps to know one of the factors controlling the evaporation process. The droplets size in liquid jets depends of the processes of atomisation and coalescence, which are mainly functions of the local conditions of the slip velocity and the liquid concentration. The forced changes of these local conditions in pulsed high-pressure diesel oil spray, as here, produce a very strong space-time evolution of the droplets size. These local conditions are also very sensitive to the modification of the injection conditions as done in this work.

For the results presented below, the gas density was maintained at 30 kg/m^3 as in the actual diesel engines and only the hole diameter of 0.11 mm was studied. However, the injection pressure was varied from 30 to 110 MPa to modify the injection conditions. The PDPA measurements were taken at four positions on

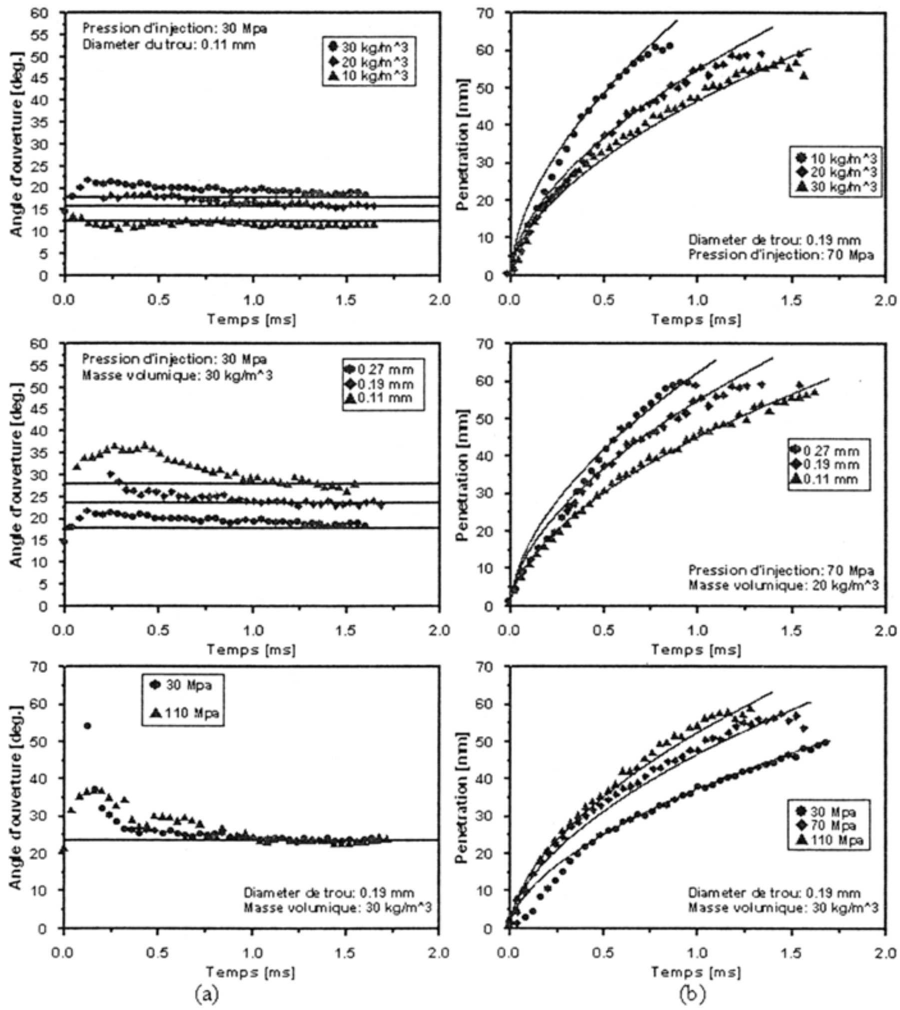

Fig. 4. Effects of injection pressure, hole diameter and gas density on spray tip penetration.

the spray axis: 20, 30, 40 and 50 mm from the injector.

Drop velocities - Figure 5 shows for the injection pressure of 70MPa together the injection velocity of the fuel at the nozzle exit, estimated from the injection rate, and the mean drop velocity on the spray axis at a distance of 30 mm from the nozzle tip. Time equal to zero corresponds to the injection beginning.

The velocity profile at a distance of 30 mm from the injector tip, compared with the first injection velocity, shows an abrupt increase. It reaches a peak velocity of 45 m/s towards 1.45 ms. It shows then a slow decrease leading to a level of quasi-constant velocity, which is kept until the injection end, i.e. at 3.8ms, followed by a second fall bringing back the drop velocity to the gas convection velocity at 5.4 ms.

The velocity profile suffers a clear deformation because of the droplets of higher velocities just after the spray tip. The droplets into the spray front are suddenly decelerated because of the drag force produced by the nearly stagnant air facing the spray tip. Just after those in the spray head, the droplets are helped by the high velocity of the gas entrained behind them, so the aerodynamic interaction becomes different. When these droplets arrive to the spray front, different phenomena may occur. On the one hand, an overtaking and acceleration of the previous spray tip; this means that the fuel concentration of the leading edge of the spray increases while moving away from the injector. On the other hand, a "pushing" of the

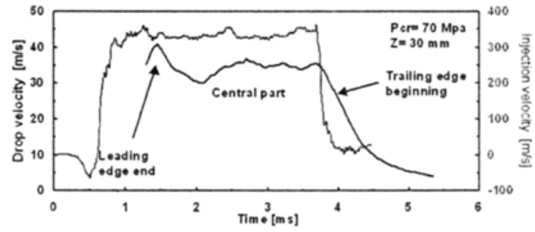

Fig. 5. Nozzle exit velocity and droplet velocities on the spray axis.

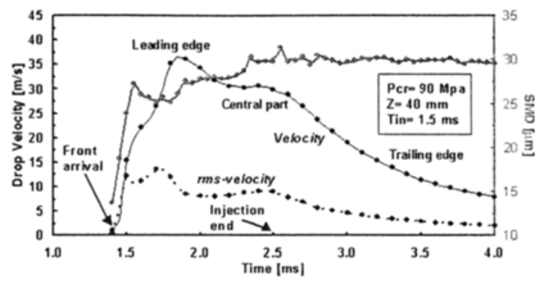

Fig. 6. Droplets velocity and SMD on the spray axis.

previously decelerated droplets occurs, what generates a vortex in the leading edge of the spray. These displaced droplets are further entrained together with air by the spray behind its tip Cho et al.(1990). Both assumptions, which are not mutually exclusive, lead to the conclusion that high droplet concentration in the leading edge of the spray must exist when it moves away from the injector. Atomisation phenomena are controlled by the droplet Weber number (We_d) and so they are very sensitive to the relative velocity between droplets and surrounding gas. Coalescence phenomena are mainly ruled by the droplet concentration. As discussed before, these two processes are unsteady and variable along the spray, due to different conditions found by the travelling droplets or fuel portions. The balance between atomisation and coalescence provides the droplet characteristic diameter.

Drop size and velocity evolutions - Drop size in the high-pressure diesel-oil spray depends on atomisation and coalescence processes, which are principally functions of the local conditions of gas velocity and fuel concentration. Due to the unstable nature of the high-pressure diesel-oil spray, the variations of the local conditions make the characteristic diameter of the drops to experience strong spatiotemporal evolution. In addition, changes in the injection conditions (gas density and injection pressure) provoke variations in the conditions of the local velocity and the spray cone angle, which influence the distribution of the drop size.

PDPA measurements are difficult in dense spray regions. In our experiments, it was impossible to acquire confident measurements at distances from the injector below 20 mm. Validation rates obtained were between 20% and 60% depending on the distance from the nozzle tip and the injection conditions. With these validation rates, a bias towards larger droplet sizes is expected. The effect of this bias will be larger on the mean diameter than on the Sauter Mean Diameter (SMD). Figure 6 shows, as an example, the time evolution of the droplets velocity and SMD at a distance of 40 mm from the injector nozzle, on the spray axis, for an injection pressure of 90MPa, and an injection time of 1.5 ms.

The velocity graph of Fig. 6 is qualitatively coincident with that of Fig. 5. With regard to the SMD, the smallest values of 14 µm are obtained in the spray tip. After that, an abrupt increase of the SMD has been measured up to a value of 27 µm; next, a slow decrease leads it to 25 µm at 1.7 ms, before main velocity peak, i.e. "first half of the leading edge". Finally, the SMD increases gradually in the second half of the leading edge and in the central part to reach the value of 30 µm, and then it remains constant for all the trailing edge of the spray. This behaviour is qualitatively similar to that found in references (Kuniyoshi et al., 1980; Jawad et al., 1992; Quoc and Brun, 1994) and differs from measurements taken at atmospheric density [for instance Arcoumanis et al.(1993)] where the SMD in the leading edge is very similar to the one of the trailing edge, or even greater. It should be also noted that the minimum of SMD coincides perfectly with the rms-velocity peak.

Figure 7 shows the axial evolution of the SMD at different times since the leading edge until the trailing edge for the test case (*Pcr=30 MPa, Tin=3 ms*). Solid lines in the figure are just extrapolated lines without experimental evidence. The trends of the curves are all similar; they begin with a decay of the SMD followed by an increase. The starting point for this increase coincides roughly with the axial distance z=30 mm from the injector in this case. In other words, the atomisation process is more efficient than that of coalescence for low axial distances (z<30), while coalescence efficiency is higher for the high axial distances (z>30) with an emphasis in the leading edge (time=2.3 ms, z=40 mm) and (time=3.05 ms, z=50 mm). It can be assessed that no equilibrium condition seem to exist in the early injection stage where drop/gas slip velocities and droplet Weber numbers are higher, what explains the more efficient atomisation process and the lower air entrainment. At late stages of the spray evolution, droplets and entrained gas are closer to equilibrium with high gas velocities. Therefore, the fuel concentration decreases, but at the same time, the SMD of drops increases.

Radial distributions of velocity, SMD and concentration - Figures 8 and 9 show the velocity and SMD distribution for injection pressure of 30MPa at a distance of 40 mm for different instants from the arrival to the end of the spray. In Fig. 8, the mean velocity has been normalized by the averaged velocity at the spray axis, u_c, for each instant, while the radial distance is normalised by the distance from the injector z. In Fig. 9, the SMD at any radial distance and any instant is normalised by the value measured at the spray axis.

In Fig. 8, the radial distributions of the velocity for the first three consecutive times are above the line (leading edge), however for the five remaining times they lie reasonably on the same line (central part and trailing edge), taking into account the uncertainties and the scatter of this type of measurements. Half of the centreline velocity is obtained at a normalized radial distance of about 0.08. A further decay to one quarter of the centreline velocity is obtained at $r/z \approx 0.11$. The decay to 1% of the central velocity, which determines the opening angle of spray, is located at $r/z \approx 0.21$. The dynamic opening angle of the spray determined from it is of about 24°.

SMD and velocity are not correlated Coghe et al. (1994) as shown by the Fig. 9. The SMD has time dependence, as explained before, but a very weak radial dependence. The SMD shows a nearly constant value along the spray radius or a increasing of less than 15% for a radial distance of 0.15. These results are in agreement with results in similar conditions obtained by Coghe et al. (1994) under non-vaporization conditions.

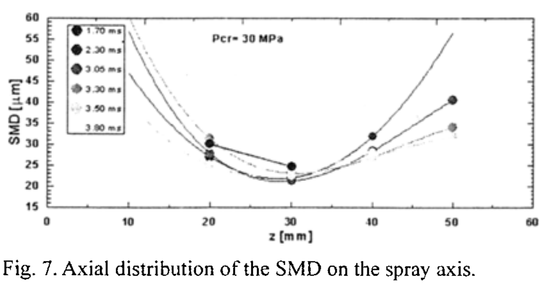

Fig. 7. Axial distribution of the SMD on the spray axis.

The drops concentration distributions were also estimated in these measurements and drawn in Fig. 10. Larger droplets concentrations exist on the spray axis with a decay as the radial distance increases. The radial decrease of the droplet concentration attain the 1% of the centreline concentration at a $r/z \approx 0.28$ giving a spray opening angle of about 31°. Sometimes the fuel concentration becomes higher than the exponential curve at the outer spray region. It is considered that this phenomenon is produced by the entrainment of the surrounding gas simultaneously with the formation of small vortices of high densities of fine droplets in the spray boundary.

A constant SMD along the spray radius implies a new balance between processes of atomisation and coalescence. While aerodynamic forces decrease by increasing radial distance, coalescence effects increase

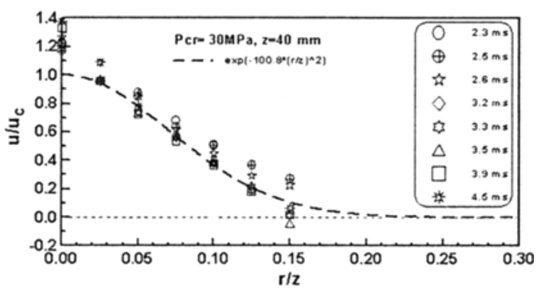

Fig. 8. Radial velocity distribution.

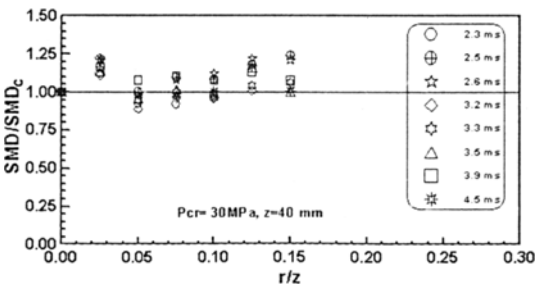

Fig. 9. Radial SMD distribution.

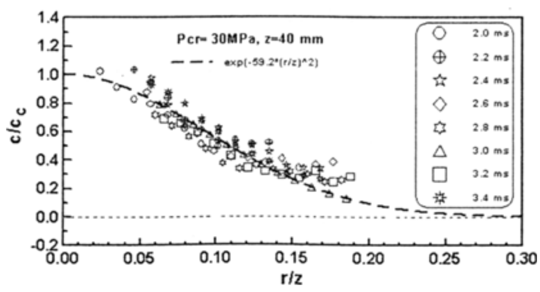

Fig. 10. Radial fuel concentration distribution.

near the spray axis because of the higher droplets concentration. The coefficient of Schmidt is defined by the ratio $C/C_C=(u/u_C)^{Sc}$. In our case, the value of Sc is of about 0.59. The behaviour discussed in these paragraphs for the injection pressure of 30 MPa at 40 mm from the injector was also qualitatively found for other injection pressures and axial positions.

4. Conclusion

The evolution and the development of the high-pressure diesel oil spray have been studied experimentally. The measurements of velocity and size of the fuel droplets have been taken by the PDPA technique to different axial distances from the nozzle tip with a radial sweep, in addition of taken shadowgraph measures by a CCD camera . Injections have been done with a common-rail injection system in a test rig, reproducing the same conditions as in the actual diesel engine. The results obtained in this study are summarized as follows:

1. At the gas densities as in actual diesel engines at the end of compression (TDC), the high-pressure diesel oil spray behaves as a "completely atomised" spray, even for very low injection pressures corresponding to that in idle conditions.

2. The cone angle for completely atomised sprays was found independent of injection conditions and only dependent on the gas density, in agreement with works reported in the literature.

3. The lowest drop sizes were measured at the leading edge of the spray, showing the capital importance of aerodynamic forces in the spray tip. Largest drop sizes were measured at the trailing edge of the spray. Coalescence and weaker aerodynamic interaction are responsible for the behaviour.

4. The radial distributions of the fuel droplet velocity at a given fixed axial distance are self-similar in time, despite the non-steady character of the high-pressure diesel oil spray. The radial distributions of the fuel concentration showed also self-similar profiles in time at a fixed axial distance. These two findings lead to a constant ratio between concentration and drop velocity independently of the radial position (Schmidt coefficient Sc=0.59).

5. The radial distribution of the SMD is almost constant for a given time. The axial distribution of the SMD shows a bathtub profile with a decrease followed by an increase. The primary atomisation process dominates the decreasing SMD phase, where the measured values of SMD should depend on the exit injection conditions and the distance from the nozzle. However, in the increasing phase the coalescence is more efficient.

6. Despite the fact that more measurements are needed to explain the behaviour and development of engine-like sprays, the spatial and temporal evolutions of the SMD seem to be mainly dependent on the gas density, and very little of the injection conditions. Some kind of balance between atomisation and coalescence appears in the leading edge to nearly constant axial and radial SMD distributions.

7. No equilibrium conditions are evidenced in the early stages of the injection process whereas in the last stages, a situation close to that of fuel-gas balance can be noticed.

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