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ABSTRACT

An axi-symmetric, five-hole V.C.O. nozzle mounted on an electro-injector was used to analyze the spray produced by each hole varying feeding pressure, injected quantity and timing. An advanced experimental apparatus has been used to investigate particle size and velocity of the sprays. The investigation comprized a hydraulic characterization, a photographic one with back-light technique, the analysis of the droplet size distribution through laser diffraction technique via MALVERN 2600 SERIES and the analysis of particle size and velocity using PDPA technique (AERMETRICS DSA 4000) with the extremely dense spray produced by the common-rail electronically controlled injection system. Four feeding pressures (25, 30, 90, 120 MPa) and five injected quantities (2, 4, 10, 25, 40 mm^3/shot) were chosen to characterize the nozzle behavior.

Sprays from different holes appeared different in shape but very similar in the droplet size distribution. Each spray had a dense internal core with low SMD and a periphery with a higher one. PDPA techiques showed severe limitations in the investigation of a so highly dense spray and for this reason a feeding pressure of 15 MPa was chosen after having reduced the probe volume with a spatial filter of 50 μm and having increased the laser power up to 5 W.

INTRODUCTION

The growing interest in internal combustion engines emissions reduction produced a growing interest in the study of the spray produced by Diesel injectors. Experimental, theoretical and numerical studies achieved important results that provided the guidelines for the designing of injection systems and combustion chambers.

Previous studies [1, 2, 3] found a link between the geometry of the single hole of a multi-hole nozzle, not axi-symmetric, and its spray. Different energy losses due to the different geometry of the nozzle holes caused different spray characteristics. Particularly, the hole with the highest inclination respect to the nozzle axis had the worst penetration and worst granulometry. An analysis on an axi-symmetric nozzle was necessary to confirm these conclusions. Those studies stressed the importance of avoiding micro-defects in drilling the nozzles. Every small defect can cause a big difference in the geometry of the spray characteristics (inclination, penetration, outlet diameter, spray angle) but not in the SMD of the spray. According to these experimental analyses no substantial differences were found in the five sprays that concerned the droplets mean diameter.

Other researchers investigated which parameters were influencing the spray formation and the combustion process occurring in the engine cylinders [4, 5, 6]. The nozzle geometry was first studied for this purpose and the influences of hole diameter and of lenght/diameter ratio were found [6, 12]. Different solutions for the general configuration of the nozzles were studied and tested (i.e. V.C.O. nozzles [7]). Then, the working parameters were investigated like feeding pressure and fuel injected quantity, and their influences on the macroscopic geometrical quantities here pointed out [3, 4, 7, 11]. Other Authors developed empirical equations to correlate macroscopic parameters like outlet diameter, penetration, inclination and spray angle [15, 16, 17, 18, 19].

These studies brought manufacturers to direct their efforts towards new injection devices and controls that could let the fuel reach a good atomization and an optimal distribution in the cylinders to lower the emission and to make the Diesel performances grow [7, 8, 9, 15].

The characterization, made in the present study, consistes in a hydraulic, a photographic, a particle size and a velocimetric investigation, to analyze the behavior of an electro-injector to be employed in a four-valve per cylinder direct injection Diesel engine. The electro-injector had a five-hole axi-symmetric nozzle. Holes diameter was of 0.194 mm.

Nine running conditions were chosen to carry out the tests as presented in TABLE I.

TABLE I -Test conditions		
Feeding Pressure [MPa]	*Energizing time [μs]*	*Inj. Quantity [mm³/shot]*
25	336	2
30	384	4
30	624	10
30	1280	25
90	320	10
90	656	25
90	1008	40
120	544	25
120	864	40

Table I: Test conditions

Injection times were so determined (Figure 1):

E.T. (*Energizing time*): time in which the magnet of the servocontrol is excited that corresponds to the ideal time of the needle lifting up;

T.A.S. (*Needle opening time*): the time the needle is actually lifted up;

T.R.I.I. (*Needle opening timing delay*): the delay between the start of the E.T. and the needle opening time;

T.R.F.I. (*Needle closing timing delay*): the delay between the end of the E.T. and the needle closing time.

The totally electronically controlled injection system has many important features:

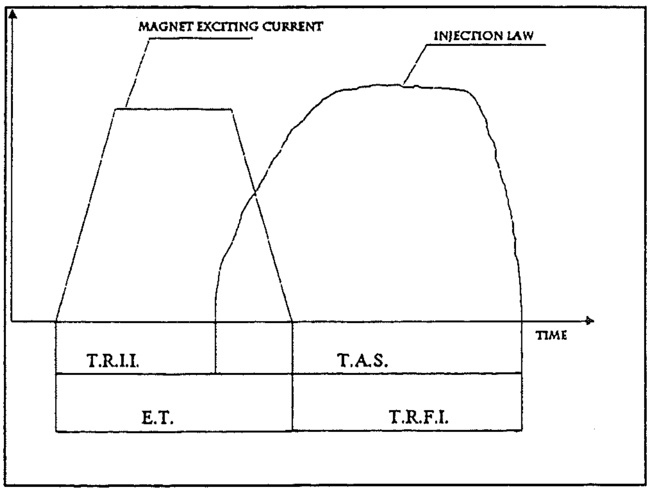

Figure 1: Injection Times

- every quantity of fuel can be injected through the nozzle hole varying only the Energizing Time at a fixed feeding pressure;
- the control unit can manage several signals coming from different probes and so can adequate its parameters to the real instantaneous running conditions;
- for the purpose of this work of investigating the spray generated in a windowed vessel the electronic control allowed the setting of a fixed timing between the injection and the data acquisition. Photographs and laser acquisitions got started using a square wave signal coming directly from the injection control unit.

This way of managing the acquisition was needed to overcome the negative consequences of triggering the acquisition at the first obscuration. In this way, every information about the repeativeness of the spray would have been lost and no precise time reference to the time of the injection could have been stored.

EXPERIMENTAL APPARATUS

A test rig was set up to acquire images for the photographic characterization and data for the two laser analyses (Figure 2, 3) [1, 3]. A cross section of the vessel used is shown in Figure 4.

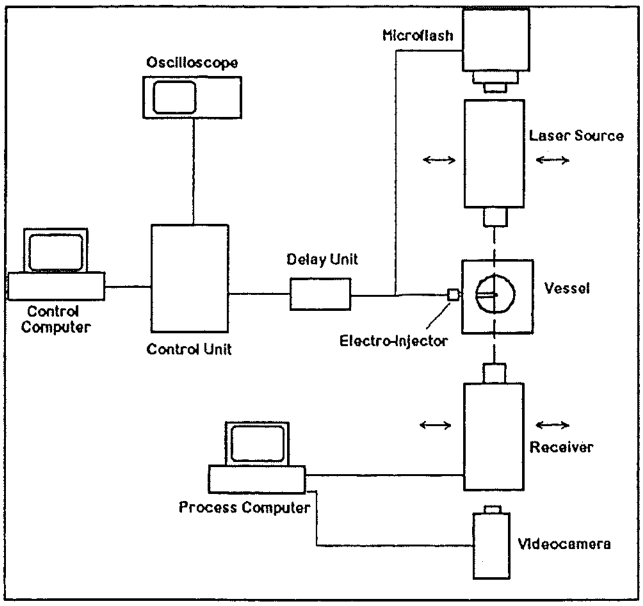

Figure 2: MALVERN laser instrumentation schematic layout.

A purposely designed structure was used to keep the alignment between the probes (either with MALVERN or with PDPA) and to let them move throughout the spray. A delay unit was used to control the time window during the acquisition. A square wave signal was generated by the main control unit at a fixed time with respect to the original Energizing Time and was sent to a delay unit that provided a further start delay (from 0 up to 4000 μs) and stopped the acquisition. In this way, a data acquisition time window could be produced up to 1 μs (nearly instantaneous acquisition) wherever during the injection.

Regarding the photographic characterization, a single shot acquisition was chosen for the high intensity of light coming from the nanolamp needed almost 5 seconds to be repeated.

The oil used for this work was ISO 4113 at a temperature of 40°C.

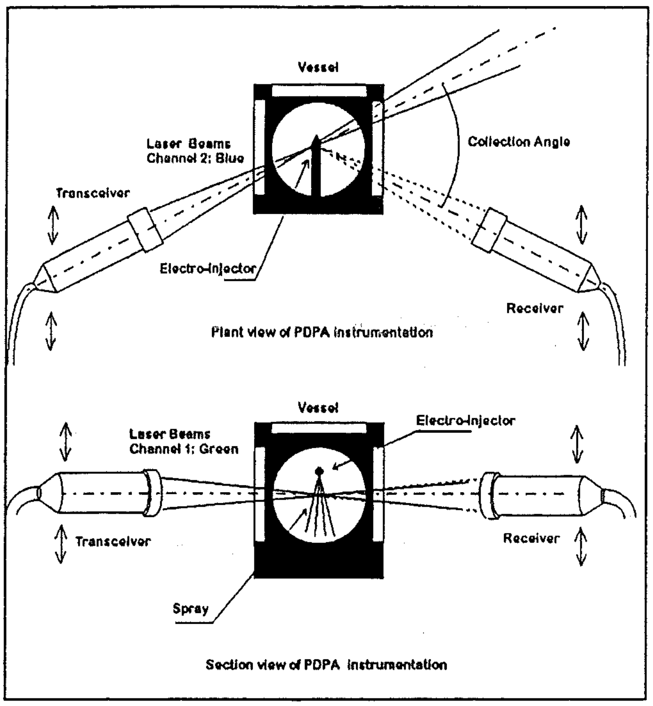

Figure 3: PDPA laser instrumentation schematic layout.

The pump speed was set at 150 rpm corresponding to an equivalent engine rotating speed of 300 rpm and to an injection frequency of 2.5 Hz; this choice was due to the vessel scavenging problems without influencing the injection system behavior and the sprays, because of the characteristic behavior of common-rail injection system.

HYDRAULIC CHARACTERIZATION

This characterization was carried out using two different hydraulic instrumentations in order to get two different information about the injector. A BOSCH 615A bench was used to determine the fuel injection law and to set the *Energizing Times* on the control unit in order to inject the right quantities of fuel chosen for the experimental campaign.

A HARTRIDGE DS2 bench was used to reveal a possible multi-modal behavior of the injector. This analysis was possible measuring the dispersion of the injected quantity of fuel per injection.

It was possible to complete the information about the hydraulic behavior of the nozzle using a special "cap", *ad hoc* designed, to measure the quantity injected by only one hole at a time. This information was very useful to compare the single hole fuel quantities injected by this axi-symmetric nozzle.

PHOTOGRAPHIC CHARACTERIZATION

Every hole was examined independently from the others thanks to the use of a special cap which keeps closed the others while the one is under investigation. A PCO FLASHCAM (single 1 ns acquisition) was used to take images at a determined time since the start of the *Energizing Time*. The *Backlight Photography* tecnique was adopted using an EG & G mod.549-11 nanolamp (50 x 10^6 cd; flash duration=0.5 μs).

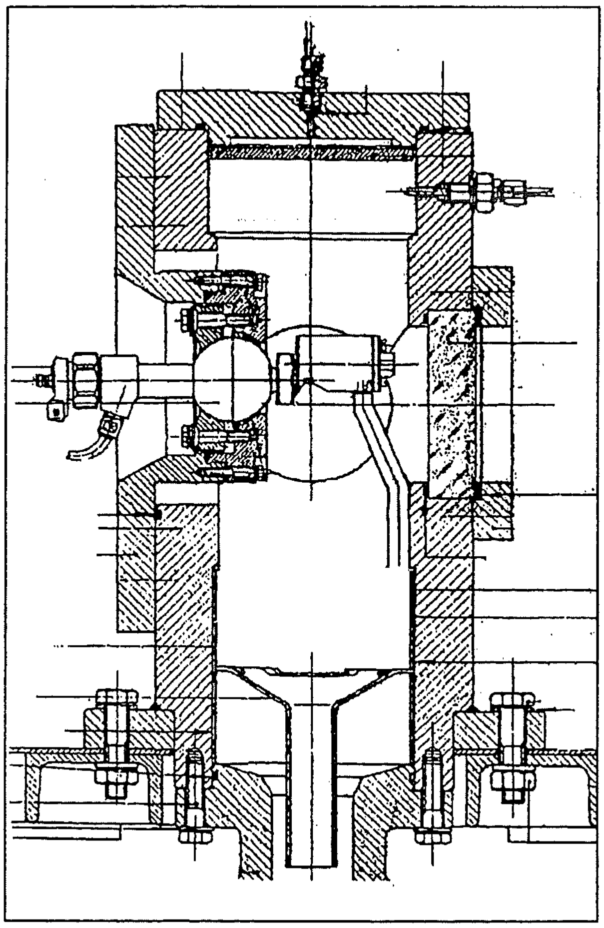

Figure 4: Vessel cross section.

For every hole from 4 to 8 photographs (Figure 5) were taken depending on the injection duration so that the important instants of the injection could be observed. The real starting time, the end and some significant times, from which understanding the temporal evolution of the spray, could be precisely located. Photos were taken and immediately stored on a hard disk in a TIFF format so that they could be examined and processed later. Many information could be taken from this analysis (penetration, spray angle, inclination and outlet diameter) that provided a first analysis on the differences among the sprays coming from different holes.

Such an instrumentation allowed a video animation as well: all pictures taken by the FLASHCAM could be also collected using a common video recorder and so seen as photograms of a short movie. In this way, even if it did not work as a high velocity camera, it was possible to observe the spray in its development process. The spray developed could be seen more evidently and some qualitative information quickly taken.

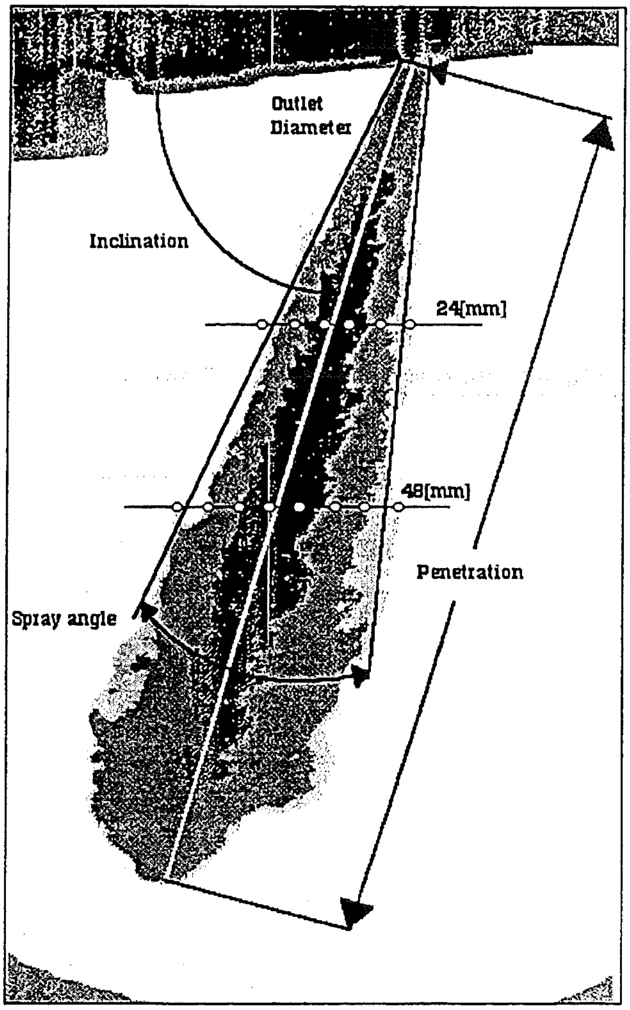

Figure 5: Geometrical quantities and measurement positioning.

SPRAY ANALYSIS

A complete characterization with MALVERN was carried out applying conditions found to be the best in the previous work by *F. Di Giorgio, D. Laforgia, V. Damiani* [3]. In order to keep clean the vessel windows an appropriate scavenging system was used (air flow = 400 m^3/h). 10 injections were carried out before every valid MALVERN acquisition [20, 21, 26]; 20 injections per acquisition were carried out for a single data set made and for the background acquisition as well, in such a way the statistics could be made with results of scientific interest.

As already stated, the chosen injection frequency could be considered far from the real engine conditions, but this is a wrong interpretation since the injector functioning is independent from the injection frequency.

The acquisition timing for the MALVERN investigation was chosen of 100 μs before the end of the injection time, in such a way to examine a completely developed spray. Measurements were made at two axial levels (24 and 48 mm) from the hole and at several radial distances (with an interval of 2 mm one from the other, Figure 5) from the spray axis (the point with the highest obscuration for every axial position) in order to obtain a valid acquisition (obscuration not lower than 0.1). The sampling time for Malvern was of 10 μs. Such a characterization was repeated for all the chosen conditions and for all the holes.

In order to operate all the features of the PDPA instrumentation it was necessary to superimpose the acquisitions coming from different injections at the same time scale. Also a variable time window was needed to manage acquisitions with reference to the injection times. A delay unit, directly controlled by the main electronic control unit, was used. It received a simple square wave and generated a precisely delayed signal compatible with PDPA instrumentation, from 1 μs up to 4 ms long. To superimpose different acquisitions a jumper had to be set on the *Controller Board*, and the acquisition to be controlled at the chosen frequency using a BNC input. The software, provided with the instrumentation, allowed to superimpose acquisitions mantaining the same time reference, and to store a file with droplet measurements that were virtually part of a single injection, while they actually came from different shots.

Problems deriving from the high density of Diesel sprays had imposed a different feeding pressure of 15 MPa in order to take significant results.

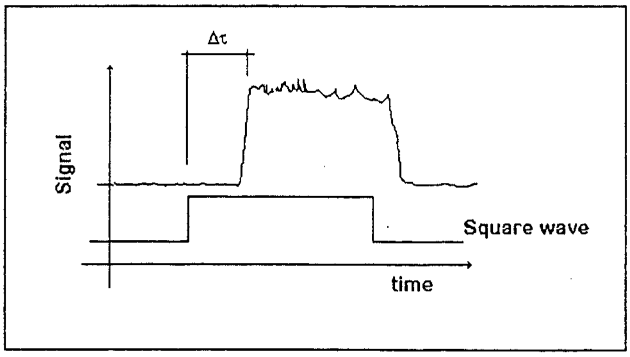

Figure 6: Electronic HP Oscilloscope Output.

That was the first time that a PDPA instrumentation was used coupled to a so persistently dense spray. No one could know if results coming from this analysis could be correct and reliable. A completely independent way of measuring particle velocities had been carried out to test the reliability of the velocity measurement by PDPA. At a known distance from the nozzle, the axis of the Transceiver probe was positioned and the electrical signal, coming from the first passing of the spray particles, was recorded on the video memory of a digital HP Oscilloscope. It was then printed to measure the maximun velocity of the spray and of the fastest particle at that location in that instant (Figure 6). A normal operation of PDPA then was done at the same positon and the results coming from the two different and independent measurements were compared.

When the chosen running conditions were tested, especially with a high feeding pressure, very different velocities came out from the comparison. For the 120 MPa conditions the "independent test" gave an initial velocity of about 220 m/s, while Aerometrics of about 70 m/s. This happened even if the probes were moved throughout the spray trying to reach low density regions. Therefore, inconsistent times of the passage of the first droplets pass were found.

Several attempts at different feeding conditions, among those chosen for the analysis, were made without acceptable results. Maximum initial velocities (and so frequencies) were so high that no electronic filter could be used to acquire them, and so all spikes could not be removed from the photomultipliers signals. So that, the test conditions eventually chosen for the AEROMETRICS analysis, were the following:

regarding the injection system settings,

- Feeding pressure = 15 MPa;
- *Energizing Time* = 1200 µs;

regarding to the AEROMETRICS settings,

- Transceiver lens focal lenght = 250 mm;
- Receiver lens focal lenght = 250 mm;
- Spatial filter width= 50 µm;
- Photomultiplier voltage = 350 V;
- Acquisition controlled by the *Inhibit* in BNC port at 130 µs after the time origin and 2000 µs up to 2800 µs long according to the axial position (in order "to follow" the Diesel spray);
- Velocity range on Channel 1 = -3 ÷ 100 m/s;
- Velocity range on Channel 2 = -15 ÷ 15 m/s;
- Diameter range = 2 ÷ 103 µm;
- Filter configuration deriving from the *Auto Velocity Setup* routine;
- *SNR* = 0,1 on the two channels;
- *Threshold* = 40 mV on the two channels;
- Error correction active in the *Transit Time* feature;
- Laser power = 5 W;
- Refraction index = 1.45;
- Scattering angle = 30 ° with calibration curve slope from AEROMETRICS;
- Two velocity components (green (1st) and blue (2nd) channels) and *Diameter Acquisition* feature on;
- Acquisition was stopped if 4000 samples were taken or 90 seconds passed.

The experimental campaign consisted of a complete data acquisition at six axial levels (from 5 up to 30 mm with an interval of 5 mm) and all radial levels that gave almost a minimum quantity of bursts for the statistics (with an interval of 1 mm)

The rejection percentage was of about 30% if information only on the velocities were collected and of about 70% if the diameter acquisition was on. This was certainly due to the sphericity check on droplets that was on only when *Diameter Acquisition* feature was on too.

DISCUSSION OF RESULTS

The hydraulic characterization made possible the setting of the Energizing Times on the electronic control unit. These analyses confirmed that the injector had a regular behavior, as one can see from the diagram on Figure 7 for the injected quantity versus the Energizing Time. T.A.S., T.R.I.I., T.R.F.I. versus E.T. showed a regular, expected behavior too and the dispersion of results was negligible.

Very important results came from the single hole hydraulic investigation that showed what the real differences among the five holes were (Figure 8). At the E.T. set in the previous test (corresponding to the nominal injected quantities at the chosen feeding pressure conditions), using the special "cap", hole no. 1 seemed to be the one through which the highest quantity of fuel passed with the exceptions of the 4 and 2 mm³/shot conditions. Holes no.2 and no.3 and no.5 were the ones that injected almost the same quantity for the same operating conditions. Hole no. 4 was the less efficient. These trends were different for the 4 and 2 mm³/shot condition.

The trends coming from the photographic analysis (Figures 9a, 9b, 9c) seemed to be the same as those reported in scientific literature:

- the spray angle, for most cases, decreased versus time giving an ever more defined conic shape to the field;
- the spray inclination, after the starting of the injection causing uncertainties, reached the nominal inclination of 78° of the nozzle holes. These uncertainties could be explained with the difficulties coming from the reduced space, in which the fuel had to pass. During the start of the injection, in fact, the needle comes up and produces high pressure losses before the holes;
- the outlet diameter was bigger when the injection either started or ended and this was due to the small needle lift and the high pressure losses occurring in the tip of the nozzle during these phases. It was more regular and small during the "steady" injection;
- the penetration followed a linear dependence from time with some exceptions due to the not very good repeatitiveness of the sprays and to the single shot acquisition.

Every hole presented its own behavior:

- Hole no. 1 had the longest injection duration at high feeding pressure (perhaps an asyimmetric deformation of the needle or of the nozzle);
- Hole no. 2 had the most irregular behavior and no interpretation could be carried out;
- Hole no. 3 produced a particular spray with two or even three edges. This could be due to some difficulties in the hole feeding and so to high differences of fuel start velocities in the outlet section;
- Hole no. 4 had a repeatitive thin and long spray;
- Hole no. 5 was cavitating in all conditions.

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- Hole no. 5 was cavitating in all conditions.

With data coming from the MALVERN characterization, several diagrams were made to see the influence of the different feeding conditions, of the position throughout the spray and of the holes on the droplet size distribution. From figures 10a and 10b it appears that SMD grows while going far from the spray axis and that this trend is less visible going far from the nozzle hole under investigation.

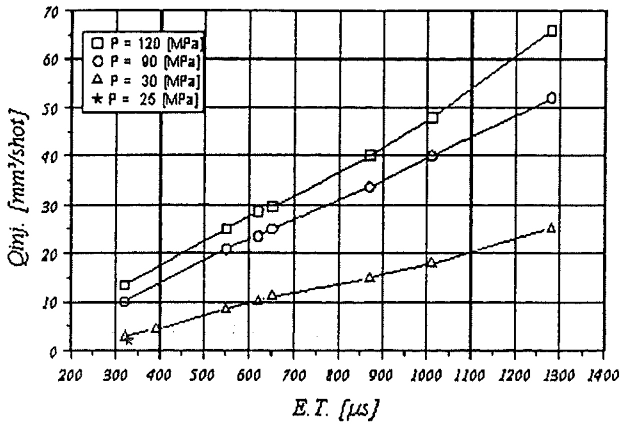

Figure 7: Output of the hydraulic investigation. Injected Quantity versus Energizing Time.

This behavior could be due to the lower inertia of the smallest particles that are easily brought near the axis of the spray field by the air moved by the injected fuel. Another hypotesis could be made regarding this phenomenon: the high velocities, and so the kinetic energy of the particles close to the spray axis, could be responsible for the disintegration of the other droplets supplied earlier in the injection. A different behavior can be observed on the periphery of the spray. Here, the biggest particles can be seen because coalescence is the prevalent phenomenon due to the low velocities.

Measurements at 48 mm below the nozzle inform that these differences are less visible and this is due to the vaporization that occurs to droplets that remained in the vessel atmosphere for a longer time.

The different holes do not give different results with regards to the SMD. Comparing the droplet size distribution of the five holes, no significant difference can be found in the axial distribution but only in the radial one. The latter certainly due to the different general configuration of the five sprays already observed with the help of the photographic characterization. For example, hole no. 4 is the thinnest one and has the minimum value of data acquired by MALVERN scanning the spray field in the radial direction. Hole no. 1 produced the spray with the longest duration and so its field was seen to be the widest.

The second set of diagrams (Figures 11a, 11b, 11c) compares data coming from the same hole with all the injected quantities for different feeding pressure values. It is really evident the dependence of the SMD from pressure. The higher is the pressure the lower are the diameters of the droplets. It is recognized that this is due to the higher kinetic energy of the droplets coming from a high pressure ambient (such as the common-rail).

It is certainly more difficult to say what is the influence of the injected quantity on the droplet size distribution. No trends can be definitely found observing the third set of diagrams reported on figures 12a, 12b, 12c. In a previous article [3] it was stated that the higher was the injected fuel quantity, the higher was the SMD. And this because of the more probable coalescence of particles due to the higher number of them. This behavior can be observed in this work only when referring to the 30 MPa condition. It must be stated that even if it is true that more particles can more easily bring to a better coalescence, it is also true that they can interact in the sense of disintegrating each other. Empirical equations, found considering the influence of the injected quantity, agree with the first interpretation but do not have into consideration the trend of the droplets to coalescence and disintegration.

The AEROMETRICS experimental campaign, previously did not achieve interesting results for Diesel engines running conditions. The drop size distribution of a spray fed at 15 MPa versus time showed the presence of particles of all diameters with some preferences for about 10 μm and 100 μm. Diagrams could not be wider as the instumentation limits in those conditions were reached. Particularly, the trend of generating particles having the size stated before is more visible in the final part of the injection. Figure 13 refers to four of the six axial levels scanned (15, 20, 25 and 30 mm from the nozzle on the spray axis) at the more significant radial position..

Figure 14 refers to the droplets Sauter Mean Diameter versus radial position for a fixed axial position. It is evident that SMD increase with radial distance from the axis increase

Diagrams concerning velocities measurements are also reported in figure 14. They are Mean Axial and Radial Velocity and Maximum Axial and Radial Velocity versus radial position, particles velocities versus time (Figure 13) for some conditions reported on the diagrams. The velocity distribution in the field can be observed as expected. The central core contained particles with the highest velocities. The proper characteristics of the common-rail injection system can be observed with reference to the diagram concerning the single injection time (the difference from the traditional way of injecting can be seen in [24]). High velocities are present for all the injection period and have not a pronounced maximum as it could be observed in other works. The feeding pressure is actually high and constant during the needle opening time. When no more enthalpy is furnished to new particles, the velocities decrease and the penetration ends.

In order to check diagrams validity some precise references were reported on them such as the measured start of injection (T.R.I.I.) and the expected timing of the first particles passing at the probe volume location.

A very interesting result is that coming from the comparison between diagrams reporting SMD versus radial position, and that reporting the Arithmetic Mean Diameter. They have an opposite behavior; this could be probably due to a highly dispersed distribution of diameters. It must be remembered that the SMD measured, using the MALVERN software is calculated supposing a Rosin-Rammler drop size distribution. This is very different from AEROMETRICS software that does not suppose any drop size distribution for its data.

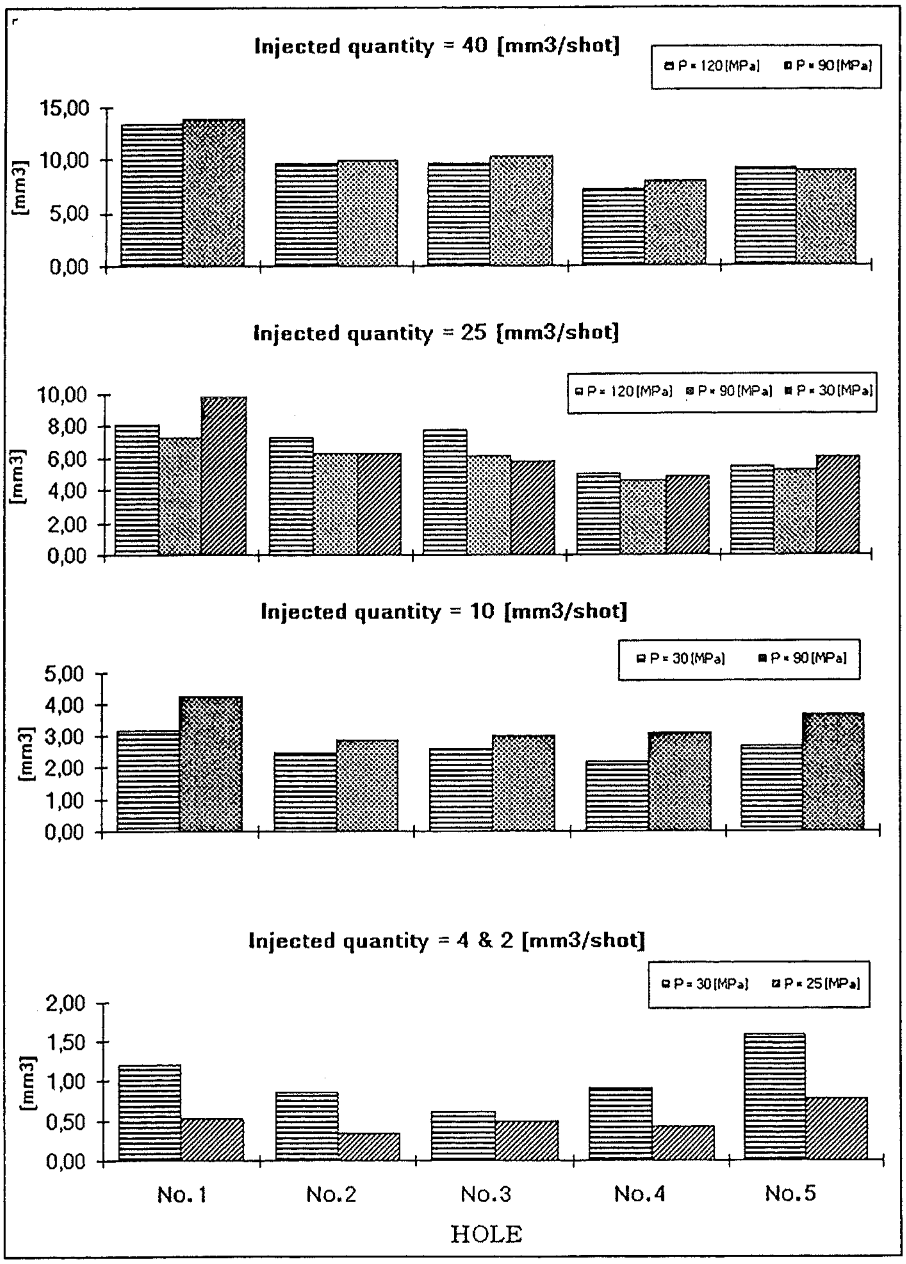

Figure 8: Fuel quantity injected by each hole at the chosen operating conditions.

The consistence of these sprays is particularly dense. This is due to the common-rail system that keeps a high feeding pressure for a period of time comparable with the duration of the injection. The quantity of injected fuel is so high in a short time that laser beams cannot penetrate them to allow a correct measurement.

In order to have a correct measurement [22, 23, 24, 25] the two intersecting beams have to reach the point of intersection without being stopped. Only in this way it is possible to correctly form the probe volume (Figure 15). If one of the beams is intercepted by a particle before the probe volume that measurement cannot be done and is rejected. Moreover, there are other cases in which the measurement cannot be successful. If two particles contemporarily pass through the probe volume the signal coming from the photodetector will be probably very different from a Doppler one (Figure 16). If the light scattered from a single particle passing through the probe volume is intercepted by other particles or ligaments passing behind the probe volume (between the probe

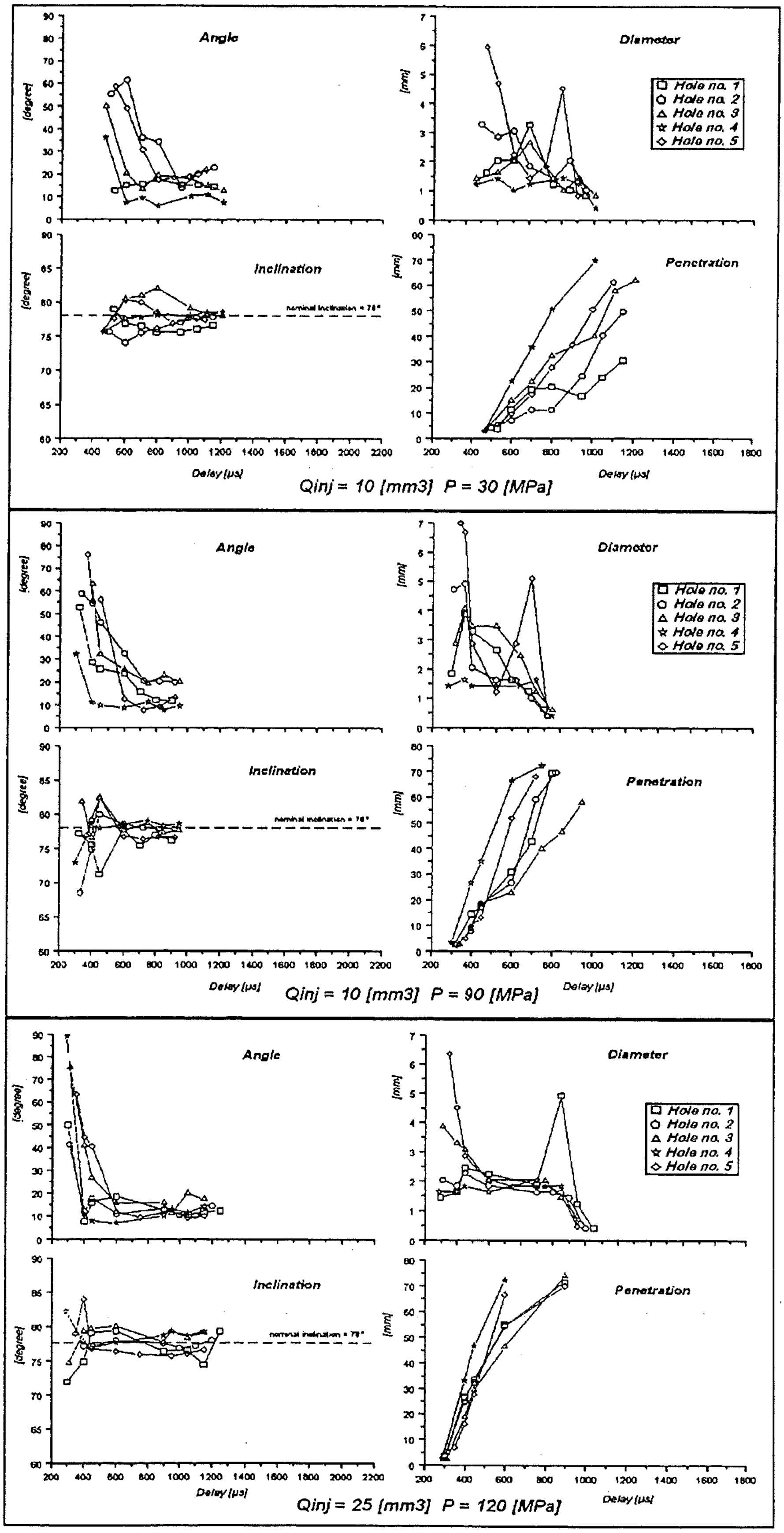

Figure 9a: Output of the Photgraphic investigation : comparison of the geometrical quantities.

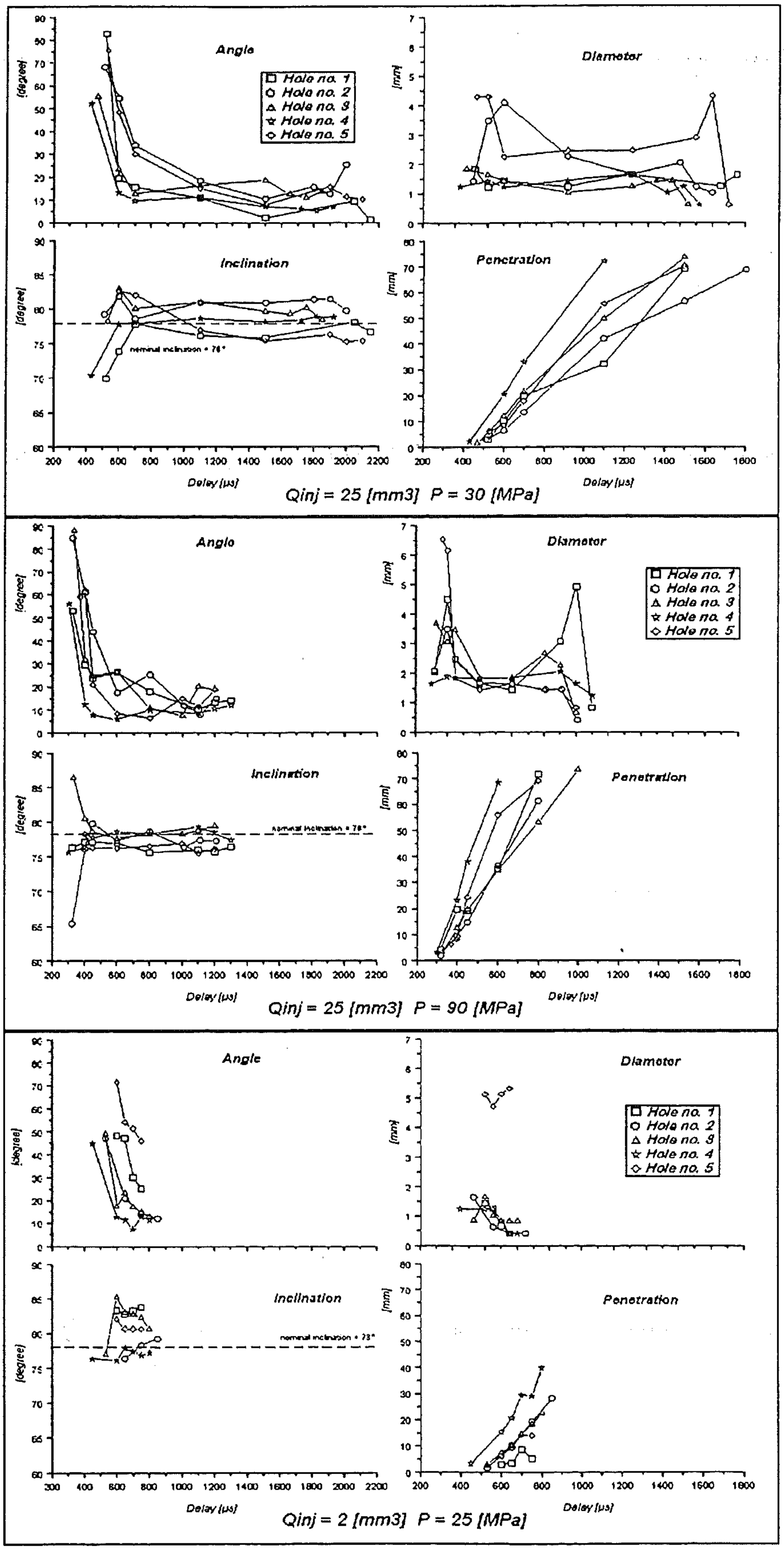

Figure 9b: Output of the Photgraphic investigation : comparison of the geometrical quantities.

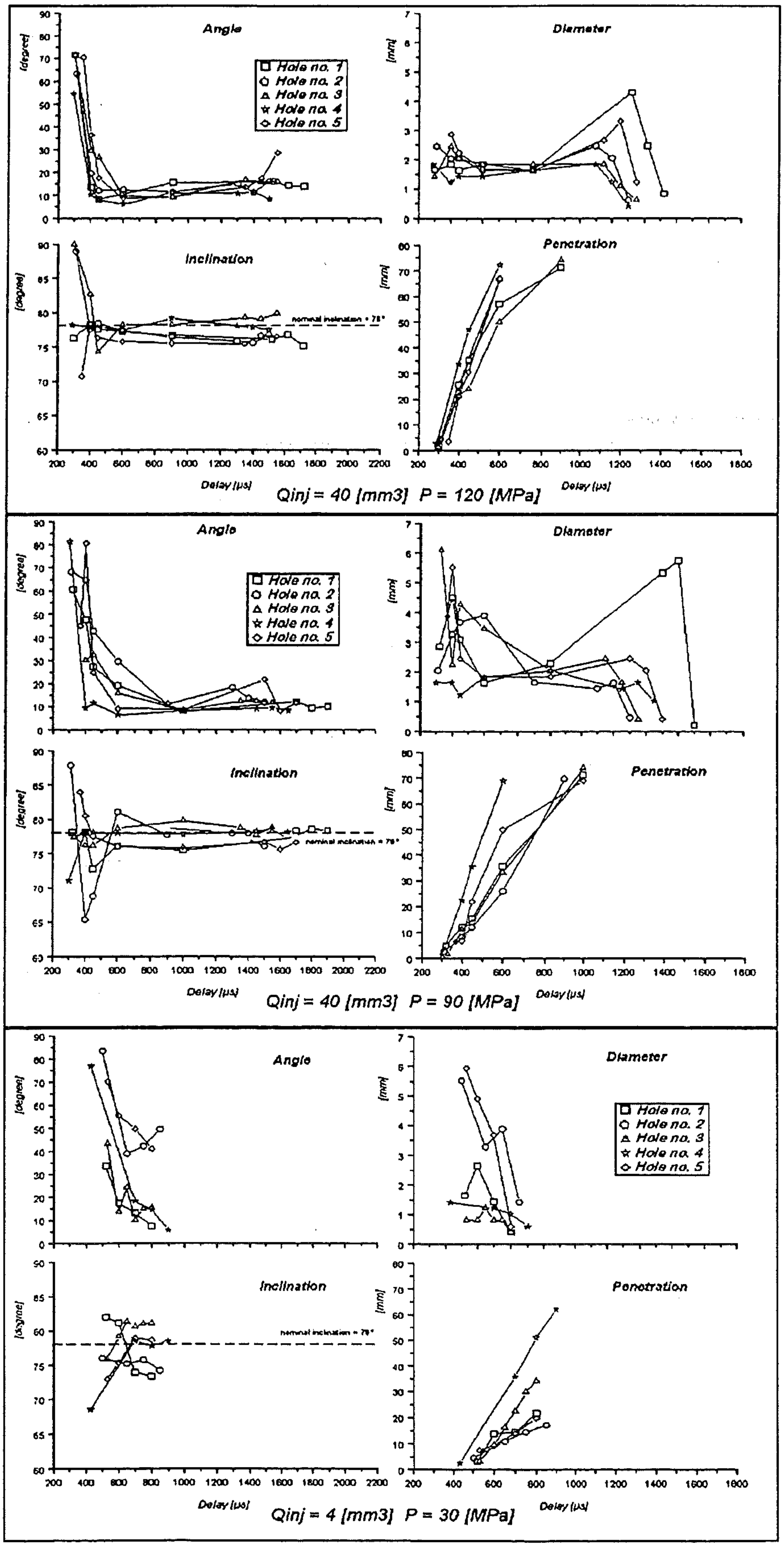

Figure 9c: Output of the Photgraphic investigation : comparison of the geometrical quantities.

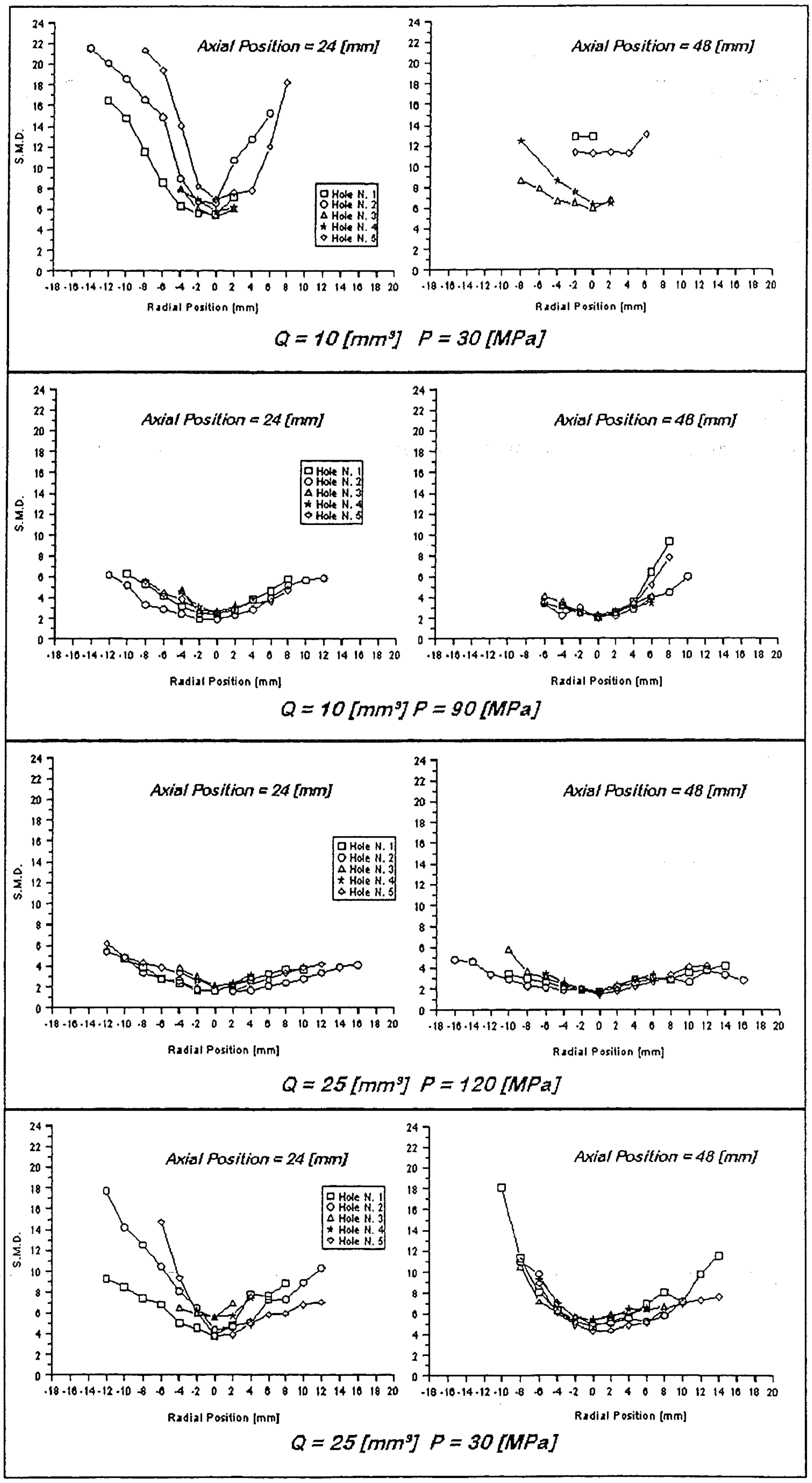

Figure 10a: MALVERN output : comparison of different positioning in the spray.

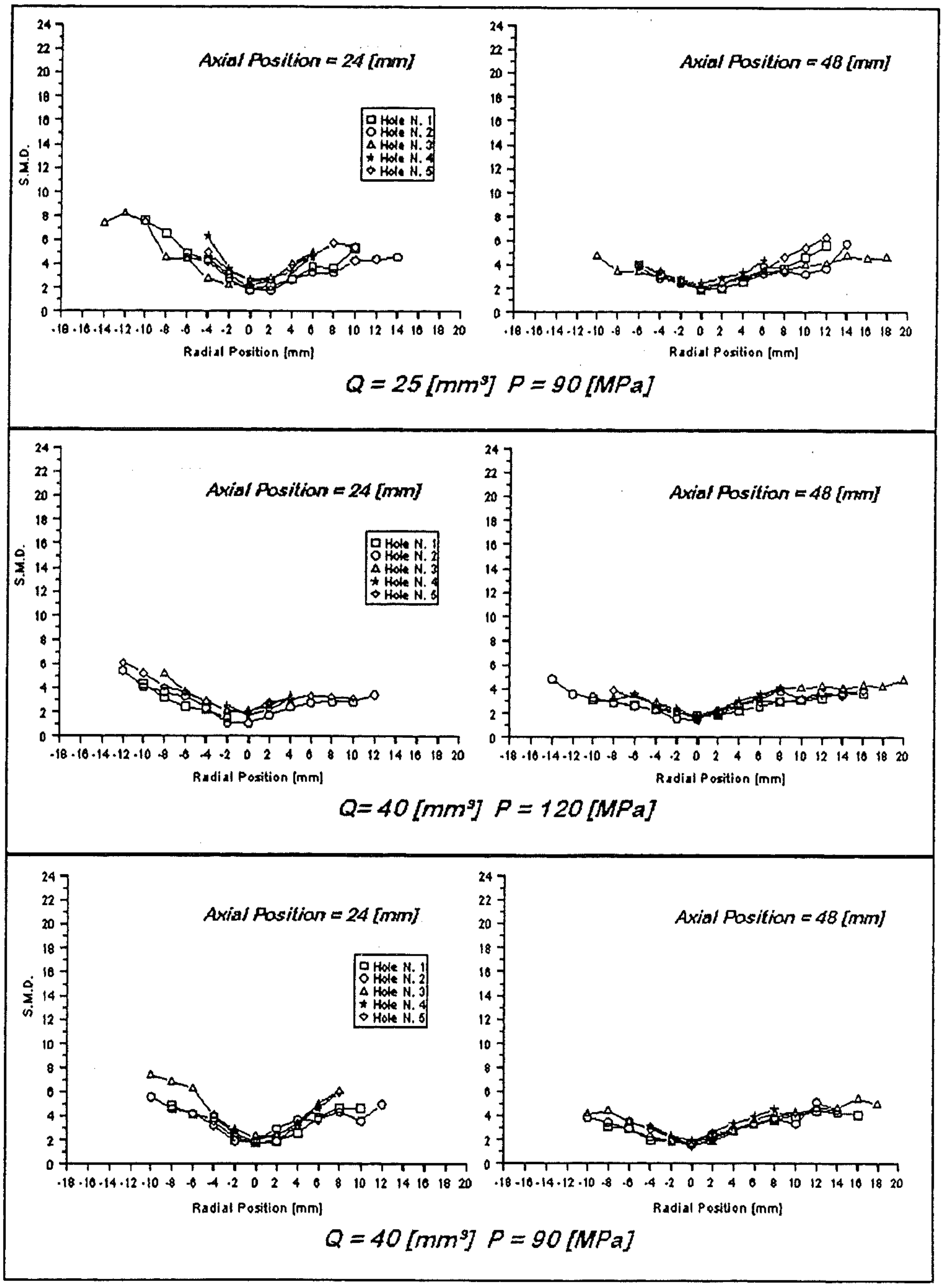

Figure 10b: MALVERN output : comparison of different positioning in the spray.

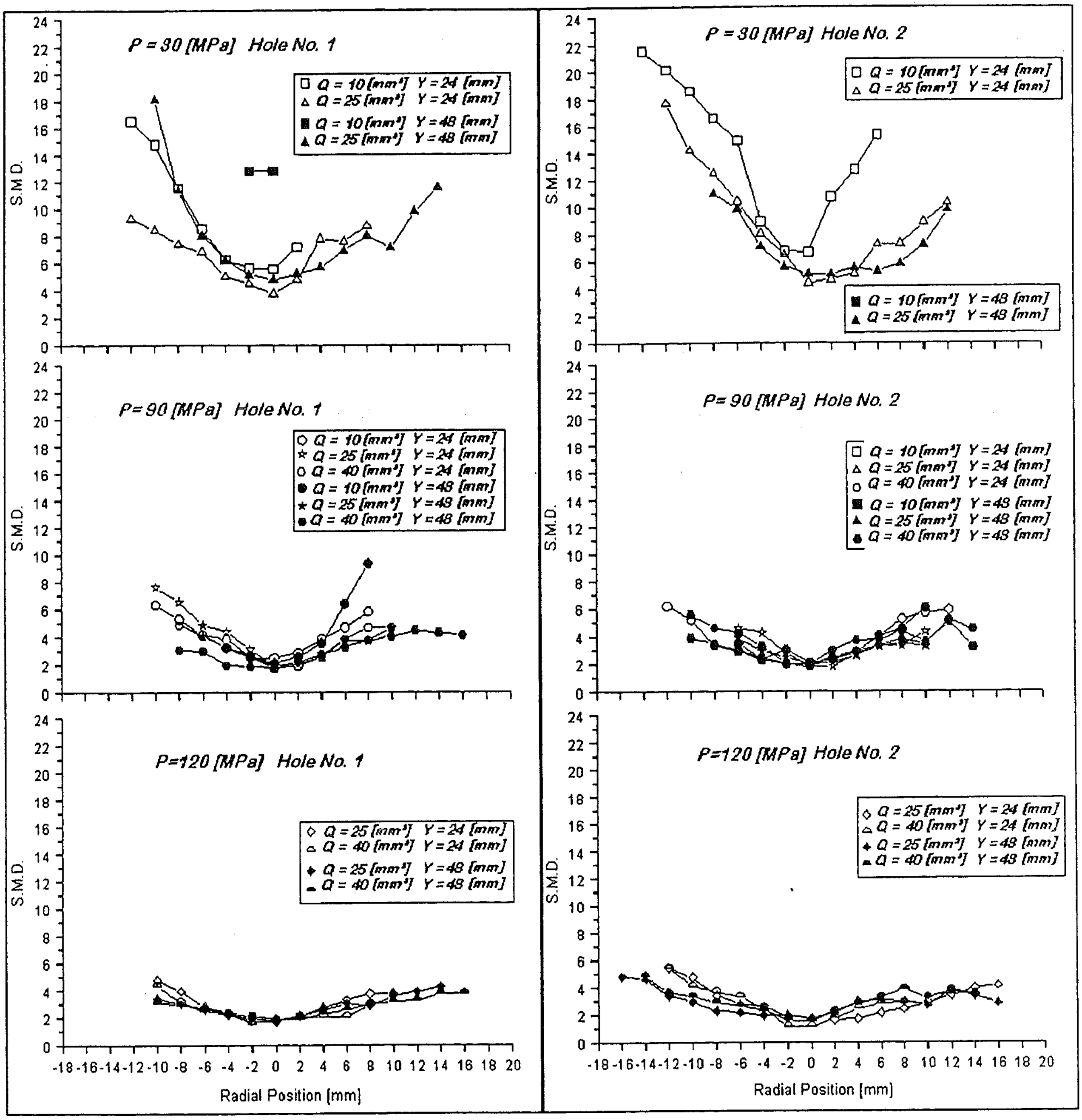

Figure 11a: MALVERN output : Sauter Mean Diameter versus Radial Position at different feeding pressure.

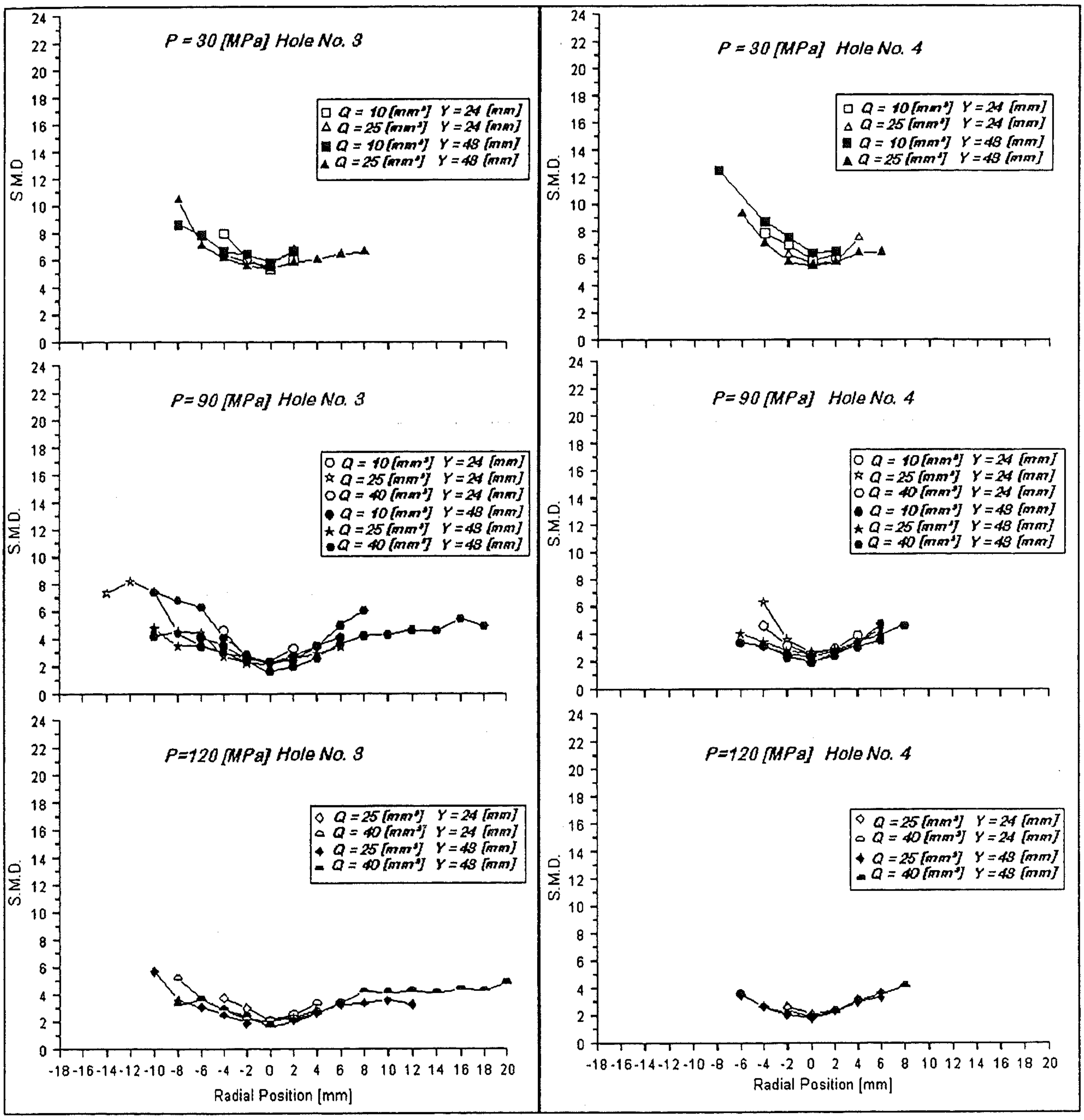

Figure 11b: MALVERN output : Sauter Mean Diameter versus Radial Position at different feeding pressure.

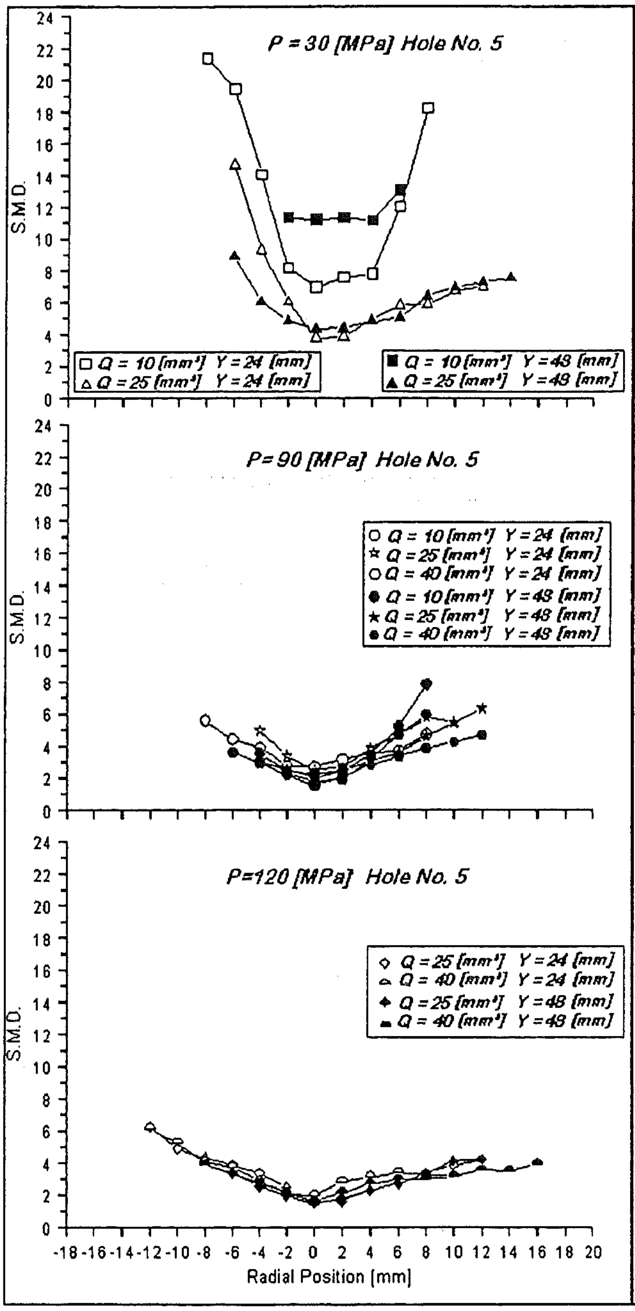

Figure 11c: MALVERN output : Sauter Mean Diameter versus Radial Position at different feeding pressure.

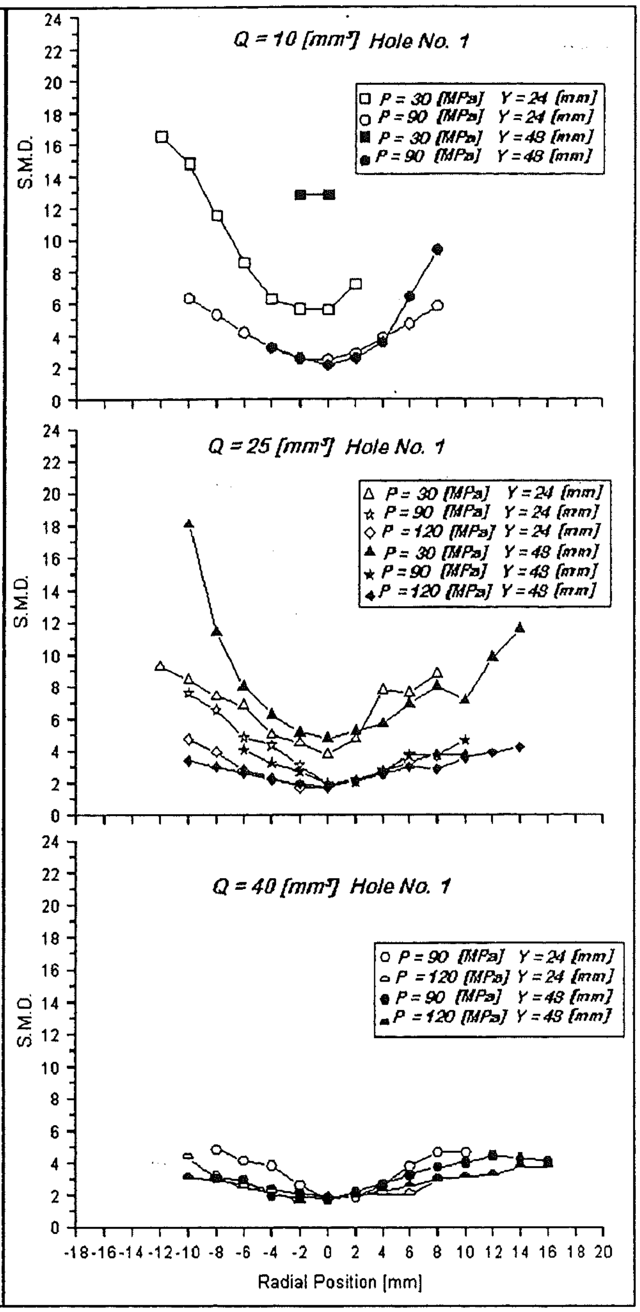

Figure 12a: MALVERN output : Sauter Mean Diameter versus Radial Position at different injected quantities.

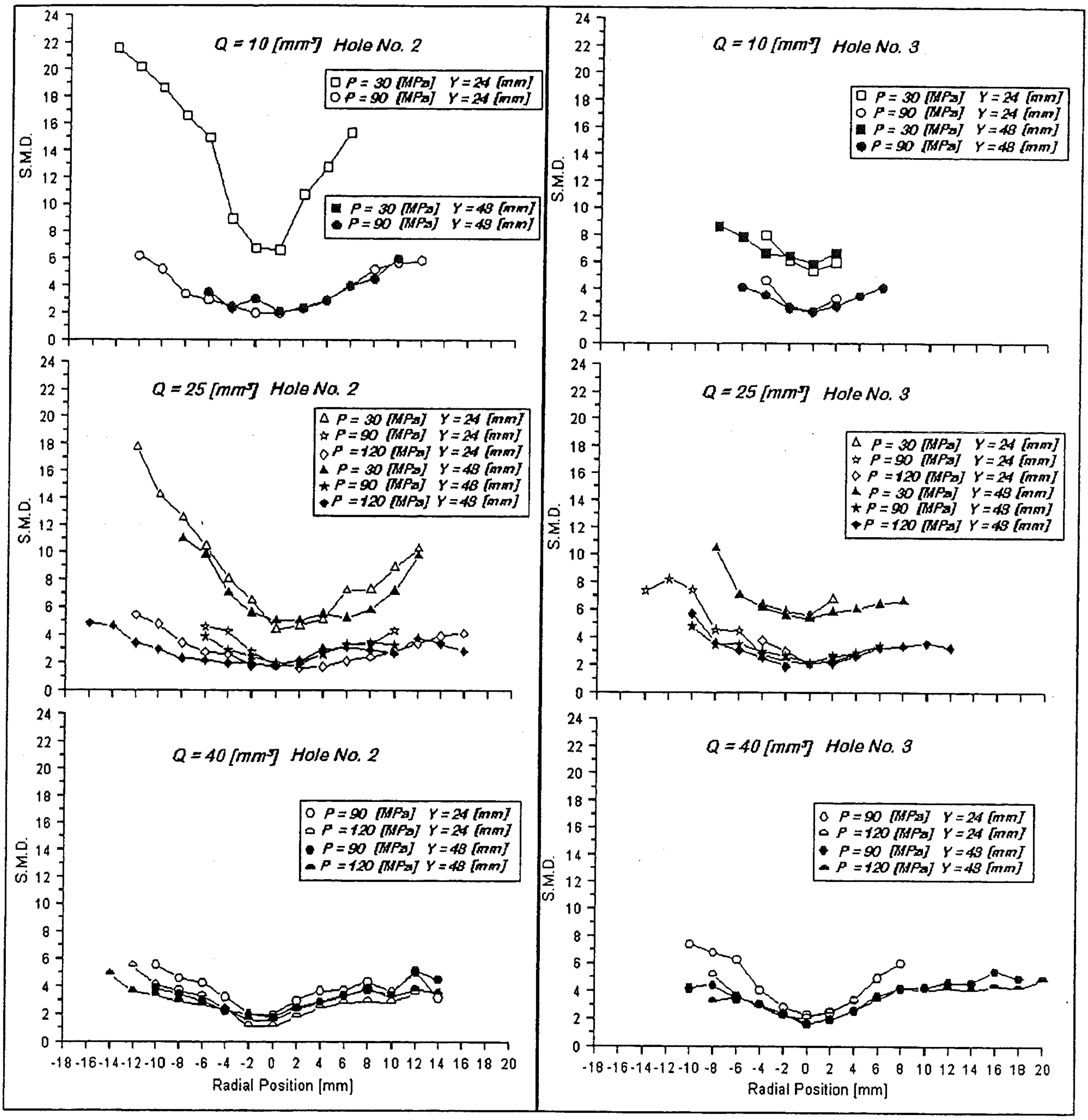

Figure 12b: MALVERN output : Sauter Mean Diameter versus Radial Position at different injected quantities.

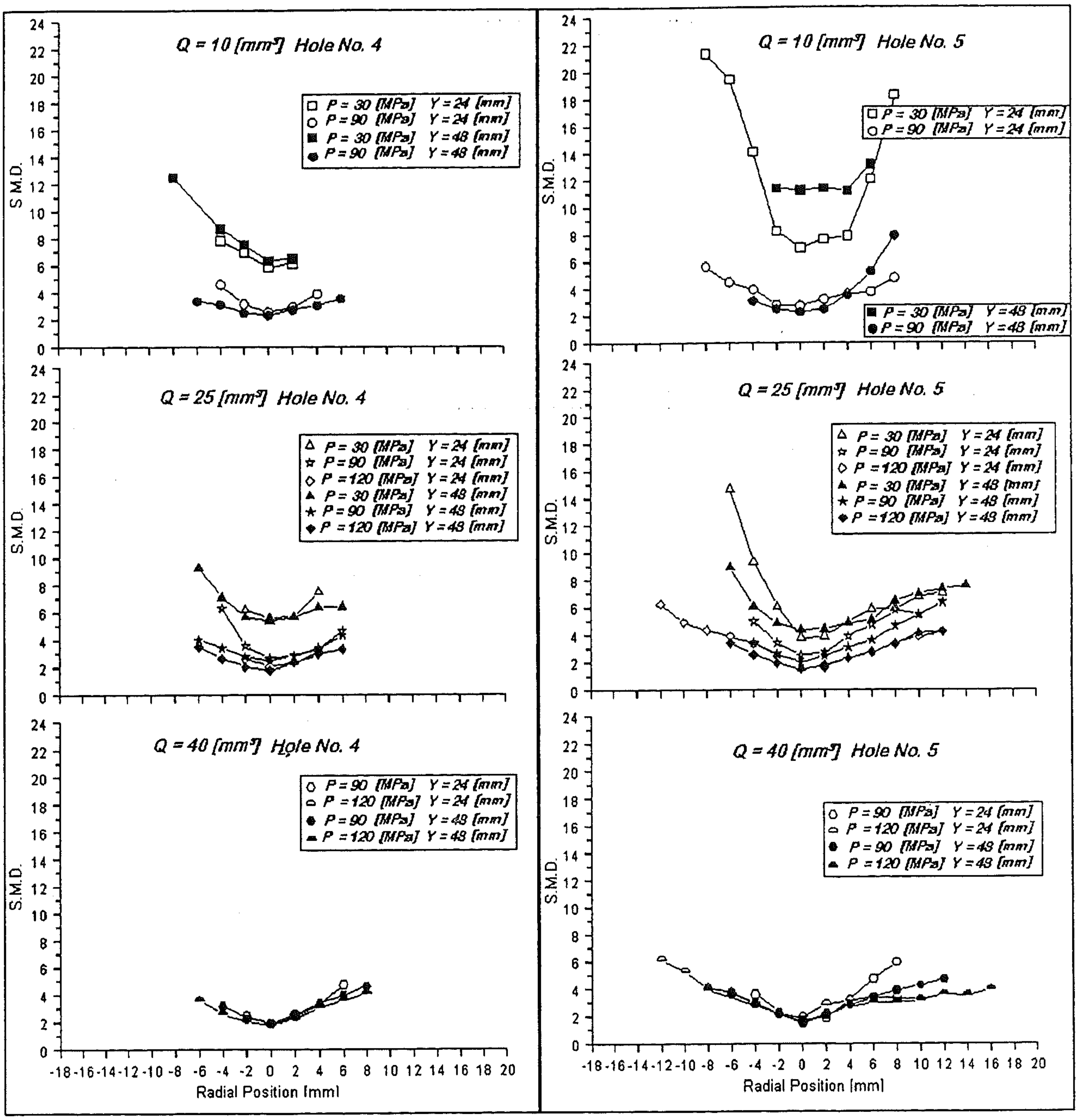

Figure 12c: MALVERN output : Sauter Mean Diameter versus Radial Position at different injected quantities.

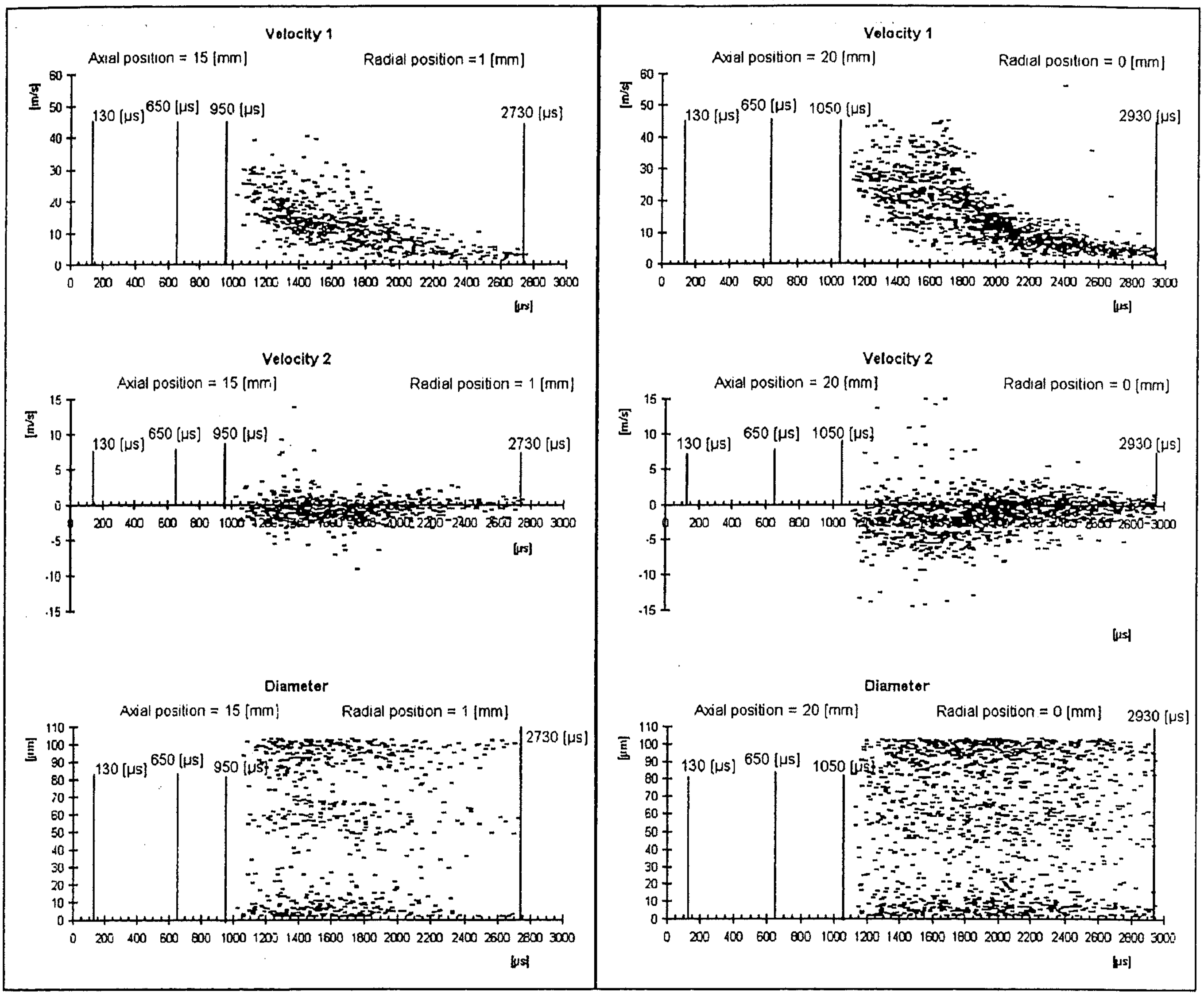

Figure 13a: PDPA Output : single injection. Axial (component 1) and Radial (component 2) Velocities and Diameter coming from different injections superimposed on the same time scale.

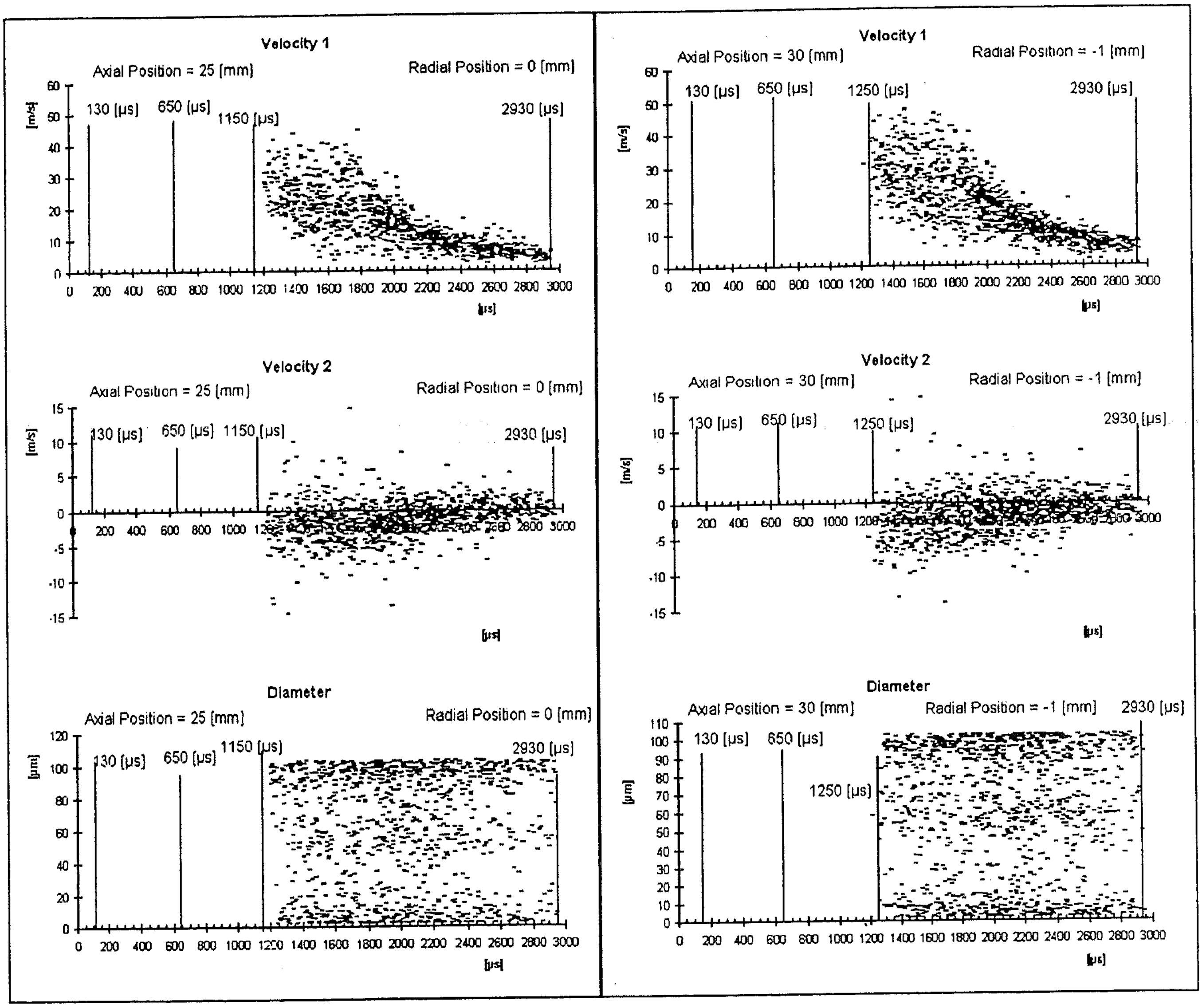

Figure 13b: PDPA Output : single injection. Axial (component 1) and Radial (component 2) Velocities and Diameter coming from different injections superimposed on the same time scale.

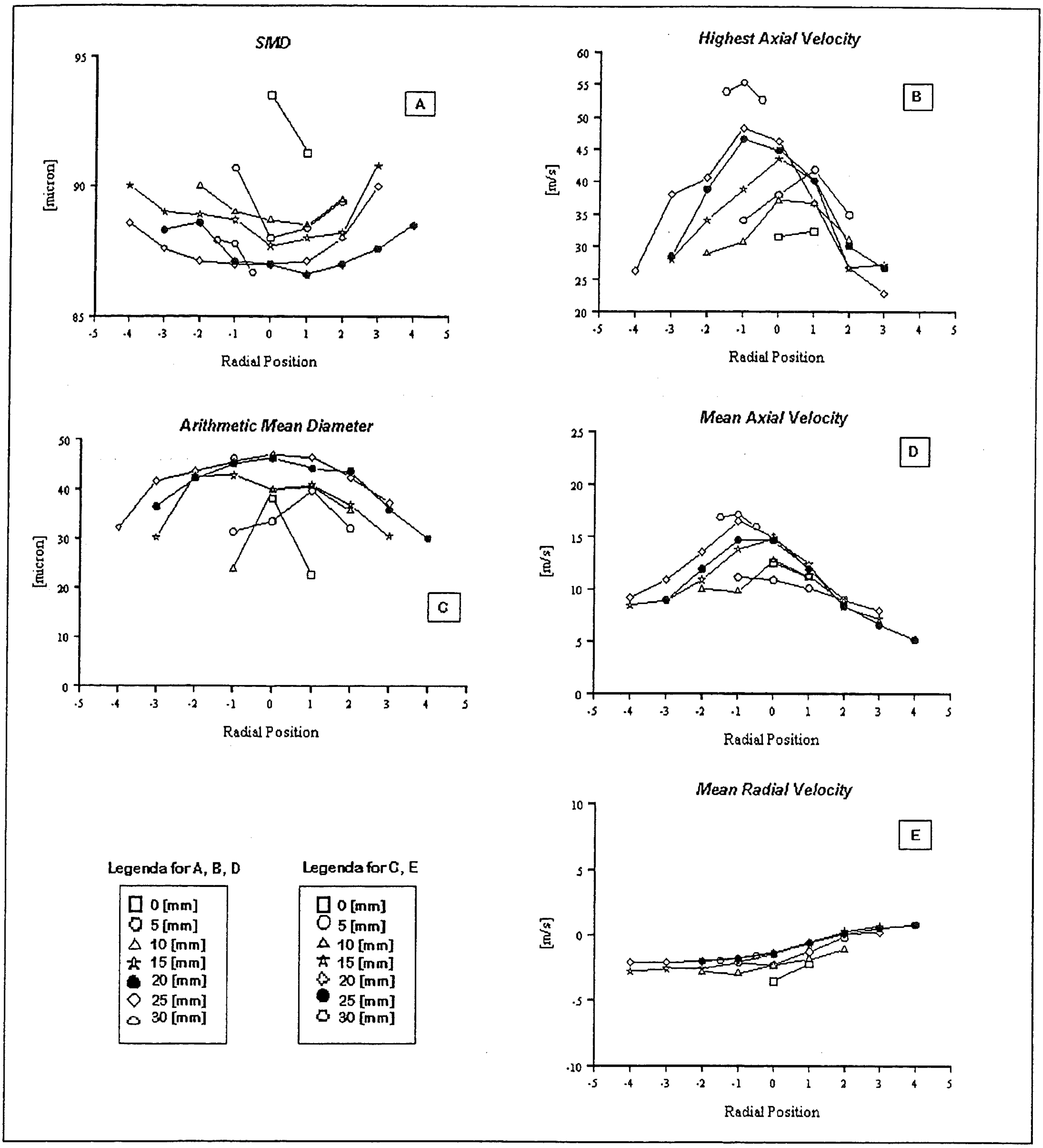

Figure 14: PDPA Output :Sauter Mean Diameter, Arithmetic Mean Diameter, Highest Axial Velocity, Medium Axial and Radial Velocity versus Radial Position in the spray.

volume and the Receiver) the measurement must be rejected. Finally, the droplet in the probe volume must be only one and spherical; otherwise, an easy misunderstanding on its velocity and diameter could occur. For this reason AEROMETRICS could check these particular events by using two different photodetectors that must give the same dimension to the same burst.

It is very difficult that PDPA can be successful with this type of spray. It is necessary to reduce the probe volume (reducing the spatial filter width and/or reducing the transmitter focus lenght) or to reduce the feeding pressure. Some results have been achieved using this last way but they have scientific meaning only: no real direct injection Diesel engine can be supplied at a so low feeding pressure (15 MPa).

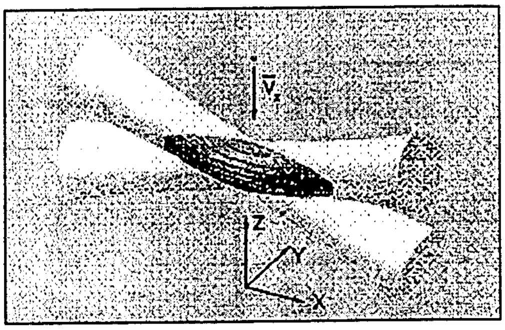

Figure 15: PDPA probe volume.

Even if a low feeding pressure was used, the measurement could be successful only at a certain distance from the holes: 30 mm. The particles velocities, were used to test the reliability of the drop size distribution measurements.

CONCLUSIONS

A complete analysis of the hydraulic and granulometric characteristics of the sprays produced by a D.I. Diesel engine, V.C.O., five-hole, axi-symmetric nozzle was carried out.

This work brought to the following conclusions:

- there are some differences in the characteristic times of the injection among the holes. Each hole has a particular way of injecting;
- the injected quantity per shot sometimes presents dispersion probably due to oscillations of the needle and to constructive micro-defects;
- the SMD of the single holes spray fields strongly depends on the feeding pressure. Even if the fields are different one from each other, the SMD is substantially the same;
- the general configuration of the spray is different for each hole even if the nozzle is axi-symmetric;
- the spatial variation of the droplet size is complex. A central core can be observed with a SMD lower than the periphery of the field. These differences are ever less visible while going far from the axis of the spray;
- SMD decreases as the feeding pressure grows;
- the injected quantity seems not to have a particular effect on the spray SMD especially at high feeding pressure.

There are several and severe limitations to the coupling of the PDPA tecnique with the investigation on so dense spray fields. Hypothesis of the PDPA theory were verified with many difficulties using a Diesel spray generated with a common-rail injection system [22, 23, 24, 25].

It was necessary to reduce the spatial filter, in order to reduce the probe volume, and to increase the laser power up to 5 W. No reliable results were achieved until the the feeding pressure was reduced to 15 MPa; a condition very far from the realistic Diesel injection operation conditions.

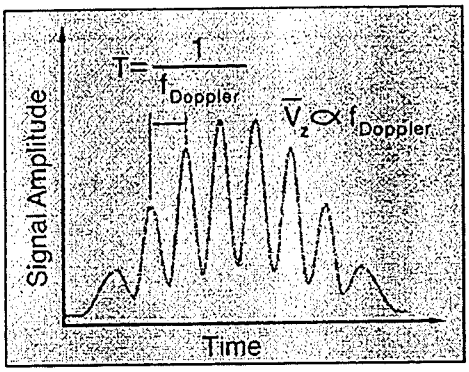

Figure 16: Doppler signal.

The real possibilities of this apparatus have been tested checking the reliability of results in a different reliable way.

The diameter distribution seems to be independent from the time of acquisition during the injection.

Particles velocities have been used to confirm size results. Their distribution follows the one theoretically expected. A high velocity is present at the start of injection that gradually decreases with time when there is no more kinetic energy coming from the following particles.

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