Visualization and Measurements of Sub-Millisecond Transient Spray Dynamics Applicable to Direct Injection Gasoline Engine*
(Part 2: PDA Measurements and Analysis of Instantaneous Spray Patterns)

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A high-pressure swirl type spray has been experimentally analyzed by using a phase Doppler anemometer (PDA). The experiment was performed with an injection pressure of 5 MPa and an injection frequency of about 46 Hz. The PDA data was obtained in a two-dimensional plane and arranged with the injection phase angle. The arranged data of mean velocity, Sauter mean diameter, and droplet number density were visualized by using commercial software. In this paper, the data were compared with the results of visualization. It is indicated by the experiment that the large velocity and large size droplets initiated from the injector with small spray angle at the beginning of the valve opening duration. This stage was called core jet. In the next stage called quasi umbrella spray, the spray developed with large spray angle. After closing the valve, the spray remains increasing its velocity and diameter. This was caused by the "post injection". Using PDA, the detailed feature of the spray can be discussed with high temporal resolution.

**Key Words**: Gasoline Direct Injection, Phase-Doppler Anemometer, Transient Dynamics, Instantaneous Spray Patterns

1. Introduction

In Part 1 of the present paper series the results of High-Speed Video Camera visualization for swirling spray applying to gasoline direct injection (GDI) have been presented and discussed. The key point dealt with sub-millisecond dynamics. By using high temporal resolution has, it is possible to observe the development of spray in axial and radial direction, and finally to analyze spray tip penetration and its velocity and a post injection effect as well. All of the results obtained with high-speed video camera and Argon-Ion Laser Sheet Imaging of fuel particles were analyzed with respect to measurement timing of 24.7 μs that allowed an indication of important details of vastly developing transient spray formation. In order to get an advanced development of GDI concept concerning swirling spray formation, it is necessary to obtain detailed knowledge of instantaneous dynamic characteristics of the flows, up- and downstream from the injector.

The purpose of the second stage of the present study is to evaluate the instantaneous pattern series of the spray flow with a phase Doppler anemometer (PDA). Because GDI systems need a short interval between injection and ignition, it means the system needs very short injection duration. The quality of fuel atomization becomes very important, and for the improvement of spray characteristics it is necessary to obtain detailed instantaneous information with high temporal resolution. On the other hand, to validate the new theory suggested recently for the spray flow, instantaneous distributions of velocity, particle size and particle number density must be measured and

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spatially vectored. A number of novel experimental techniques are suggested to fulfill this issue for mono-fluid and multi-fluid spray flows. The results of the present study will demonstrate that high temporally resolved PDA-measurements may be regarded as a competitive tool compared to those available to deal with the problem of instantaneous spatial pattern series of the mono-fuel spray flow.

In the experiments, the same injector with a swirl nozzle and the same fuel \( n \)-heptane were used. Injection frequency was kept constant at 46 Hz, and injection duration was set separately at 1, 2 and 4 ms. Special computing codes were developed to build up a 3D data-incorporated matrix, and to use a graphic Tecplot-based software to reconstruct instantaneous patterns of the spray flow. The temporal resolution of PDA with an encoder was equal to 27.8 \( \mu \)s, so that it was close to that of the high-speed video camera which was used in the previous work. Then, more detailed mechanisms can be discussed with the results from both PDA and high-speed video camera.

The PDA measurement technique is described in section 2. Measurement results and analysis of mean and instantaneous values characterizing the spray flow dynamics are discussed in section 3. And the conclusions are discussed in the last section 4.

**List of symbols**

- \( D_{50} \): Sauter mean diameter
- \( f_{data} \): average data rate
- \( N_{bin} \): fixed number of encoded bins per injection period
- \( N_{proba} \): instantaneous probable number of particles
- \( N_{c} \): measurement samples number
- \( r \): radial position referred from axis of injector
- \( T \): cyclic injection period
- \( T_{run} \): run or measurement time
- \( U_{ax} \): instantaneous axial velocity
- \( x \): spatial coordinate
- \( y \): spatial coordinate
- \( z \): axial position referred down the injector nozzle
- \( a \): angular phase within cyclic period
- \( CJ \): core jet fraction of present swirl spray flow
- \( QU \): quasi-umbrella fraction of present swirl spray flow

2. PDA-Measurement and Treatment Routine

Phase Doppler Anemometer (PDA) with a counter type signal processor model PDP–3100, which is based on the Aerometrics PDPA series, was used for the measurements. The sketch of actual experimental setup employed in the PDA measurements is shown in Fig. 1. This setup consists of three parts that are (i) low/high pressure pump system for the fuel injection, (ii) PDA-based facilities and (iii) a series of supplementary units to control the operating regime of the measurements. An alternative fuel of \( n \)-heptane was used in the experiments. Its main physical properties with respect to PDA measurements are indicated in Table 1. The measurements were carried out at a constant room temperature and a normal atmospheric ambient pressure.

The same injection system as used in the previous work was used in the present experiment, namely consisting of a pressure-pumping supplement incorporating a fuel tank and low and high-pressure pumps with the maximum limit of 7.0 MPa. A high-pressure gasoline injector developed by Unisia Jecs Co. connected to the high-pressure pump through flexible pipe, was vertically adjusted on a test stand, that allowed the traverse of the injector in vertical and lateral directions. The center of the nozzle exit was set to the origin, and the center line of axis and the perpendicular axis were set to the \( z \)– and \( r \)-axes, respectively.

The PDA optical configuration was set at an angle of 30° off-axis. All the parameters for the configuration are shown in Table 2. The data rate was varied from 5 to 18 kHz in spite of the measuring position of the spray. The lowest rate was observed at the edge of spray 25 to 35 mm away from the injector nozzle where the number density of fuel droplets significantly decreases as the results will
show.

The results of the visualization in the last paper(1) show that the spray structured consists of a Core Jet (CJ) and a Quasi-Umbrella (QU) spray as sketched in Fig. 2(a). Based on the results, a plan for 2D planar measurement of spray flow field in axial and radial directions was considered as the following.

The radial measuring points around the z-axis with 10 mm were placed in increments of 1 mm. Measurements of the rest radial area were placed in increments of 4 mm, until the measuring position reached the edge of induced spray where data rate was drastically decreased. The axial measurement grid was every 1 mm within 5 mm of injector nozzle. From 5 to 55 mm away from the nozzle, a traversing grid was arranged at 5 mm. And in the measurement range of 55 to 95 mm away from the nozzle it was expanded to 20 mm. These measuring points are also shown in Fig. 2(a).

At each measurement point, 3 000 samples were collected by PDA including the injection phase angle, which was obtained by encoder with a resolution of 720 bins/cycle. The PDA raw data was arranged with the measuring position and phase angle. Mean velocity, Sauter mean diameter and droplet number density of spray were calculated from the raw data. Then, the results were visualized at each injection phase angle by using commercial software, Tecplot-7 released by Amtec Engineering Inc.

The number of validated samples $N_v$ and the runtime $T_{run}$ at each specified spray flow point were obtained from PDA-measurement. The ratio of $N_v/T_{run}$ represents an average data rate $f_{data}$. The product of the data rate $f_{data}$ and the injection period $T$ which is a constant of 21.7 ms in all the present experiments, is the total average number of the droplets within an injection period. Dividing the encoded number of bins $N_{bin}$, which is presently 720 bins/cycle, one can get the probable number of the droplets

<table>
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<tr>
<th>Laser wavelength</th>
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<tr>
<td>Laser beam diameter (1/6)</td>
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<tr>
<td>Focal length of transmitting lens</td>
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<td>Beam separation</td>
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<td>Intersection beam waist</td>
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<td>Fringe spacing</td>
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<td>Maximum velocity</td>
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<td>Off-axis receiving angle</td>
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<td>Theoretical droplet size spans (min)</td>
<td>1.9 $\mu$m</td>
</tr>
<tr>
<td>Theoretical droplet size spans (max)</td>
<td>276.1 $\mu$m</td>
</tr>
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</table>

Fig. 2 Mean velocity and Sauter mean diameter in the spray $p=5$ MPa, $r=1.0$, 2.0 and 4.0 ms

$N_{proc} = f_{data} \cdot T_{run}/N_{bin}$. In other words, that is a statistical probability of number of droplets counted within an injection period at each encoding time phase.
After sorting the raw data, an actual droplet number \( N_{\text{part}} \) with regards to the injection phases was obtained and the number was normalized as \( N_{\text{part}}/N_{\text{prop}} \). That allows a comparison between the data measured with a different data rate at different points, and an analysis of the spatial and temporal distributions of spray characteristics. The processed PDA data was employable to be compared with those obtained as instantaneous spray pattern series by visualization discussed in Part 1\(^{11}\).

3. Results and Discussion

3.1 Droplets velocity and size

The sketch of the developed spray pattern, droplet mean axial velocity (\( U_{ax} \)) and Sauter mean diameter (\( D_{25} \)) and the correlation of \( U_{ax}-D_{25} \) on the \( z \)-axis are plotted in Figs. 2(a)-(c). For the further explanation, the spray flow was represented by three transient spatial zones, referred to as “A”, “B” and “C” in the Fig. 2. In the Fig. 2(c), the blank diagonal line directed from “A” to “C” indicates a general behavior of the correlation between \( U_{ax} \) and \( D_{25} \). From the axial distributions of the mean velocity and the Sauter mean diameter, it can be seen that the dispersed fluid jet is the main component of the spray in the first zone “A” where \( z<5 \) mm. Either of the distributions have a peak in zone “A” related with a breakup of the liquid jet which can be seen clearly in Fig. 2(b). In this transient space, the penetration path lines have non-symmetric distribution and the maximum mean velocity is observed at a very thin layer about 1 mm at conical edge with an angle of 45 degree from the centerline. The radial distributions of mean velocity and Sauter mean diameter in zone “A” for \( z=1, 2, 3 \) and 4 mm are shown in Fig. 3. From this figure, “A” zone has high velocity and small size droplets.

Fig. 3 Radial distribution of mean axial velocity and Sauter mean diameter \( p=5 \) MPa, \( r=4.0 \) ms for cross-sections at \( z=1, 2, 3 \) and 4 mm

Fig. 4 Radial distributions of mean velocity and normalized mean velocity at \( z=25, 50, 75 \) and 95 mm

Coming back to Fig. 2, within zone “B” where \( z > 5 \text{ mm} \), the spray becomes fine with fuel droplet size of 20 \( \mu \text{m} \) irrespective of injection duration. In the downstream where \( z > 25 \), a fully developed homogeneous spray appears. Figure 4 illustrates radial distributions of mean and normalized mean velocity for axial cross-sections \( z = 25, 50, 75 \) and 95 mm at the injection durations \( t = 1, 2 \) and 4 ms respectively. Velocity pattern at the central part of the spray is well governed by the Gaussian profile. The behavior of spray flow in the outer area where \( r/R_0 \) is over 1, is dependent on the axial position. Velocity distributions for positions \( z = 75 \) and 95 mm are close to the Gaussian profile when \( t = 1 \) and 2 ms. At longer injection duration, \( t = 4 \text{ ms} \), these profiles indicate negative velocity due to the vortex at the radial spray edge.

Intensity of the vortex is dependent on the injection duration. Profiles at \( z = 25 \) and 50 mm indicate an acceleration in the outer area that is strong in the cross-section \( z = 25 \text{ mm} \) irrespective to injection duration. As shown in Fig. 2(b) and (c), Sauter mean diameter in zone “C” is ranged from 17 to 23 \( \mu \text{m} \).

### 3.2 Instantaneous characteristics of the spray flow

The time series of velocity \( (U_{ax}) \), the Sauter mean diameter \( (D_{Ss}) \) and the normalized particle number \( (N_{part}/N_{pros}) \) were processed for each measurement position. Examples of such series measured at \( r = 5 \text{ mm} \) and \( z = 5 \text{ mm} \) are illustrated in Fig. 5. The axis of angular phase \( \beta \) in Fig. 5 was calculated as \( \alpha = 2\pi t/T \), where \( T = 21.7 \text{ ms} \) is one cyclic period time and \( t \) is the time phase. The injection started at \( \alpha = 75^\circ \). After the start of injection, the velocity and Sauter mean diameter present oscillations with a maximum peak settled at a time phase delay for 1 ms on injection period in this particular case. However after the stop of the injection a number of the points in velocity and normalized particle number series and the peaks in Sauter mean diameter series indicates a post injection spraying.

To view the spray flow dynamics within a whole period, time series of instantaneous velocity \( (U_{ax}) \), droplet size \( (D_{Ss}) \) and droplet number density \( (N_{part}/N_{pros}) \) are plotted in Fig. 6 with respect to two cross-sections at \( z = 5 \) and 10 mm. The angular phase is represented through rotation of radial actual position \( r = \sqrt{x^2 + y^2} \), where \( (x, y) \) point is positioned in the \( x-y \) grid [mm]. In present plots of Fig. 6 the angular phase \( \alpha = 0^\circ \) corresponds to the vertically settled line. Quarter rotation sector, for instance the duration from vertical line to lateral line, represents a quarter of stroke-period while \( \alpha \) varied from 0 to 90 degree. The variation of color along radial lines indicates the distributions of \( U_{ax}, D_{Ss} \) and \( N_{part}/N_{pros} \).

Black ground indicates an absence of injected droplets.

The plots of \( U_{ax} \) and \( D_{Ss} \) show a radial line from about \((0, 0)\) to \((-2, 10)\), after an active injection the post-transient spraying takes place. There are planar co-axis cross-sections of spray flow specified at the different time phases.

For an illustration of the spray dynamics, time series of velocity \( (U_{ax}) \), Sauter mean diameter \( (D_{Ss}) \) and normalized particle number \( (N_{part}/N_{pros}) \) are sampled in Fig. 7. These results were obtained with an injection duration of 1 ms and injection period of 21.7 ms. Four time phases were selected to plot dynamic series, from a start-phase of injection, \( t = 4.521 \text{ ms} \) (\( \alpha = 75.0^\circ \)), to final active injection phase, \( t = 5.877 \text{ ms} \) (\( \alpha = 97.5^\circ \)).

Velocity time series \( (U_{ax}) \) indicates that at starting

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**Fig. 5** Series of instantaneous axial velocity \( U_{ax} \), Sauter mean diameter \( D_{Ss} \) and normalized particle number \( N_{part}/N_{pros} \) at \( z = 5 \text{ mm} \) and \( r = 5 \text{ mm} \).
Injection where $\alpha=75.0^\circ$, the fluid core jet (CJ) goes down very fast. At the next angular phase where $\alpha=82.7^\circ$, jet breakup at 5 mm of axial position and form of two spray fraction CJ and QU. After a full development of the spray structure where $\alpha=90.0^\circ$, CJ and QU fractions are separated.

Actual injection time is longer than an injection duration of 1 ms dealt with angular phase interval $\Delta \alpha=16.6^\circ$. At the phase $\alpha=97.5^\circ$, the spray flow continues to propagate down but in a middle axial range of 30 to 60 mm, the spray has an intensive mixing structure because of vortex.

Instantaneous planar pattern series of $D_{\text{32}}$ shows that at $z>40$ mm numerous regions with droplets size less than 15 $\mu$m always exist in the spray flow. This is due to ambient atmospheric pressure and temperature employed in the present study. At the phase $\alpha=97.5^\circ$, near the injector, Sauter mean diameter is large varied from 50 $\mu$m in the core to 20 $\mu$m on the crown. From the second series plot where $\alpha=82.5^\circ$, it can be seen the initial development of two CJ and QU spray substructures are indicated by two separated small regions at the nozzle. After their separation at $\alpha=90.0^\circ$, large size droplets moved down to crosssection $z=40$ mm while QU fraction becomes thicker. At the last phase where $\alpha=97.5^\circ$, a vortex of the spray flow indicates large-size droplets regions due to slipping of fuel droplets in the vortex space.

For the combustion process following after the spray formation, it is also important to get exact temporal information about instantaneous spatial distributions of fuel droplets size and their number density. In a firing operation the flame is propagated in space according to the fuel mass gradient. The information on the particle number density can be considered as the product component to compute mass flux probability.

In the present study, the normalized particle number ($N_{\text{norm}}/N_{\text{prop}}$) is analyzed below. From the Fig. 7, the droplet density in spray is quite stratified. Three specific areas apply to a high concentration. Namely, near nozzle area (NNA), conical edge (CE) of the QU fraction ($r=22$ mm, $z=-25$ mm) and vortex edge (VE) located between two points positioned at ($r=54$ mm, $z=-95$ mm) and ($r=46$ mm, $z=-55$ mm). High-pressure and high-temperature ambient conditions, presented in a real combustion process, suppress the effect of high droplet density in VE-area as well as change droplet size and number densities in NNA-area and CE-area.

At the initial phase of fuel injection $\alpha=75.0^\circ$, the region near the nozzle exit has a high droplet number density. Afterwards, at the second phase $\alpha=82.5^\circ$, high number density area has detached the nozzle exit. This fact results from the PDA technique, because the fluid jet area provides low data rate. The
phase, $\alpha=90.0^\circ$, illustrates the distribution of droplet number in both CJ and QU substructures. At the end of actual injection, $\alpha=97.5^\circ$, a high number density region at the nozzle exit can be observed. In meantime the droplet into spray are mainly concentrated in QU conical edge and fuel mass flux comes from QU to CJ.

Contour maps of the Tecplot 7 graphic software allows us to get detailed qualitative information about the flow structure. In order to figure out the magnitudes of spray flow values in details one needs to create maps regarding a certain flow configuration. This procedure has been done for the phase $\alpha=90.0^\circ$ degree when the spray flow structure is fully developed. On the left hand side of Fig.8 instantaneous planar patterns of velocity ($U_{ax}$), particle size ($D_{ja}$) and normalized particle number ($N_{part}/N_{prob}$) demonstrate distributions of selected values into space. To show radial distributions of the values, on the right hand side of Fig.8, the same values are plotted in a graph form as a family of the five cross-section series with respect to axial position $z=2$, 5, 20, 45 and 55 mm.

Within the space near the nozzle where $z<2$ mm, jet breakup is validated due to velocity and droplet size series. Velocity ($U_{ax}$) at $r=0$ and 1 mm are about 50 m/s lower than that of $r=2$ mm where velocity magnitude is suddenly increased to 75 m/s. Sudden velocity increase is also observed in the results at $z=5$ mm. At $r=0$ and 1 mm, the velocity is zero because of detachment of CJ and QU seen in CJ-QU separation area on the left hand side. At $r=2$ mm a sudden velocity increase can be clearly seen.

Seen from series of $z=20, 45$ and 55, the spatial
Fig. 8 Instantaneous pattern and plot series of axial velocity $U_{ax}$, Sauter mean diameter $D_{32}$ and normalized particle number $N_{par}/N_{prob}$ for time phase 5.425 ms (angular phase 90.0 degree)

Oscillation of velocity in core zone where $r<10\ mm$ indicates vortex structure into spray flow. It is well validated in the previous study$^{(1)}$ of the spray structure by visualization.

The behavior of droplet size ($D_{32}$) near nozzle shows that large-size droplets are splitting along axial propagation where $z<5\ mm$. However, where the vortex is very intense at $z=20\ mm$, the droplets slipping causes increasing droplet size where $r=10\ mm$. From $r=20\ mm$, the $D_{32}$ series at $z=45$ and 55 mm is oscillating in the range of 0 to 20 $\mu m$.

The right-hand plot of normalized droplet number
\(\frac{N_{\text{part}}}{N_{\text{prot}}}\) indicates droplets number density varies in wide range of three magnitude orders. The density is high near the nozzle as expected. Intensive vortex also provides high density for the series at \(z=20\) mm. However, at \(z>20\) mm, the number density becomes low, and the two magnitude orders differ with respect to the highest density level. That is the reason for a poor contrast image since visualization of the cross-axis laser sheet plain is down 20 mm. The last two series at \(z=45\) and \(55\) mm, indicate high density at the vortex edge, \(r>40\) mm where droplets come back with negative velocity field. Its magnitude matches the maximum of those that observed at \(z=20\) mm.

4. Conclusions

Spray flow initiated from the high-pressure swirl injector is examined using the phase Doppler Anemometer in 2D planar frame. Experimental data are processed to reconstructed time-series of instantaneous spray patterns. Based on the results discussed above we consider the conclusions as:

1. PDA technique can be effectively incorporated with advanced computing facilities to easily get information on instantaneous fuel spray flow. The processed data are available to obtain accurate quantitative spatial and temporal characteristics of velocity, size and number density of the fuel droplets needed for optimization of the combustion process.

2. The time-series of dynamic values allow detailed analysis of the spray flow transitions. At the phases corresponded to the start and end of active injection, the instantaneous spray dynamics in CJ and evolution of CJ and QU are evaluated. After the active injection, the post-injection effect takes place in the flow.

Velocity series can indicate instantaneous breakup position. Instantaneous pattern of Sauter mean diameter shows that downstream 40 mm the homogeneous spray consists of small particles with the size less than 15 \(\mu\)m. Droplet number density changes within three orders of its magnitudes.

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