Fluid dynamics investigation of fuel spray for SIDI engines by Particle Image Velocimetry

M. Auriemma°, G. Caputo°, G. Valentino°, J. Zarinchang°°

° Istituto Motori, CNR, Italy
°° University of Shiraz, Iran

In this paper, results of an experimental investigation on the interaction of fuel spray, for spark-ignition direct injection (SIDI) engines, with air motion are presented. Experiments were carried out, by planar imaging and Particle Image Velocimetry (PIV) techniques, to provide information about the spray structure evolution and instantaneous velocity distribution of air motion and fuel droplets at different operative conditions.
The experimental set-up included an engine head and a prototype cylinder with optical accesses suitable to stabilize conditions of tumble flow representative of SIDI engines. The intake flow rate was supplied, under steady state conditions, by a blower and the fuel was sprayed by a common rail injection system equipped with a swirled type injector. Tests were taken at the injection pressure of *10 MPa*, a pressure drop between the intake manifold and cylinder of $350\ mm\ H_2O$, and two valve lifts: $h_v=5$ and *9 mm*.
Results of the planar imaging technique of the spray evolution depicted, at the first stage of injection, a fuel jet with a compact structure and an axial penetration mainly controlled by the fuel momentum. At later time, during the main spray growth to the typical hollow cone structure, the fuel jet provided a smaller cone angle compared to that obtained under flow quiescent conditions. In the last part of injection, because of the tumble motion, the fuel spray was distorted and disintegrated with the formation of large clusters of droplets that were transferred in a wide region within the cylinder.
PIV results showed a droplets velocity distribution with a profile that supports the liquid column-like typical of the pre-spray penetration. When the fuel jet reached the steady cone angle, the droplets instantaneous velocity distribution depicted an intense momentum exchange with the tumble airflow that becomes, in the final stage of injection, the controlling parameter for the jet break-up and the dispersion of droplets within the cylinder.

1. Introduction

During the last years, automotive industries have introduced to the market spark ignition engines equipped by direct injection technology (SIDI). The first gasoline direct injection car introduced to European market was produced by Mitsubishi followed by Renault, PSA and recently by Alfa Romeo. The attraction for SIDI engines, due to their improved fuel economy and reduced exhaust emissions, is related to the prospect to fulfill the stringent regulations on pollutant formation that will come into force by 2008. One of the key elements for SIDI engines development is the design of the combustion system to improve the mixture formation process in terms of fuel spray atomization and its interaction with the air motion within the cylinder. In fact, the momentum exchange between fuel spray and air motion affects the combustion efficiency, pollutant formation and fuel consumption that are the targets to accomplish the success of SIDI engines. To achieve these objectives, common rail injection systems with swirled type injectors have been preferred because they provide

an appropriate fuel spray penetration associated with an acceptable atomization for different pressure conditions [1,2,3].
A lot of research laboratories have focused their activities on fuel spray atomization in terms of velocity and size of fuel droplets in order to optimize atomization, dispersion and penetration of fuel droplets at different injection pressures [4,5,6,7]. The current literature also provides an extensive data base on swirled type injectors, illustrating the fuel spray structure under ambient temperature and different ambient pressure conditions [8,9,10] but, up to now, inadequate analysis has been made to comprehend the influence of air motion on the fuel spray evolution inside cylinder engines.
In this paper, results of an experimental investigation on air-fuel mixture formation within a SIDI engine are presented. Tests taken by injecting fuel within a steady tumble flow, generated by the intake system of a prototype SIDI engine, have allowed to follow the fuel spray structure evolution and estimate the instantaneous velocity distribution of air flow and fuel droplets at different operative conditions.

2. Experimental set up and test procedure

The aim of this work was the analysis of the structure and instantaneous velocity distribution of fuel spray injected in the tumble air-flow. Considering the complexity of the problem, a prototype engine, composed by an engine head and a cylinder suitable to stabilize conditions of tumble flow close to those of real engines, was developed [6].
Figure 1 shows a sketch of the system that was used for the experiments. It includes an engine head, 4-valve per cylinder, a prototype cylinder with optical accesses for a laser sheet input and collection of reflected light at 90°. A blower provided the intake flow rate under steady state conditions. As the tumble motion depends on the intake manifold geometry and interaction of air with the cylinder wall and the piston head, the cylinder was blocked at the bottom with a flat plate to a depth equal to the stroke of the engine, and provided on the lateral surface with two cylindrical ducts, used as outflow ports. The engine head was equipped with a swirled type injector with a nominal cone angle of 50° and a nozzle diameter of 0.55 mm. The injector was sited between the two intake valves tilted at 25° with respect to the horizontal plane.
2-D imaging and PIV techniques were used to follow the global evolution of the spray, as function of the injection time, to estimate the jet development and the droplets velocity distribution. The illumination source consisted of two *Nd:YAG* lasers working at their second harmonic (*532nm*), connected to an optical linkage to generate a laser sheet. The light scattered from the spray was collected by a *cross-correlation CCD* camera with a resolution of *1280x1024 pixels* and a minimum straddling time of *200 ns*. The CCD camera, set at 90° with respect to the laser sheet, was connected to a frame grabber and was driven by a synchronizer, externally triggered by a pulse generator also used to drive the ECU of the injection system.
Tests were carried out setting the pressure drop between intake manifold and cylinder at *350 mm* H_2O, valve lifts at $h_v=5$ and *9 mm* corresponding to a flow rate, measured by a turbine flow meter, of *165* and *181* m^3/h, respectively. PIV tests on the air motion, without injection, were taken by supplying, within the intake manifold, TiO_2 particles with an average diameter of $0.2\ \mu m$. Planar imaging and PIV tests of fuel spray were carried out at the same operative conditions by setting the injection pressure to *10 MPa* and the injection interval at *3.0 ms*. Measurements were taken on a plane across the cylinder and injector axes with a field of view of *47 mm* in diameter.

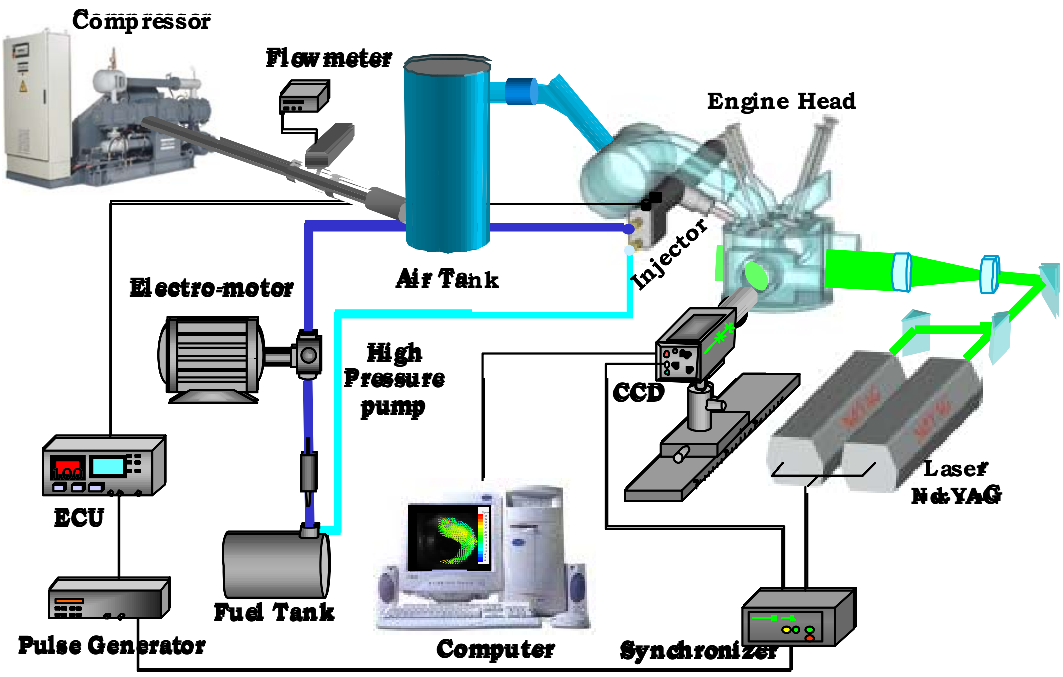

Fig. 1 Experimental set-up for visualization and PIV measurements

3. Results

This paragraph will illustrate, first, the results of the planar imaging technique that was used to capture the spray evolution at different injection time. Because of the boundary of the optical access, the field of view centered across the cylinder axis and injector nozzle, was restricted to *47 mm* in diameter. It must be pointed out that the spray sequence is relative to different shots of injection cycles.

Figure 2 shows the images sequence of the spray evolution, obtained setting the valves lift at the average value of $h_v=5.0\ mm$. The first appearing of fuel, on the left side of the field of view, was observed at 0.65 ms after the start of injection. The fuel jet depicts a compact shape, like a dense liquid column, well-known as pre-spray and made by large clusters of fuel droplets that travel mainly along the injector axis at high velocity. These clusters of droplets, because of their high momentum, may reach the piston surface becoming a source for HC emissions. Afterward, the fuel spray proceeds without any change of penetration axis and develops larger clusters of fuel droplets that exchange momentum with the air flow.

At the end of the pre-spray stage, the spray cone angle reaches its nominal value and the atomized jet penetrates as a hollow-cone structure producing a greater atomization and dispersion of fuel droplets as confirmed by the images sequence. At the injection time $t_i>1.5\ ms$ and later, images provide a cone angle with a value less than the nominal one (50°) that was also checked under quiescent conditions [8]. This result, which was confirmed at different operative conditions, engages a careful analysis on the layout of injector within the engine head to avoid impingement of fuel on the piston and cylinder wall. During the last stage of injection, because of the tumble motion, the main spray is strongly distorted after that it collapses and is dispersed in a wide region within the cylinder.

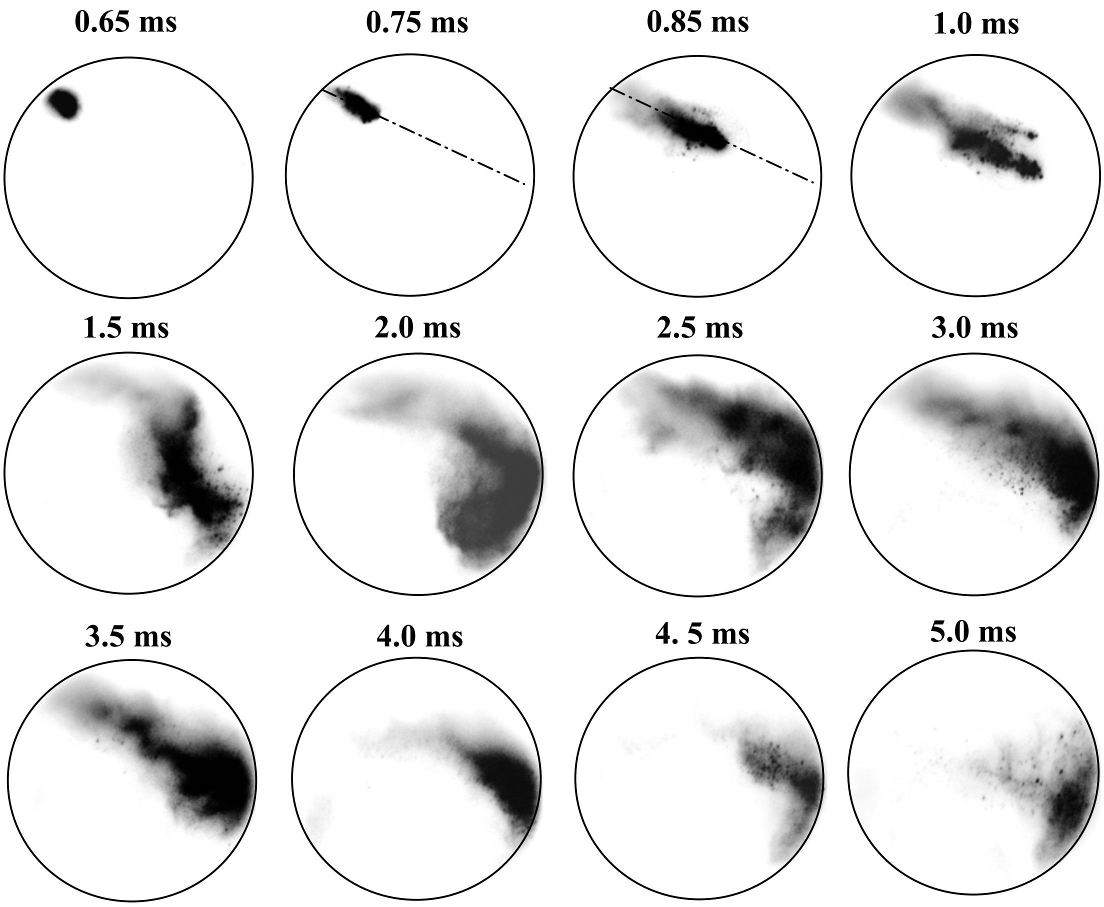

Fig. 2 Spray evolution under operative the condition of P_{inj}=*10 MPa* and h_v=*5 mm*

PIV tests were firstly performed to characterize the flow field generated by the intake system within the cylinder without fuel injection. Results of the instantaneous velocity distribution, of the flow field evolving within the cylinder, are shown in figure 3. The vector distribution depicts, at both valve lifts, a clockwise rotating structure that gives an off-axis with respect to the outflow ducts axis. This behavior is due to the direction of incoming flow from the intake manifold that pushes downwards the entrapped air. The vector distribution indicates a similar behavior at both valves lifts with a maximum velocity that reaches a value of about *60 m/s* at h_v =*5 mm* and *80 m/s* at h_v =*9 mm*.

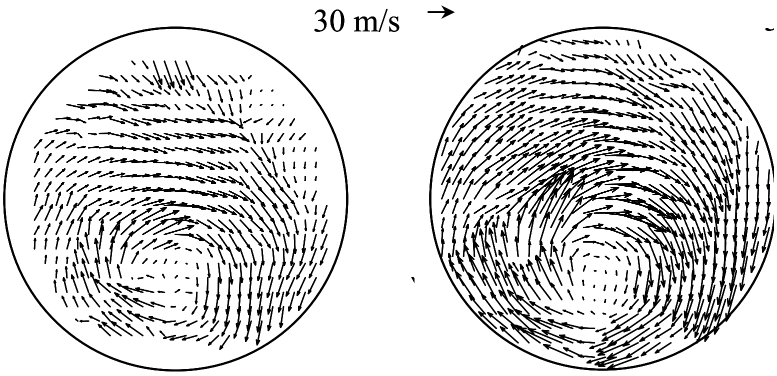

Fig. 3 Velocity vector distribution of air motion at h_v=*5mm (left plot)* and h_v=*9 mm* (*right plot*) at the pressure drop of 350 mm H_2O.

Results of PIV measurements, obtained injecting the fuel at P_{inj}=*10 MPa* for an interval of *3.0 ms,* and a valves lift of h_v=*5 mm*, are reported in figure 4. The droplets velocity distribution in the first stage of injection confirms a spray structure having a behavior liquid column like that penetrates along the injector axis at high velocity.
As already mentioned discussing the figure 2, the first appearance of spray in the field of view is characterized by a compact structure with velocities up to 70 m/s in the core of the pre-spray. In fact, the velocity distribution, shown in figure 4, makes known a pre-spray that penetrates almost undisturbed along the injector axis through the tumble motion with velocities up to 75 m/s. At 1.25 and 1.5 ms because the spray has reached the stability and has a tendency to a hollow-cone structure the maxima velocities decrease ranging up to about *65 m/s*.

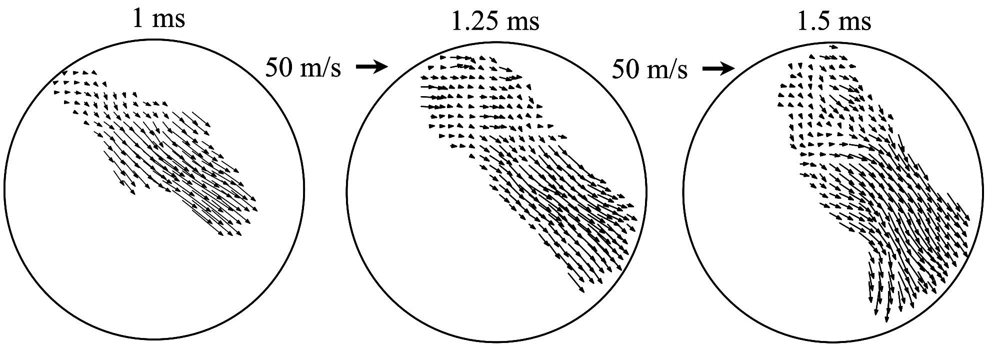

Fig. 4 Instantaneous velocity distribution of fuel droplets at h_v=*5 mm*

Next figure shows the results of the spray evolution obtained at the same injection pressure and injection interval for the valves lift set at h_v=*9 mm*. The fuel spray evolution shows some differences with respect to the previous one; in fact, the tumble motion, which has an intensity up to *30%* higher than the h_v=*5 mm* condition, produces a displacement of the spray penetration axis, figure 5. Observing the injector axis that has been plotted as dash dot style, the jet fuel travels following a path shifted to the right side of field of view. This behaviour is due to the effect of the higher intensity clockwise tumble motion that moves the incoming fuel jet and detaches fuel droplets from the main jet.
During the transition to steady state injection, at *1.5 ms* and later, the spray seems to collapse and the picture shows the transport of fuel in a wide region within the cylinder. Later during the injection, because of the hollow cone structure, the main spray has a reduced straight penetration and assumes a recirculation shape similar to the in-cylinder tumble motion. The air vortex affects strongly the fuel jet silhouette producing a reduced cone angle, compared to the nominal one that was estimated under quiescent conditions. The images sequence depicts a fuel spray confined at the right top side in the field of view with clusters of droplets which already were taken off from the main spray during the first stage of injection. Starting from *3.0 ms*, the tumble motion produces a large displacement of fuel jet towards the up-right side of the field of view, becoming the controlling parameter of mixture evolution.
Figure 6 shows the sequence of instantaneous velocity distribution by injecting fuel at *10 MPa* for *3.0 ms* under the operative condition h_v=*9 mm*. Plots depict the velocity distribution of fuel droplets characterized by coloured vectors overlapped to monochromatic ones, which denote the air motion distribution. The instantaneous velocity distribution of the air flow evolving within the cylinder, already discussed in the previous paragraph, depicts the characteristic rotating clockwise fluid dynamics structure having an off-axis with respect to the outflow ducts one. At the first stage of injection, fuel droplets show high velocity (*75*

m/s) along the spray axis. The fuel spray proceeds compact in the tumble motion until *1.25 ms* then, it is distorted and fuel droplets are dragged in rotation by air motion. At injection time greater than *2.5 ms*, the droplets velocity distribution tends to assume the same direction as air motion. At the end of injection and later, the instantaneous velocity distribution of the fuel droplets shows direction and intensity similar to those of the air motion so confirming the major role of the air flow structure in the mixture formation process.

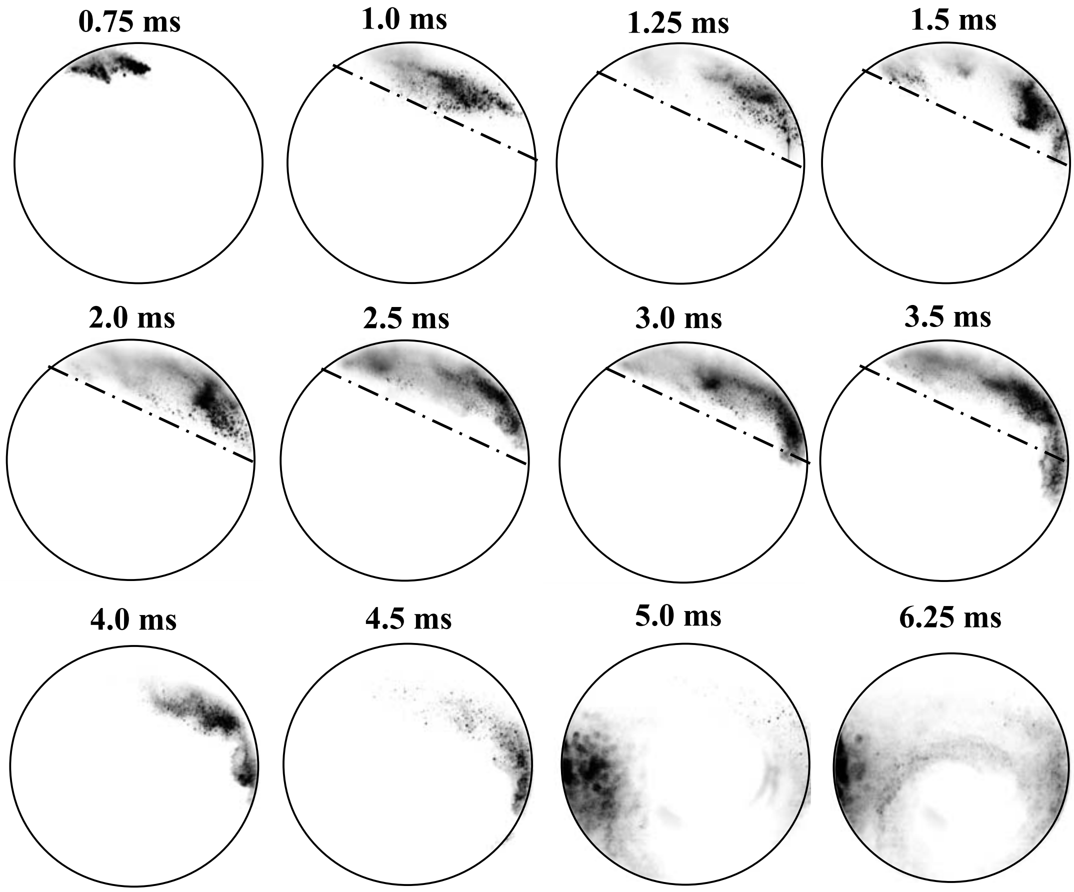

Fig. 5 Spray evolution under operative condition $P_{inj}=10\ MPa$ and $h_v=9\ mm$

4. Conclusions

The spray evolution inside the tumble motion was investigated, by the 2-D planar imaging technique, in a steady state flow rig comprising a prototype SIDI engine head and a cylinder designed to simulate the tumble flow development. The injector was located between the intake valves and tilted at *65°* with respect to the cylinder axis. Visualization and PIV measurements of spray evolution were performed at the injection pressure of *10 MPa* for two valves lifts: the average ($h_v=5.0\ mm$) and maximum ($h_v=9.0\ mm$) values.
The main results can be summarized as follows:

- Images of the spray depicted the first appearance of fuel as a dense liquid column traveling mainly alongside the injector axis not affected by the tumble motion because of its initial high axial momentum. At later injection time, during the spray development to fully developed conical hollow-cone spray, the fuel forthcoming from the main spray penetration appeared strongly distorted by the tumble motion and collapsed in the final stage of injection, transporting fuel droplets in a wide region within the cylinder. The fuel spray was distorted by the tumble motion and showed a reduced cone angle with respect to the nominal one.

- PIV results highlighted a pre-spray velocity vector distribution that confirmed the column liquid like shape with high velocity values, reached within the core of the fuel jet. After the end of injection, the droplets were dragged into rotation by the air motion and the droplets velocity vector had a tendency to assume a direction similar to that of the tumble motion.

In summary, the initial high momentum of the pre-spray controls its penetration within the air flow field whilst, in the final stage of injection and later, the tumble motion intensity may be taken as a whole responsible for the droplets distribution and mixture formation.

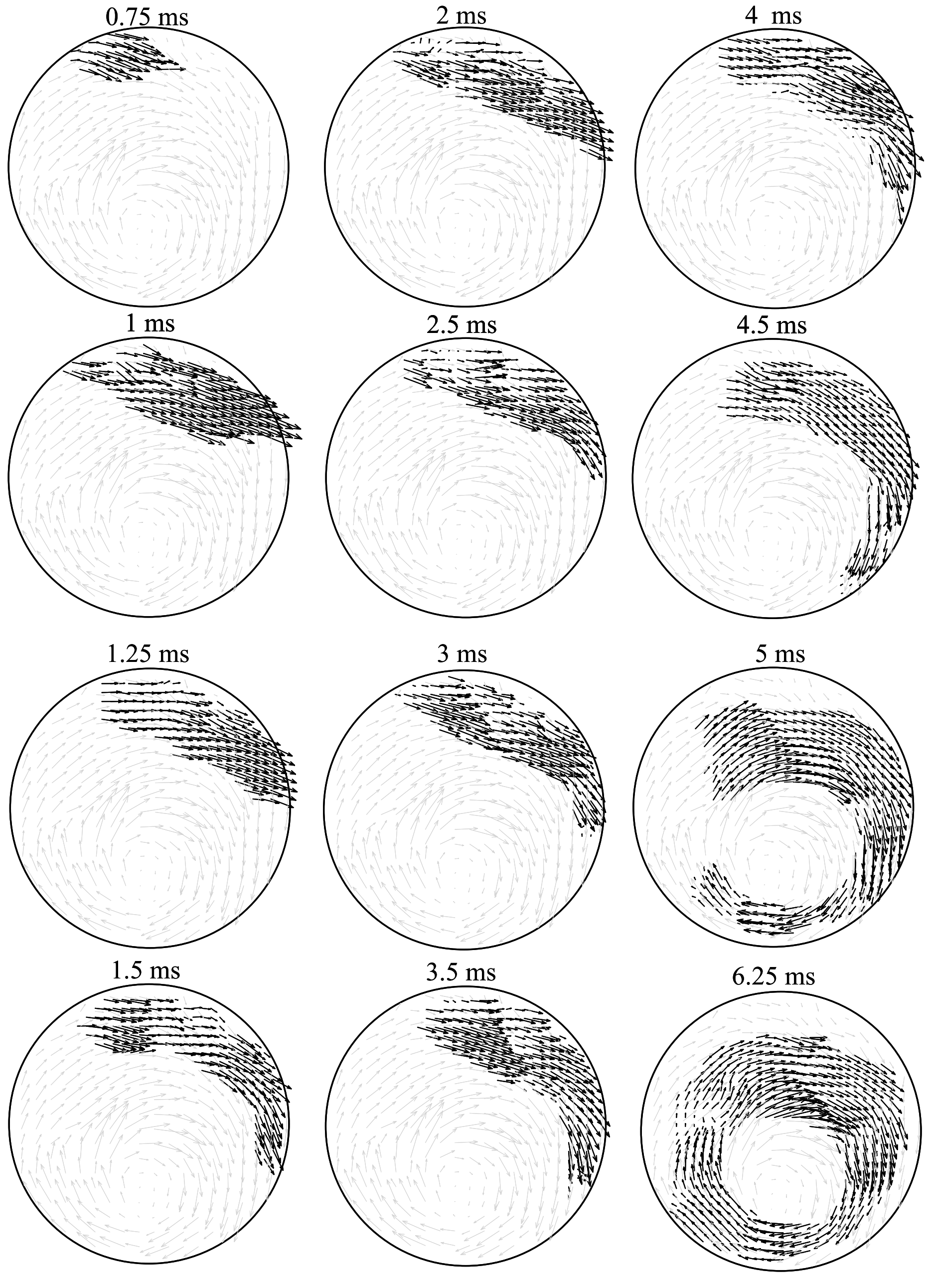

Fig. 6 Instantaneous velocity distribution of fuel droplets at $P_{inj}=10\ MPa$ and $h_v=9\ mm$.

5. Acknowledgments

The work presented in this paper was conducted within the frame of the work-package "Studio ed ottimizzazione di motori ad accensione comandata" with the financial support of MURST, "Tecnologie Eco Compatibili" – Cluster 20.
The authors would like to express thanks to Mr. Alfredo Mazzei for the significant contribution in the design and assembly of mechanical parts as well the assistance during the experiments and Dr. Giuseppe Saragò, who got the degree in Mechanical Engineering at the University of Naples "Federico II", for setting up the PIV experiments.

6. References

[1] W. Hentschel, Optical Diagnostics for Combustion Process Development of Direct-Injection Gasoline Engines, Proceedings of the Combustion Institute, Volume 28, 2000/pp.1119-1135.

[2] M. Pontoppidan, M. Gaviani, G. Bella, V. Rocco, Improvement of GDI injector Optimization Tools for Enhanced SI Engine Combustion Chamber Layout, SAE paper 980498

[3] E. Karaiskos, C. Arcoumanis, T. Hale, Flow and Spray Investigation in Direct Injection Gasoline Engines, SAE paper 2002-01-0832.

[4] Allocca L., Valentino G.:, Droplets Size and Velocity Distributions of a Transient Hollow-Cone Spray for GDI Engines, Part. Part. Sys. Charact. 18 (2001) 2632-270, WILEY-VCH Verlag GmbH.

[5] Miok Joh, K.Y. Huh, Joon-Ho Yoo, Ming-Chia Lai, Numerical Prediction and Validation of Fuel Spray Behavior in a Gasoline Direct-Injection Engine, SAE paper 2001-01-3668.

[6] Auriemma M., Corcione F. E., Diana S., Police G., Valentino G., Investigation of the Intake Flow in a DISI Engine by a New Prototype Steady State Test Rig, 5th International Conference, ICE 2001, September 23-27, 2001, Capri

[7] K. Kawajiri, T. Yonezawa, H. Ohuchi, M. Sumida, H. Katashiba, Study of Interaction Between Spray and Air Motion, and Spray Wall Impingement, SAE paper 2002-01-0836.

[8] Auriemma, M., Caputo, G., Corcione, F.E., Valentino, G., Analysis of a Fuel Spray for DISI Engines and its Interaction with the Tumble Flow, XXIV Annual Task Leaders Meeting IEA, Throndheim, Norway, June 23-26, 2002.

[9] Hoffman, J.A., Eberhardt, E. Martin, J.K., Comparison Between Air-Assisted and Single-Fluid Pressure Atomizers for Direct-Injection SI Engines Via Spatial and Temporal Mass Flux Measurements, SAE Paper 970630, 1997.

[10] Zhao, F.Q., Yoo, J.H., Liu, Y., Lai, M.C., Spray Dynamics of High Pressure Fuel Injectors for DI Gasoline Engines, SAE Paper 961925, 1996.