

Fluid Dynamics Investigation of a GDI Fuel Spray by Particle Image Velocimetry

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Abstract

In this work, result of experimental investigation on interaction of fuel spray generated by a swirled type injector, with air motion in a prototype cylinder are presented. Experiments were carried out by planar imaging and particle image velocimetry (PIV) techniques in order to provide information about the spray structure evolution and instantaneous velocity distribution of air motion and fuel spray at different operating condition. The experimental setup includes an engine head and a prototype cylinder with optical access suitable to stabilize conditions of tumble flow close to the real SIDI engines. A common rail injection system was used with a swirled type injector of a nominal cone angle 50° and a nozzle diameter 0.55 mm. A blower, under steady state condition, supplies a suitable intake flow rate to simulate that one evolves in real engines at different operating conditions. Tests were carried out by setting the pressure drop between the intake manifold and cylinder of 350 mm H₂O, valve lifts h_v = 5 and 9 mm and injection pressure 10 MPa. The measurement, have been done on a plane across the cylinder and injector axis with a field of view of 47 mm in diameter. PIV of air motion shows a fluid dynamics structure clockwise rotating with homogenous structure. The velocity profiles show 30% increasing of maximum velocity at operating condition of h_v = 9 mm with respect to h_v = 5 mm. At the first stage of injection, results of planar imaging show a fuel spray that depicts a solid structure with a penetration axis primarily controlled by the fuel momentum at later time; the fuel spray depicts a less cone angle with respect to those obtained by analyzing the spray under air flow quiescent condition. Then, because of tumble motion, the fuel spray is distorted and disintegrated. Images show the formation of large clusters of fuel which are transferred in wide region within the cylinder. At the first stage of injection, PIV results of instantaneous velocity distribution of fuel spray show a strong exchange of momentum with air motion evolving inside the cylinder. At later time, velocity profiles of fuel droplets indicate a strong correlation with tumble motion that becomes the parameter regulating breaking, dispersion and transferring liquid fuel in the periphery cylinder.

Keywords: GDI, Fluid Dynamic, Fuel Spray, PIV, Velocimetry

1. Introduction

Automotive industries have introduced spark ignition engines equipped by direct injection technology (SIDI) to the market. The first gasoline direct injections car introduced to European market was produced by Mitsubishi followed by Renault, PSA and recently by Alfa Romeo [1-3]. The attraction of SIDI engines is improved fuel economy, reduced exhaust emissions in order to satisfy the more stringent regulations on the pollutant formation. One of the key elements for SIDI engines development is the design of the combustion system and the improvement of mixture formation process in terms of fuel spray interaction with fluid dynamics structure inside engine cylinder [4-6]. In fact, the momentum exchange between fuel spray and air motion affects the combustion efficiency, pollutant formation and fuel consumption which are targets to match to affirm SIDI engines on the market [7-10].

To match these objectives, direct injection, common rail system with swirled type injector are used; they provide an appropriate fuel spray penetration associated with a fine atomization at different pressure conditions. The spray structure is influenced both on the operative conditions and nozzle geometry.

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. The current literatures on swirled type injectors show that fuel spray structure in a vessel under ambient temperature and atmospheric pressure conditions is hollow-cone type with filling of the central region at later time; and in a vessel at a higher pressure has a structure of solid - cone type. Up to now, inadequate research activities have been done to understand the influence of air motion on the fuel spray evolution inside the cylinder.

In this work, some results of experimental investigation on formation process of air-fuel mixture of a SIDI engine have been introduced. Tests were taken by injecting fuel in an engine model, composed by a head and a prototype cylinder equipped with optical accesses. The fuel spray structure generated by a common rail system with swirled type injector, has been characterize at different operative conditions using planar imaging technique. PIV technique has been used to estimate the instantaneous velocity distribution of air and fuel droplets.

2. Experimental setup and test procedure

The aim of this work is to analyze the structure and instantaneous velocity distribution of a fuel spray injected in a fluid dynamics surroundings, typical to SIDI engines .considering the complexity of the problem, an engine model was developed, constituted by an engine head and a prototype cylinder suitable to stabilize conditions of tumble flow close to those of real engines.

Fig. 1 shows the sketch of the system which used for the tests. It includes an engine head, 4 valves per cylinder, and a prototype cylinder with optical accesses for input of laser sheet and collection of reflected light. The cylinder was blocked at the bottom with a flat plate to a depth equal to the stroke of the engine, and completed at the lateral surface with two cylindrical ducts at outflow ports. The intake flow rate under steady state condition was provided by a blower. As the tumble motion depends on the intake manifold geometry and interaction of air with the cylinder wall, the system proposed here is more accurate than conventional type for study the tumble, intake manifold efficiency and the characterization of interaction with fuel spray .The engine head was equipped with a swirled type injector of a nominal cone angle 50° and a nozzle diameter 0.55 mm.

The injectors were placed between the two intakes valves tilted at 25° with respect to the horizontal plane.

PIV system consists of two laser ND: YAG working at its second harmonic (532 nm), an optical linkage to generate a laser sheet, a CCD camera type cross-correlation with resolution of 1280×1024 pixel and minimum straddling time of 200 ns. A pulse generator sends a TTL to ECU and PIV synchronization device to synchronize acquisition and injection time. The pulse separation between the two lasers has been optimized according to the measured velocity field and the size of interrogation region.

Tests were carried out by setting the pressure drop between intake manifold and cylinder of 350 mm H₂O and valve lifts h_v = 5 and 9 mm which corresponds to a flow rate of 165 and 181 m³/hr. PIV tests on the air motion were taken by seeding TiO₂ particles with average diameter of 0.2 μm on upstream of intake manifold. 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 injection time 3 ms. The measurements have been done on a plane across the cylinder and injector axis with the field of view of 47 mm in diameter.

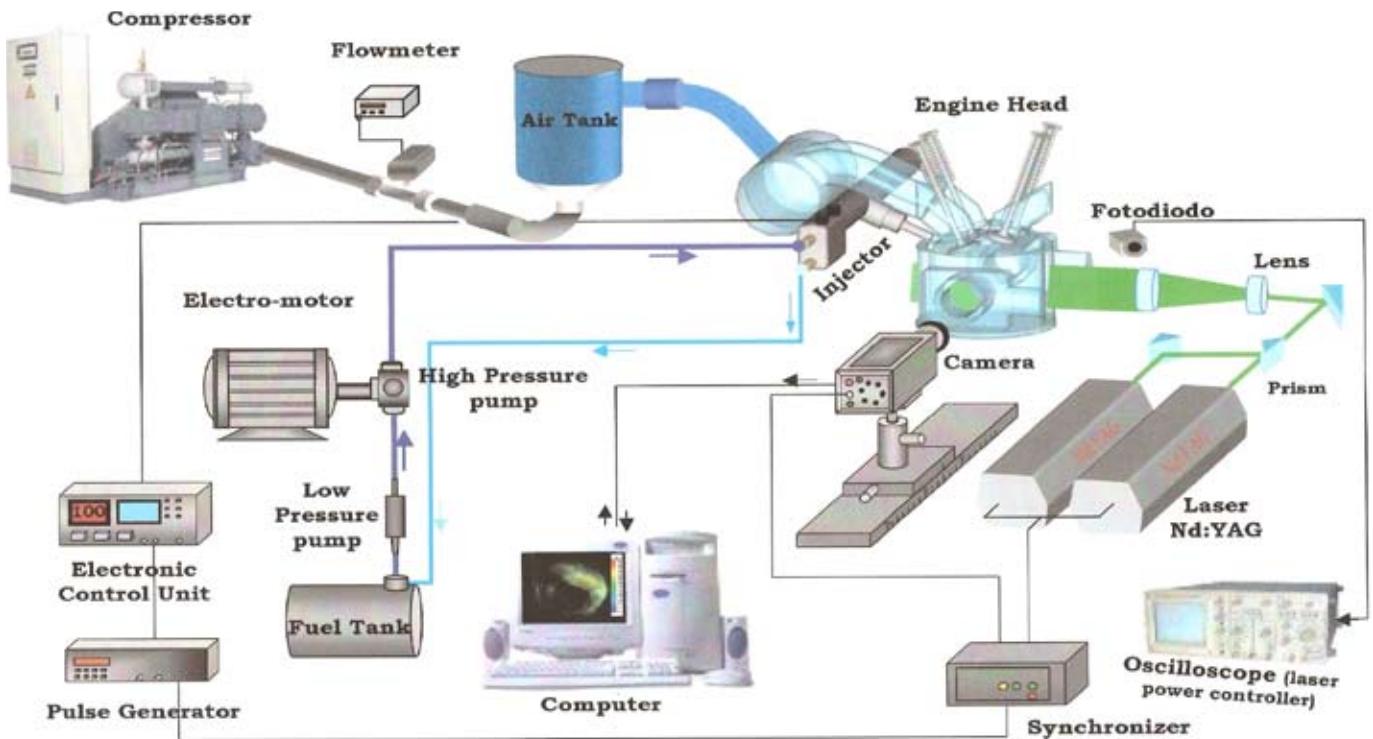


Fig. 1. Experimental setup

3. Results

Fig. 2 shows the fuel spray evolution at different injection time, under operative condition of $P_{inj}=10$ MPa and $h_v=5$ mm. At 0.65 ms, the fuel appears on the left side of the field of view showing a compact shape, which can be assimilated as a dense liquid column. Its penetration axis is almost the same as injector axis. This structure which is well-known as pre-spray, is made by large clusters of fuel droplets. It travels at high velocity and may reach the piston surface and becomes a source for HC emissions. Subsequently, the fuel advances without any change of penetration axis and develops large clusters of fuel which exchanges momentum with air flow.

At the end of pre-spray injection, the cone angle reaches its nominal value and atomized spray penetrates with hollow cone structure. Greater atomization and dispersion of fuel droplets with respect to pre-spray is confirmed by the images sequence. Because of tumble motion, the main spray is strongly distorted in a wide region within the field of view. At injection time $t_i > 1.5$ ms, the cone angle is reduced than 50° which measured in absence of air motion. This result which was confirmed at other operative conditions, involves a careful analysis on the layout injector with engine head to avoid the impingement of fuel on the piston and the cylinder wall. At the end of injection, the fuel spray collapses and transfers in wide region in cylinder.

Fig. 3 shows instantaneous velocity distribution of air flow evolving inside the cylinder. Tests were taken by PIV at same operative conditions without fuel injection. The vector distribution depicts clearly a fluid dynamics structure, rotating clockwise with an axis different from outflow ducts ones. This result is due to the direction of incoming air from intake manifold and going down to cylinder. Fig. 3 at right shows the velocity vectors extracted on segments crossing the center of tumble motion .the vectors indicates similar profiles with maximum velocity which reaches about 60 m/s.

Fig. 4 shows PIV results of fuel spray injected within the tumble motion until 1.5 ms of injection time. The velocity profiles along an orthogonal axis of penetration, confirm a spray structure type liquid column which travels at high velocity. These results confirm the consideration emerged by planar imaging. At first injection, the images depicted a compact structure of fuel spray with large clusters of droplets at high kinetic energy. The instantaneous velocity distribution indicates a spray penetration which is not affected by the tumble motion due to the high kinetic energy of fuel droplets.

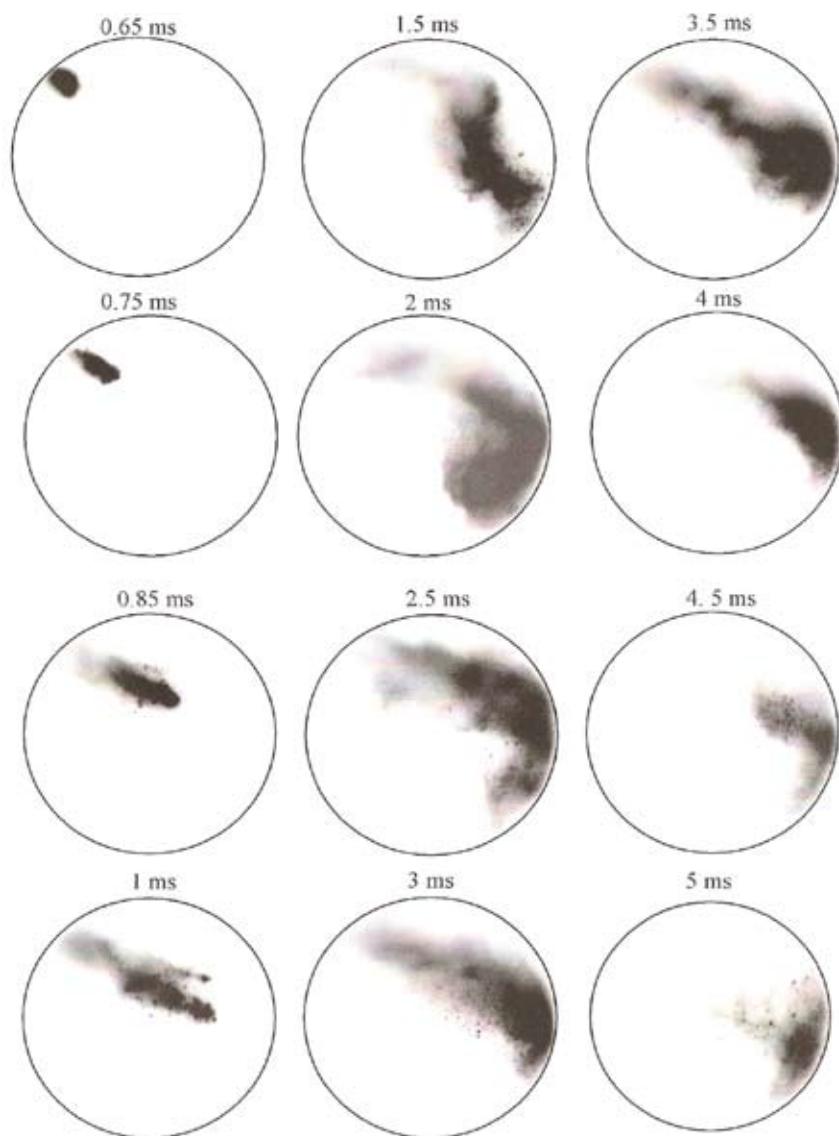


Fig. 2. Spray evolution under operative condition $P_{inj}=10$ MPa and $h_v=5$ mm

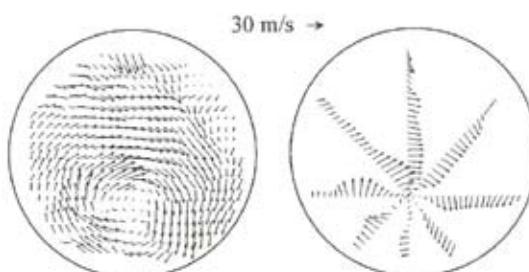


Fig. 3. PIV results of air motion at $h_v=5$ mm

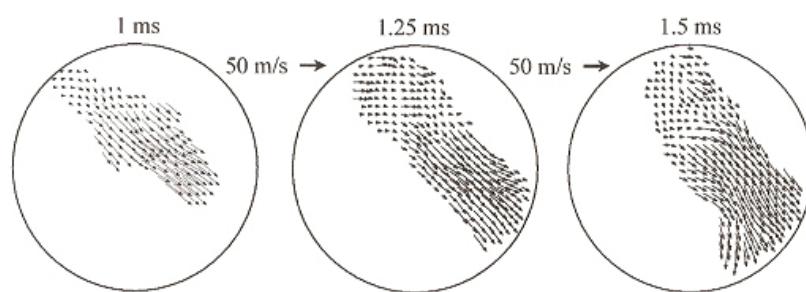


Fig. 4. Instantaneous velocity distribution of fuel droplets at $h_v=5$ mm

At operative condition $P_{inj} = 10$ MPa and $h_v = 9$ mm, the fuel spray evolution shows some substantial differences with respect to the previous condition. In this case the tumble motion, which has a higher intensity (about 30%) than condition $h_v = 5$ mm, causes a movement of penetration axis. Fig. 5 shows a spray in the top region of the field of view after 0.75 ms from the start of injection and depicts a compact shape with penetration axis different to the condition $h_v = 5$ mm. Images show the fuel spray at right top in the field of view with clusters of droplets which already were taken off from main spray at the first stage of injection. The fuel spray shows a decrease of cone angle with transfer of fuel inside the air vortex and dispersion of droplets in wide region of field of view.

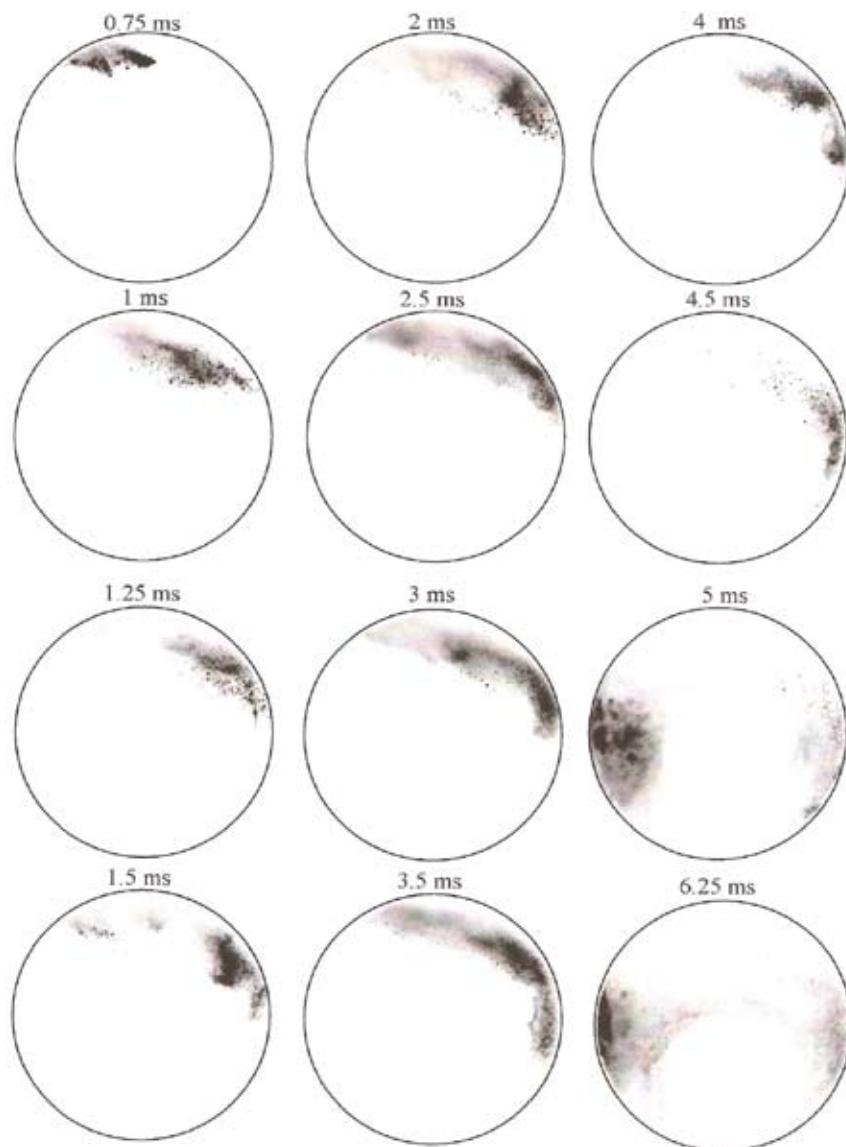


Fig.5. Spray evolution under operative condition $P_{inj} = 10$ MPa and $h_v = 9$ mm

Fig. 6 shows the results of instantaneous velocity distribution of air flow at $h_v = 9$ mm. The tumble motion has a homogeneous structure with maximum velocity about 80 m/s. Velocity profiles that extracted on segments crossing the center of tumble, depict a fluid dynamics structure which rotates clockwise with an axis different from outflow.

Fig. 7 shows the sequence of instantaneous velocity distribution by injecting fuel at $P_{inj} = 10$ MPa under operative condition $h_v = 9$ mm. Plots depict velocity distribution of fuel droplets with large vectors which placed on the top of air motion with fine vectors. At first stage of injection, fuel droplets show high velocity almost 75 m/s along the spray axis. The fuel spray advances compact tumble motion until 1.25 ms. Then it is distorted and fuel droplets are dragged in rotation by air motion. For injection time next to 2 ms, velocity distribution of fuel droplets is the same as direction and intensity of air. The tumble motion affects the breaking of fuel spray and transport of droplets. At the end of injection, instantaneous velocity distribution of fuel droplets shows a direction and intensity similar to the air motion. These velocity profiles show that the transport of fuel droplets is due to tumble motion.

4. Conclusion

This paper shows results of experimental investigation on interaction of fuel spray SIDI engines with air motion inside a photo type cylinder. Test were carried out by using planar imaging and particle image velocimetry , injecting fuel into tumble flow at operative conditions $h_v = 5$ and 9 mm , pressure drop 350 mm Hg and $P_{inj} = 10$ MPa. The main results can be summarized as follows:

- During the first injection time, the fuel spray shows a compact shape with penetration axis affected principally by the fuel momentum.
- At late injection time, the fuel spray is distorted by tumble and shows a cone angle decreased with respect to one measured in absence of air motion.
- During the final stage of injection, the fuel is broken by air motion and forms clusters of fuel which are transported in wide region in cylinder.
- The instantaneous velocity distribution of fuel confirms a compact shape with a velocity profile of liquid column.
- At the end of injection, the instantaneous velocity distribution of fuel is similar to the air, in terms of direction and intensity. The tumble motion becomes the parameter of controlling dispersion and transporting of liquid fuel in the mixture formation process.

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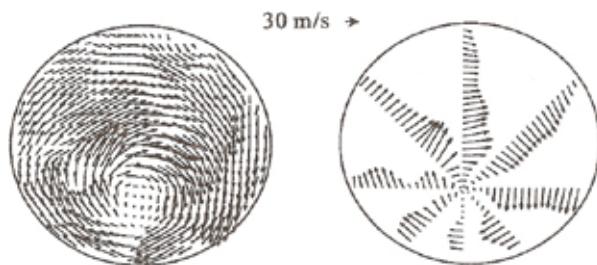


Fig.6. PIV results of air motion at $h_v = 9$ mm

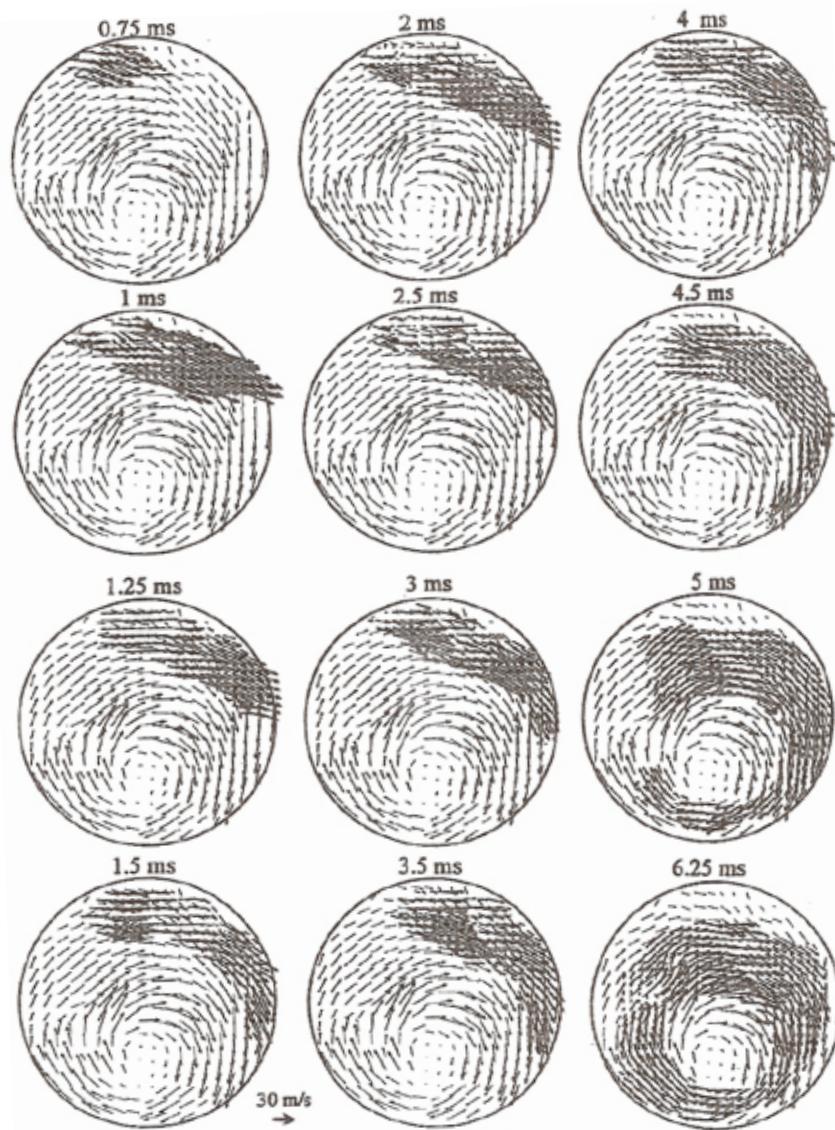


Fig.7. Instantaneous velocity distribution of fuel droplets at $P_{inj} = 10 \text{ MPa}$ and $h_v = 9 \text{ mm}$

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