PIV Measurements in a Diesel Spray from a Common Rail Injection System under Realistic Engine Conditions

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The XXVIII Annual Task Leaders Meeting IEA Implementing Agreement on Energy Conservation and Emissions Reduction in Combustion

Subtask 1.2 C

ABSTRACT

This paper shows the results of an experimental investigation, by using the Particle Image Velocimetry (PIV) technique, to measure the fuel droplets flow structures during the mixture formation process between the liquid fuel jet of a diesel spray and the swirl motion under realistic engine conditions. Mean flow fields are presented both with and without fuel injection in order to explore the behavior of fuel jet distortion at different swirl intensity.

Experiments have been taken using a common rail high pressure injection system equipped with a 5 hole, 0.13 mm diameter, 150° spray angle, micro-sac nozzle injector having a flow rate of 270 cm^3/30s@10 MPa. The fuel has been sprayed inside the combustion chamber of an optically accessible single cylinder 2-stroke Diesel engine. To reproduce fluid dynamic conditions similar to that of a real direct injection diesel engine with high swirl ratio, the engine has been equipped with a combustion chamber having a cylindrical shape, suitable to stabilize swirl conditions.

The work has been focused on the influence of the swirl intensity on the fuel spray evolution and liquid fuel droplets velocity distribution. Tests have been carried out for a multiple injection strategy (pilot, pre and main injections) typical of low load running conditions of a current light duty diesel engine. The start of injection (SOI) has been set 35° and 25° crank angle (c.a.) before the top dead center (BTDC) corresponding to two different thermodynamic conditions of the air flow and two levels of swirl intensity. PIV images have been taken lining up the laser light sheet to a plane orthogonal to the symmetry axis of the combustion chamber.

Results provide detailed information on the spatial velocity distribution of liquid fuel droplets during their interaction with the swirl motion. The velocity vector distribution shows a fuel jet, source of radial momentum, deflected from the radial path and forced to undertake a tangential motion. It has been highlighted that a higher swirl ratio reduces significantly the radial dispersion of the fuel droplets. As a result, more fuel is confined within the central region of the combustion chamber with an increase of area with richer concentration of fuel droplets and more droplet dispersions in the periphery that leads to a more dilute spray.

INTRODUCTION

In diesel combustion systems the fuel-air mixing processes play a dominant role in the evolution of the combustion and pollutant emission formations. Although, in heavy-duty diesel engines mixing is dominated by the fuel injection process, in light-duty engines the interaction of the fuel jet with the swirl flow may prevent the impact of liquid fuel on the combustion chamber wall with a reduction in smoke and HC emissions.

A lot of experimental investigations have been carried out during the last decades on the influence of the swirl ratio on the near TDC and the formation of complex vortex structure within the vertical plane of the combustion chamber that can enhance the mixing process [1,2,3,4]. The momentum of the swirl motion generated during the intake stroke, the intensity of the squish flow associated with re-entrant combustion chambers, the momentum and energy of fuel spray and the fuel impingement mutually interact making their influence on the mixture process difficult to predict. Large scale flow structures interacting with the fuel spray, which penetrates at high velocity, enhance the spray atomization and droplets dispersion decreasing the ignition delay of the premixed combustion. Additional turbulence, due to the interaction of large structures, accelerates the mixing of the unburned fuel with air promoting more rapid combustion in a heterogeneous environment under partially premixed and non pre-mixed conditions [5,6,7].

The aim of this work is to analyse the influence of the swirl ratio on the air/fuel mixing process for a late injection typical of low load running conditions of a current light duty diesel engine. The research has been carried out by an experimental investigation using the PIV technique on an experimental optically accessible 2-stroke diesel engine suitable to stabilize swirl conditions at injection time. Experiments have been taken using a common rail high pressure injection system equipped with a 5 hole, micro-sac nozzle injector for applications on light duty direct injection diesel engines.

EXPERIMENTAL SET-UP

Test bench, shown in figure 1, includes a common rail high pressure injection system able to run multiple injection strategies, an optically accessible experimental single cylinder 2-stroke Diesel engine motored by an electrical motor and a PIV apparatus. The common rail injection system has been equipped by an electro-hydraulic controlled injector with a 5 hole, 0.13 mm diameter, 150° spray angle, micro-sac nozzle having a flow rate of 270 cm^3/30 sec@10 MPa. The system is able to run up to an injection pressure of 180 MPa.

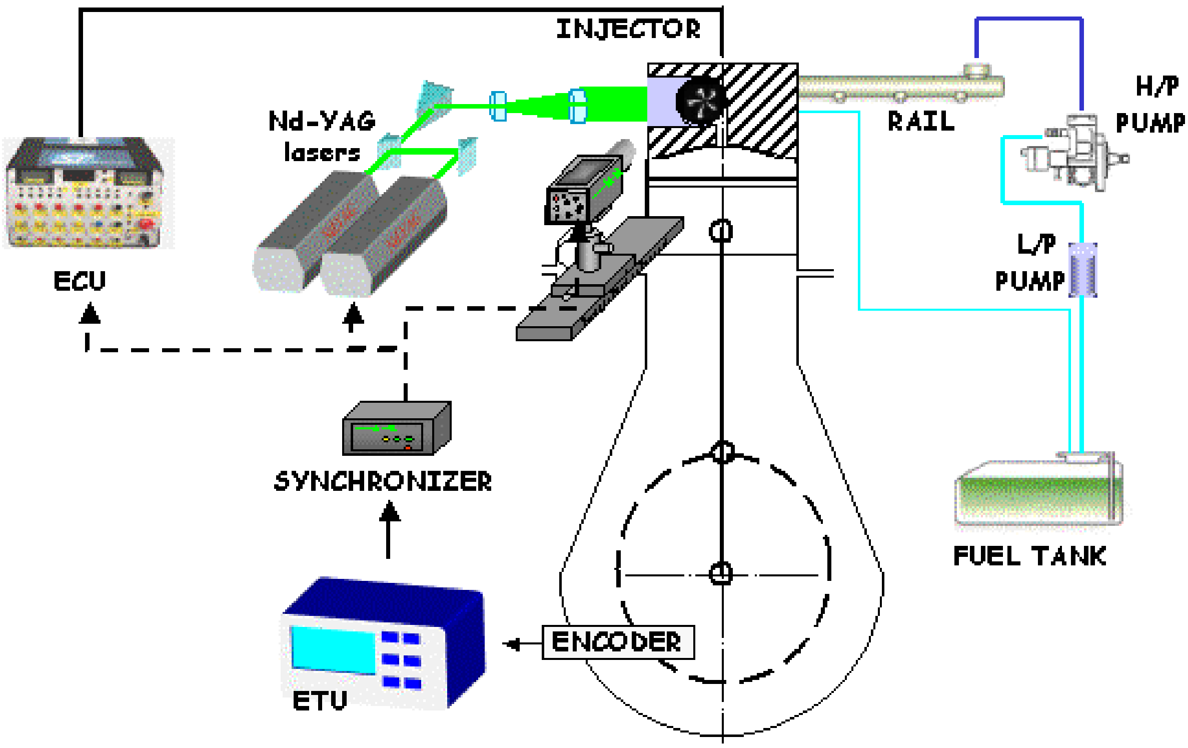

Figure 1. Test bench for PIV measurements

To reproduce fluid dynamic conditions similar to that of a real direct injection diesel engine with high swirl ratio, the experimental engine has been equipped with a combustion chamber of cylindrical shape, suitable to stabilize swirl conditions during the compression stroke. Figure 2 shows a sketch of the combustion chamber of 50 mm in diameter and 30 mm deep. The air flow, incoming from the engine cylinder, is forced within the combustion chamber by means of a tangential duct making available a swirl flow with the rotation axis coincident to the symmetry axis of the combustion chamber. The engine provides a circular optical access (diameter of 50 mm) in front of the combustion chamber, used to collect PIV images, and a rectangular one (size of 10 x 50 mm^2) at 90°, outlined on the cylindrical surface of the chamber, used for the laser sheet input. Table 1 summarizes the engine specifications [8,9]. An external coolant and lube oil system, driven by an electrical pump, is used to supply the engine oil and water at controlled temperature for warming up. The values have been set at 80 and 60°C, respectively.

ENGINE SPECIFICATIONS	
Single cylinder 2-stroke, loop-scavenged	
Bore	150 mm
Stroke	170 mm
Connecting rod	360 mm
Displacement	3000 cm^3
Combustion chamber	Swirled
Compression ratio	10.5:1
Air supply	roots blower
Intake air pressure	0.217 MPa

Table 1. Engine specifications

The PIV system is composed by two Nd:YAG lasers, a CCD camera and a synchronizer. The Nd:Yag lasers operating at their second harmonic (532 nm), are suitable to generate light pulses of 10 ns, short enough to freeze the images of the spray. The laser beam is shaped in a sheet with a thickness of 0.1mm and a height of 50mm by a series of spherical and cylindrical lenses. The light scattered from the spray is collected by a CCD camera, working in straddling mode for PIV acquisition, which provided a 1280x1024 pixels image at a resolution of 8 bits. The CCD camera, set at 90° with respect to the laser sheet, is

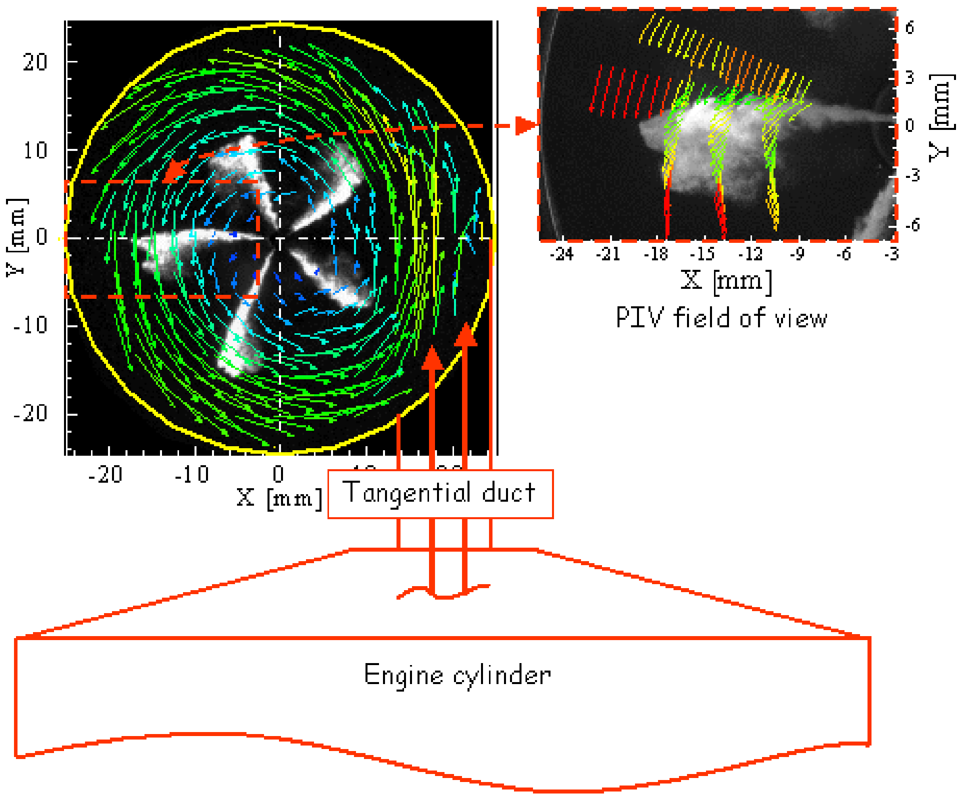

Figure 2. Sketch of the combustion chamber equipped on the experimental engine

connected to a frame grabber and is driven by a synchronizer that also fired the Nd:YAG lasers. To collect PIV images at different injection time, an engine timing unit (ETU), working by an optical encoder connected to the engine crankshaft, has been used to trigger the PIV synchronizer and the electronic control unit (ECU) of the injection system.

The work has been focused on the influence of the swirl intensity on the fuel spray evolution and liquid fuel droplets velocity distribution. Tests have been carried out for a multiple injection strategy (pilot, pre and main injections) typical of low load running conditions of a current light duty diesel engine. The injection strategy supplied a total amount of fuel of 3.31 mmg/str at an injection pressure of 28 MPa. The start of injection (SOI) has been set 35° and 25° crankshaft angle (c.a.) before the top dead center (BTDC) corresponding to two different thermo dynamic conditions of the air flow and two levels of swirl intensity. Table 2 summarize the injection and the thermo fluid dynamic conditions used for the measurements. PIV images have been taken aligning the light sheet to a plane orthogonal to the injector axis and placed at 2.6 mm from the nozzle tip. The optical set-up has provided a magnification ratio of 56 pixels/mm suitable to collect images of one of the five fuel jets (see figure 1). Data have been collected setting delay between the light pulses of 2 μs and processed applying the cross correlation method with an interrogation region by 32x32 pixels.

<table>
<tr><th colspan="8">INJECTION STRATEGY</th><th></th><th colspan="4">THERMO FLUID DYNAMIC CONDITIONS</th></tr>
<tr><td colspan="2"></td><td>Pilot</td><td>Pre</td><td>Main</td><td>dw_1 [μs]</td><td>dw_2 [μs]</td><td>Injection Pressure [MPa]</td><td></td><td></td><td>Air density [kg/m^3]</td><td>Air temperature [K]</td><td>Ω [rad/s]</td></tr>
<tr><td rowspan="2">Low Load</td><td>Solenoid exciting time [μs]</td><td>375</td><td>375</td><td>480</td><td rowspan="2">200</td><td rowspan="2">240</td><td rowspan="2">28.0</td><td rowspan="2"></td><td>SOI 25° BTDC</td><td>8.6</td><td>620</td><td>1914</td></tr>
<tr><td>Fuel injected [mg/str]</td><td>0.66</td><td>1.15</td><td>1.5</td><td>SOI 35° BTDC</td><td>5.6</td><td>531</td><td>1387</td></tr>
</table>

Table 2. Injection and thermo fluid dynamic conditions

RESULTS

The first step of work has been the characterization of the flow field evolving inside the combustion chamber without fuel injection, as illustrated in figure x. PIV measurements have been taken at 25° and 35° BTDC using as tracer a small amount of diesel fuel droplets sprayed inside the combustion chamber 60° BTDC. At the instant of PIV acquisition, some droplets has evaporated while the remaining ones are mixed with the air and are driven in rotation by the air motion evolving within the chamber. The velocity vector distribution, reported in figure 3, has been measured applying an ensemble averaging procedure over 30 instantaneous velocity vector realizations. The vector field depicts, at both crank angle positions, a counterclockwise rotating structure with the rotational axis coincident to the symmetry axis of the combustion chamber. This swirl motion is generated by means of the air flow coming from the engine cylinder through the tangential duct that connects the combustion chamber to the cylinder. The high kinetic energy of the incoming air flow produces a flow field having a high angular momentum with an outlet velocity, close to the tangential duct, of about 50 and 40 m/s at the crank angle positions of 25° and 35° BTDC, respectively. Moving away from the outlet zone, the velocity lightly decreases showing a relative maximum, at the combustion chamber periphery, of about 45 m/s and 35 m/s at 25° and 35° BTDC, respectively.

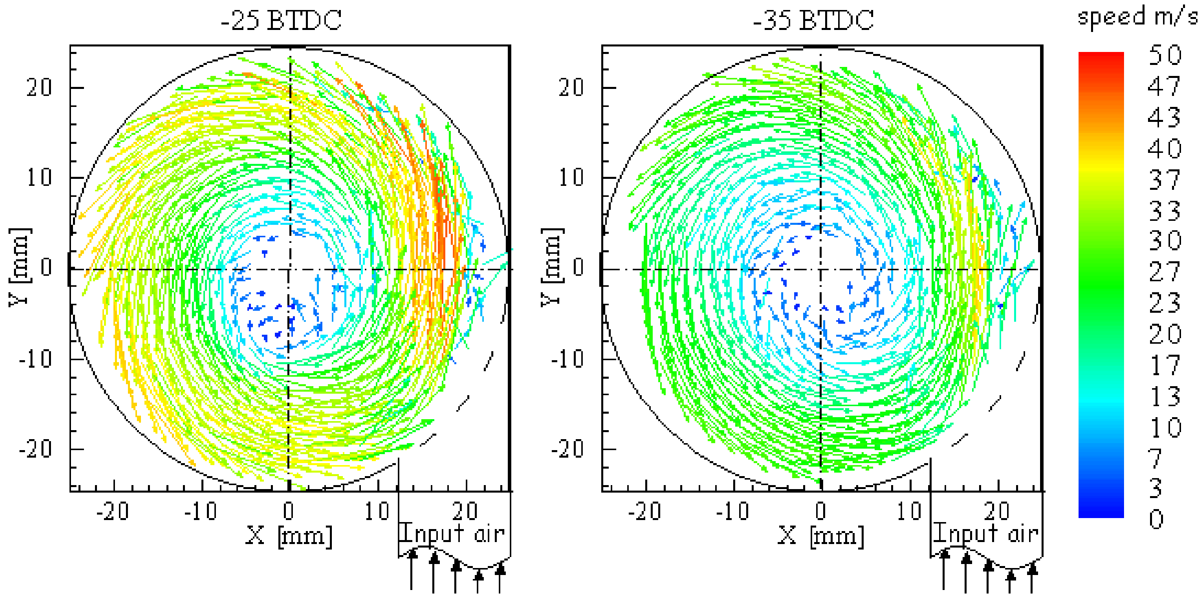

Figure 3. Velocity distribution of the air motion obtained 25° and 35° BTDC.

Considering the vector distribution of the air velocity, PIV measurements of the fuel spray have been taken, as depicted in figure 1, on the jet that evolves to the left side of the combustion chamber far from the outlet zone of the tangential duct. Before illustrating PIV results obtained on the fuel jet, an image sequence of the pilot, pre and main injection is reported in figure 4 in order to give a global view of the fuel spray evolution. Images are relative to the SOI of 20° BTDC. At early injection time, the fuel jets structure is not affected by the air motion. As matter of fact, all jets proceed undisturbed along the nozzle holes axis due to the initial high momentum of the fuel droplets that travel into the low angular momentum region of the combustion chamber [4]. The fuel jet at the bottom right, of each frame, depicts the smallest elongation because of the higher drag effect of the air flow coming from the inlet tangential duct. At 250 μs from the SOI, for each injection (pilot, pre and main), the fuel spray reaches the periphery of the combustion chamber and begins to be distorted by the air motion because of the momentum exchange between the fuel droplets, source of radial momentum, and the air flow having, on the contrary, a high angular momentum.

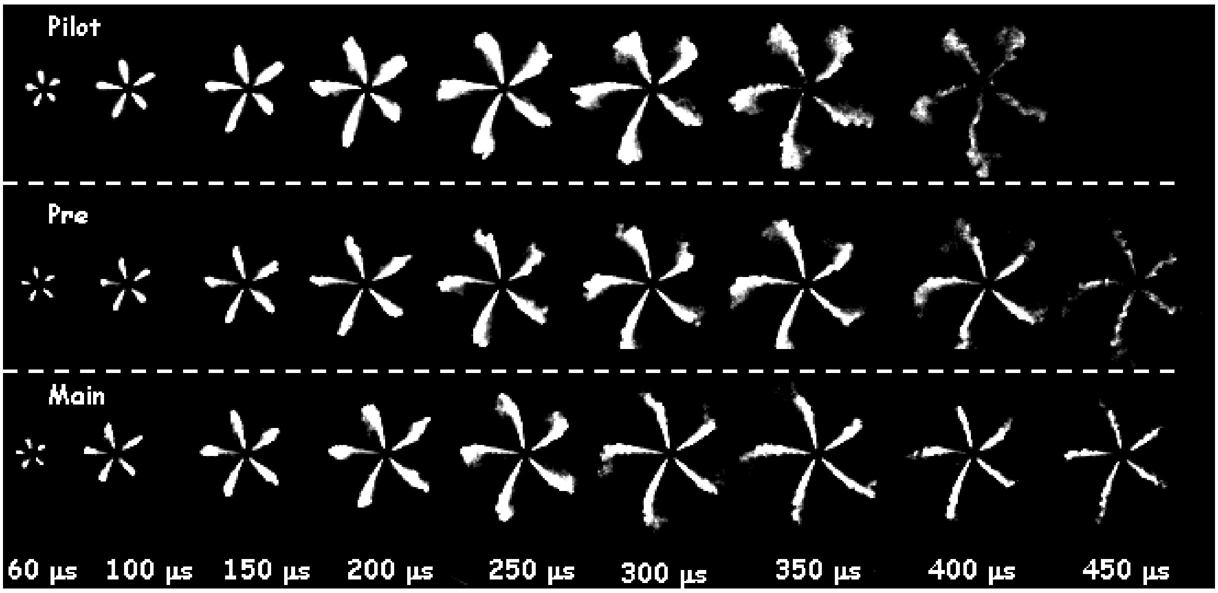

Figure 4 Image sequence of the pilot, pre and main injection for a SOI 20° BTDC.

Later, cluster of fuel droplets are detached from the main jets and dragged into rotation by the swirl flow. This behavior is less evident on the main injection spray because of the enhanced evaporation conditions.

Figure 5 shows PIV results obtained on the fuel spray setting a SOI of 35° BTDC. Plots report the ensemble averaged velocity distribution of the fuel droplets at different injection time for the pilot (top row) and the pre injection (bottom row). PIV data have been collected on the jet evolving on the left side of the combustion chamber. The vector field has been represented by a X-Y Cartesian reference system centered on the nozzle tip. The velocity distribution, estimated 310 μs from the SOI for the pilot injection (top left side of figure), shows a fuel jet deflected from the path alongside the nozzle hole axis to follow a curve trajectory because of the high angular momentum transferred to the fuel droplets from the air flow. At 377 μs from the SOI, the velocity distribution confirms the behavior of the spray showing a fuel droplets flow field that tend to assume a motion tangential to the combustion chamber wall with maximum velocity values of about 20 m/s located on the low edge of the jet. Plots on the bottom row of figure 5 report the PIV results obtained on the pre injection 315 μs and 382 μs from the start of the pre injection. Valid PIV date have been collected on a larger region with respect to that set to calculate the velocity distribution during the pilot injection. The velocity distribution confined within the fuel jet highlights a motion field related to clusters of fuel droplets that, exchanging momentum with the air flow, travel tilted with respect to the radial direction. The velocity vectors located around the spray, instead, depict a rotational flow field at high intensity connected to the fuel droplets that, delivered during the pilot injection, are still not evaporated and are dragged in rotation by the swirl flow. This droplets reach maximum velocity values of about 30 m/s on the combustion chamber periphery.

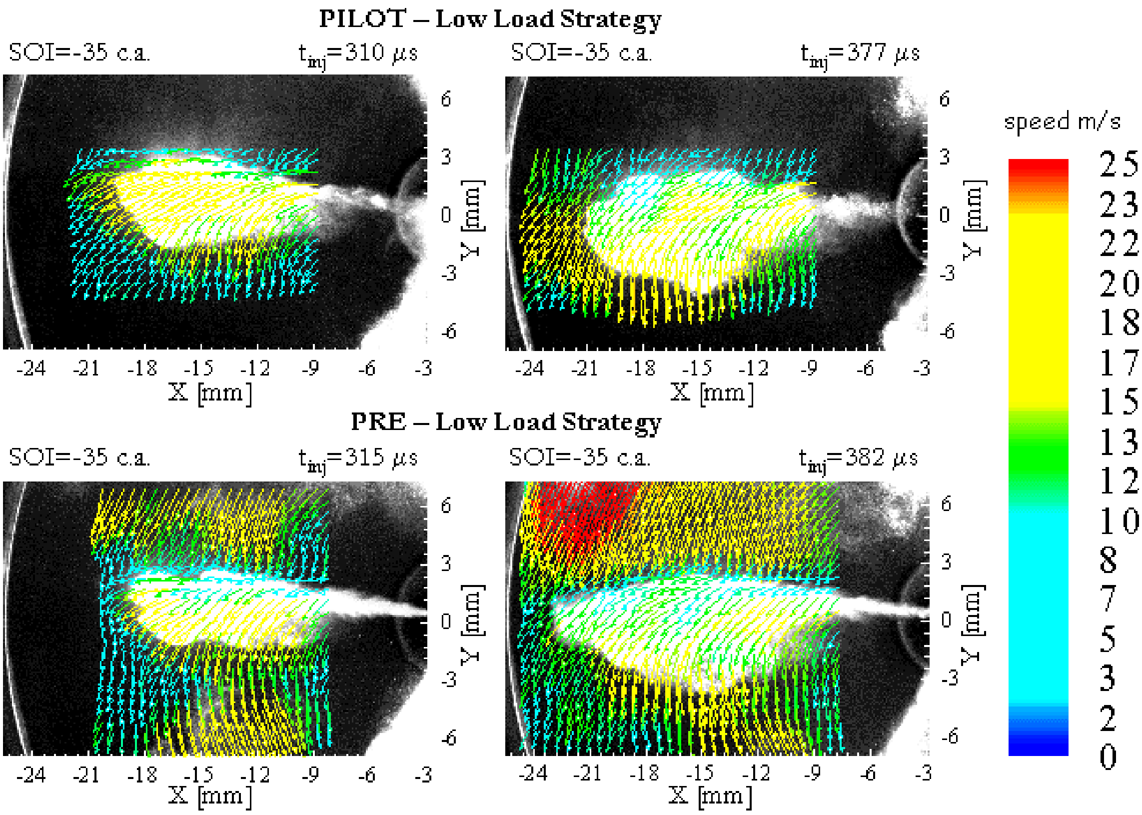

Figure 5 Fuel droplets velocity distribution on the pilot and pre injection (top side an down side, respectively) at different injection time for a SOI 35° BTDC.

Figure 6 reports the velocity distribution obtained on the pilot (top row) and pre injection (bottom row) for a SOI 25° BTDC. Results highlight that the higher swirl ratio, reduces significantly the radial dispersion of the fuel droplets. The velocity distribution, estimated 310 and 377 μs from the SOI for the pilot injection (top row of figure), shows a more distorted fuel jet with a smaller elongation because of the higher angular momentum transferred to the fuel droplets from the air flow with respect to the operative condition relative to the SOI of 35° BTDC. The fuel droplets velocity undertakes a tangential motion to the combustion chamber wall with maximum velocity values of about 25 m/s. PIV data collected at 315 and 382 μs after the start of the pre injection, bottom row of figure 6, confirm the behavior of the spray evolution showing a lower radial penetration of the fuel jet and a higher fuel droplets dispersion in a wide region of the combustion chamber. The flow field around the spray depicts a well structured rotational behavior with maximum velocity values of 35 m/s close to the chamber periphery.

As conclusive remarks, the higher swirl intensity increases the amount of fuel confined within the central region of the combustion chamber with an increase of area at richer concentration of fuel droplets and more droplets dispersion in the periphery that leads to a more dilute mixture. The swirl motion can be a useful tool to prevent the impact of liquid fuel on the combustion chamber wall with a reduction in smoke and HC emissions for late injection strategies applied to light duty diesel engines.

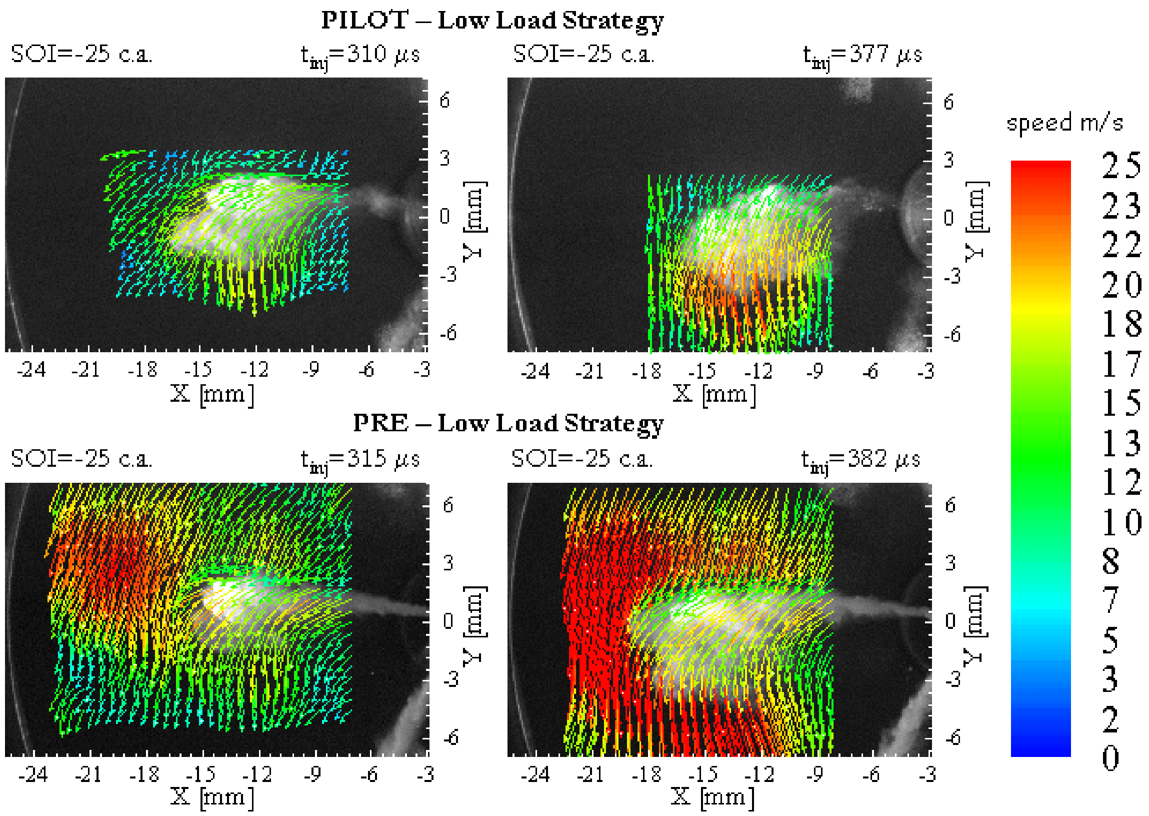

Figura 6 Fuel droplets velocity distribution on the pilot and pre injection (top side an down side, respectively) at different injection time for a SOI 25° BTDC.

CONCLUSIONS

The paper has reported the results of an experimental investigation, by using the Particle Image Velocimetry (PIV) technique, on the fuel droplets velocity during the mixture formation process between the liquid fuel jet of a diesel spray and the swirl motion under realistic engine conditions. Experiments have been taken using a common rail high pressure injection system equipped with a 5 hole, micro-sac nozzle injector for applications on light duty direct injection diesel engines with high swirl ratio. To reproduce fluid dynamic conditions similar to that of a real engine, tests have been taken on an experimental optically accessible 2-stroke diesel engine suitable to stabilize swirl conditions at injection time. The work has been focused on the influence of the swirl intensity on the liquid fuel droplets dispersion and velocity distribution. Tests have been carried out for a multiple injection strategy (pilot, pre and main injections) typical of low load running conditions of current light duty diesel engines.

The main results can be summarized as follow:

- The image sequence has highlighted two main phases of the air/fuel mixture formation process. In the first injection part, all fuel jets proceed undisturbed along the nozzle holes axis due to their initial high momentum. In the second part, the fuel spray reaches the periphery of the combustion chamber and begins to be distorted by the air motion because of the momentum exchange between the fuel droplets, source of radial momentum, and the air flow having, on the contrary, a high angular momentum.
- PIV data collected during the second step of the air/fuel mixture formation process have depicted a velocity vector distribution that shows a fuel jet deflected from the radial path and forced to undertake a tangential motion.
- Velocity vector distribution obtained at the SOI 25° BTDC highlights that the higher swirl ratio, reduces significantly the radial dispersion of the fuel droplets. As a result, more fuel is confined within the central region of the combustion chamber with richer concentration of fuel droplets and more droplets dispersion in the periphery that leads to a more dilute spray with an effect on the flow liquid aerodynamics interaction.

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