

Study of Air Entrainment of Multi-hole Diesel Injection by Particle Image Velocimetry - Effect of Neighboring Jets Interaction and Transient Behavior After End of Injection.

2010-01-0342

Published
04/12/2010

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ABSTRACT

The air entrainment of multi-hole Diesel injection is investigated by high speed Particle Image Velocimetry (PIV) using a multi hole common rail injector with an injection pressure of 100MPa. The sprays are observed in a high pressure, high temperature cell that reproduces the thermodynamic conditions which exist in the combustion chamber of a Diesel engine during injection. Typical ambient temperature of 800K and ambient density of 25kg/m³ are chosen. The air entrainment is studied with the PIV technique, giving access to the velocity fields in the surrounding air and/or in the interior of two neighboring jets. High acquisition rate of 5000 Hz, corresponding to 200 μ s between two consecutive image pairs is obtained by a high-speed camera coupled with a high-speed Nd:YLF laser. The effect of neighbouring jets interaction is studied by comparing four injectors with different numbers of holes (4, 6, 8 and 12) with similar static mass flow rate per hole. The results show that both the maximum air entrainment level and the total mass of entrained air are similar for all the injectors, and therefore are not affected by neighboring jets in the conditions studied. However the transient behavior of the air entrainment process is affected when the number of holes is high, hence when two neighboring jets are near (12 holes nozzle): the air entrainment reaches a maximum at later timings compared to the other nozzles. An analysis of the velocity fields between the two jets shows that this result is due to the air flow inertia generated when the two jets are near. The transient behaviour after the End Of Injection (EOI) is also studied using the 4-holes injector. The results show a very rapid decrease of the mean axial velocity near the nozzle after the EOI. The air entrainment becomes maximum at a

given position and this position propagates downstream towards the jet tip.

INTRODUCTION

One of the major issues the automotive industry is facing nowadays is the control of fuel consumption and pollutant emissions. Concerning direct injection Diesel engines, the major pollutant emissions are NO_x, soot and HC/CO, whose formation depends, among others, on local air/fuel ratio and thus on fuel vaporization. Siebers [1, 2] has shown that vaporization in Diesel sprays is controlled by the air entrainment into the jet. This process thus plays a prominent role in the performances of the combustion system, and has been intensively analyzed.

Especially, Ricou and Spalding [3] have shown that the rate of air entrainment (defined as the ratio between the entrained air and injected fuel mass flow rates) was inversely proportional to the diameter of the nozzle hole. A decrease of this diameter therefore enhances the combustion process by allowing to reach leaner local air/fuel ratio. This result is driving the development of Diesel engines towards the use of smaller nozzle hole diameters. However, since the fuel mass flow rate is proportional to the hole area, the number of holes has to be raised to maintain the fuel mass flow rate. As a consequence, the distance and therefore the quantity of air between two neighbouring jets is reduced. This can possibly affect the air entrainment process. Although the structure of the air flow surrounding the Diesel jets has been extensively studied [4, 5], the literature provides only few experimental results on the interactions between two neighbouring sprays. The purpose of the present work is to study these interactions.

Also, while previous research was mainly focused on the steady state behaviour of air entrainment, little information is available on the transient behaviour after end of injection. Musculus [6] has highlighted an increase of air entrainment moving downstream the spray after end of injection, which he called entrainment wave. He also proposed a model for the behaviour of the transient jet, based on the Naber and Siebers hypothesis [7] for the steady state jet. This phenomena has been studied experimentally [8] but more experiments are required to confirm the corresponding processes. The experimental results presented in this paper aim at providing a better understanding of the mixing process occurring in direct injection Diesel engines, by the study of the effects of the interaction between two neighbouring jets on the air entrainment, together with an analysis of the transient behaviour of the spray after the EOI. The analysis are based on PIV visualizations that have been carried out in a constant volume combustion vessel reproducing the in-cylinder conditions of a direct injection Diesel engine at injection.

EXPERIMENTAL APPARATUS

HIGH PRESSURE CELL

The results presented here have been performed in a high-pressure, high-temperature cell which enables the study of spray behaviour under thermodynamic conditions similar to those of a Diesel engine at a specified injection timing. The major advantage of performing measurements in an optical cell is that the gas phase conditions such as air flow, temperature and pressure are more easily controlled than in an engine, whilst providing better optical access for the application of laser diagnostic techniques. The flow in the cell is essentially that induced by the spray itself.

Further details concerning the cell and its operation can be found in previous publications [9]. The injector is mounted within the top face of the cell. Five 80 mm diameter 20mm thick sapphire windows can be mounted on the other remaining faces.

Prior to performing the experiments, the gases within the cell are heated and pressurized to reproduce typical in-engine conditions by a pre-combustion technique similar to that described in [10]. The start of injection (SOI) takes place at a specified time after pre-combustion ignition. The SOI time is determined so that injection takes place when the temperature and pressure in the cell have reached the desired values. The pre-combustion gas mixture can be computed to consume a certain quantity of the oxygen initially introduced in the cell. As a result, experiments can be performed at various oxygen concentrations. For the experiments presented in this paper, a stoichiometric mixture was introduced so that no oxygen was left after the pre-combustion, preventing auto-ignition of the jets.

INJECTION SYSTEM

Injectors

A CRI2 Bosch injector equipped with four different nozzles of 4, 6, 8 and 12 holes was used in this study. All the others characteristics of the four nozzles are identical:

- micro-sac injectors;
- $K_s = 1.5$;
- basic EDM “holes”
- holes' diameter: 110 μ m
- cone angle: 150°

The static mass flow rates of the four nozzles have been measured on an IFP injection test bench equipped with a EMI2 EFS flow rate meter. The injection pressure was set to 1000bar and the counter pressure to 20bar. Each nozzle was mounted on a different injector body, so that four couples {nozzle + injector body} have been tested on the injection test bench. Eq.1 gives an estimation of the relation between the mass flow rate (dm/dt) through an injector hole and the density (ρ), the section of the hole (S), the pressure difference (ΔP) and the flow coefficient of the hole (C_d).

$$\frac{dm}{dt} = C_d \cdot S \cdot \sqrt{2 \cdot \rho \cdot \Delta P}$$

Eq. 1

Thus, assuming that the flow coefficient is the same for all the holes of the injector, for a nozzle with N holes, the total mass flow rate can be estimated by:

$$\left(\frac{dm}{dt} \right)_{total} = K \cdot N \cdot \sqrt{\Delta P} \text{ with } K = C_d \cdot S \cdot \sqrt{2 \cdot \rho}$$

Eq. 2

For each nozzle, the coefficients K can then be determined from:

$$K = \frac{\left(\frac{dm}{dt} \right)_{total}}{N \cdot \sqrt{\Delta P}}$$

Eq. 3

This calculation has been performed with the measurements of the injection test bench. The results are presented in Figure 1. Since the density of the fuel is constant, any difference in the value of K between the four nozzles is due to a difference in the value of the product $C_d \cdot S$. The results show that this product, and thus the holes characteristics, is slightly different from one nozzle to another. However, if the 6 and 8 holes

values of K are set as references, the variation is limited to +5.7% (4 holes nozzle) and -5.5% (12 holes nozzle). These variations in flow coefficients due to different characteristics of the four nozzles will be taken into account when analyzing the results of the PIV measurements.

High-pressure line

A common-rail was mounted upstream of the injector to avoid injection pressure fluctuations. A high pressure Bosch CP1 pump was used to supply the fuel. The pressure was regulated by controlling the leakage in the common rail system (EFS system).

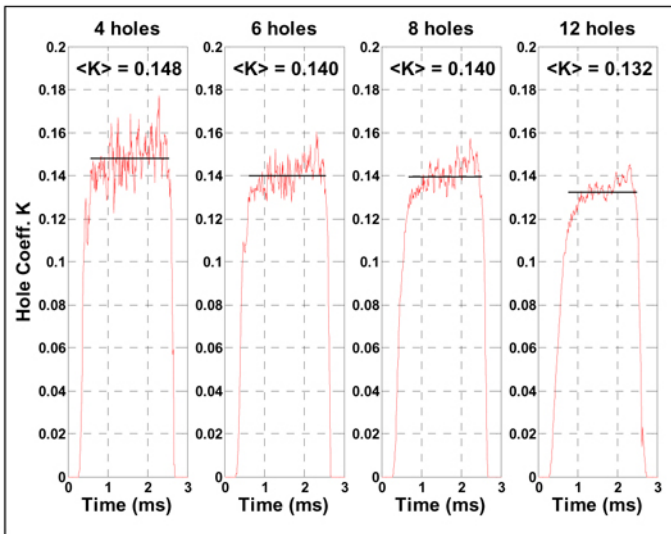


Figure 1. Estimation of the flow coefficients of the four nozzles.

SEEDING SYSTEM

The particles used for the PIV measurement are Zirconium oxide particles, mixed with a hydrophobic aerosol in order to prevent agglomeration. A high pressure seeder was used to mix the nitrogen flow and the particles [11]. Particles in suspension into air are mainly subject to inertia and aerodynamic forces. In order to verify that the particles are tracking the flow, it is necessary to ensure that aerodynamic forces are prevailing. The ratio between these two forces is determined by the Stokes number, defined as:

$$S_t = \frac{\rho_p \cdot d^2}{18 \cdot \mu_{gas} \cdot \tau_F}$$

Eq. 4

where ρ_p (kg/m³) is the density of the particles, d (m) their diameter, μ_{gas} (Pa.s) the dynamic viscosity of the ambient gas (assumed as pure N₂ since it corresponds to approximately 90% of the mass fraction after combustion) and τ_F (s) the characteristic time of the flow. For small Stokes numbers

(<1), the particles are mainly subject to aerodynamic forces, and for large ones, to inertia forces. The zirconium oxide particles have a density $\rho_p = 5,7 \cdot 10^3$ kg/m³, the dynamic viscosity of N₂ is $\mu = 3,63 \cdot 10^{-5}$ Pa.s at 800K. Finally, τ_F was determined as the time between start of injection and steady air entrainment rate, giving $\tau_F = 10^{-3}$ s in the present experiment (Figure 10). The diameter of the particles is less than 5 μm, which leads to $S_t < 1$. The particles can thus be expected to be mainly subject to the aerodynamic forces of the flow.

OPTICAL SYSTEM

Laser sheet

The optical set-up is presented in Figure 2. The laser is a Darwin Duo with two Nd:YLF laser heads at 527nm, pumped by diodes. The duration of each laser pulse is about 120ns and its energy is 3mJ at 5kHz (corresponding to a current of 20A).

The frequency of each laser head can be tuned between 0,1 and 10kHz, and was set at 5kHz for our measurements. The delay Δt between two pulses can be controlled either by an internal or by an external trigger. For this study, the external trigger has been chosen to synchronize the laser with the injector and the camera. The time between two pulses Δt has been set at 7 μs for air flow measurements outside the spray, and at 2 μs for velocities inside the spray.

The beam was formed into a laser sheet (about 1.5mm wide) using a divergent cylindrical lens of 60mm focal length, and a convergent spherical lens of 600mm focal length. In order to obtain precise measurement of air entrainment, it was necessary to precisely adjust the setup in order to obtain a laser sheet containing the axes of two neighbouring jets. The plane defined by the axes of two neighbouring sprays can be determined by three points, one of them being the injector nozzle hole. In order to obtain the two other points, a sheet of paper was placed close to the cell window, where the laser sheet enters the cell (Figure 3). Then, an injection at ambient temperature was carried out, creating two holes in the sheet of paper, each hole corresponding to the impact of one jet. These two points plus the injector's nozzle thus defined the plane containing the two axes of the sprays. The laser sheet was aligned with these three points. This operation was repeated for each of the four nozzles.

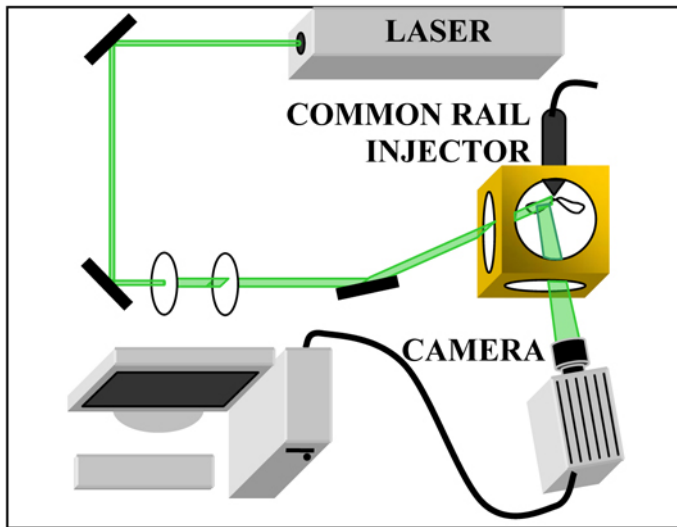


Figure 2. Experimental set-up for PIV measurements

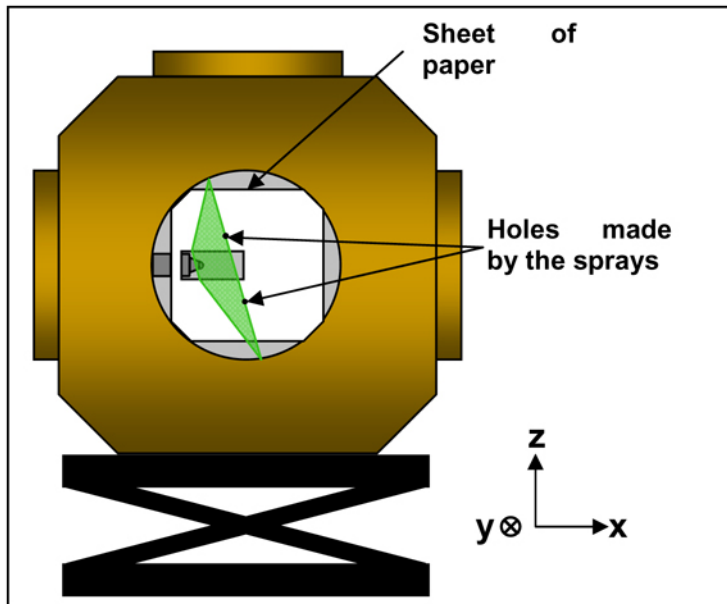


Figure 3. View of the configuration used for the alignment of the laser sheet with the axes of the sprays.
View from the laser entrance window

Signal collection

The Mie diffusion signal originating from the particles was collected by a Photron SA1 camera. Its acquisition frequency can be tuned between 50Hz and 675kHz. For this study, a 5kHz frequency was chosen for PIV, corresponding to an acquisition frequency of 10kHz for the camera as illustrated by the chronogram of Figure 4. At such a frequency, the resolution is $768 \times 768 \text{ pixels}^2$. The frames are stored in the internal memory of the camera during the acquisition and are then transferred to the PC. The camera was equipped with a Nikkor lens, of focal length 85mm f/1.4. The visualization

fields was about $40 \times 40 \text{ mm}^2$, giving an approximate ratio of $52 \mu\text{m}$ per pixel.

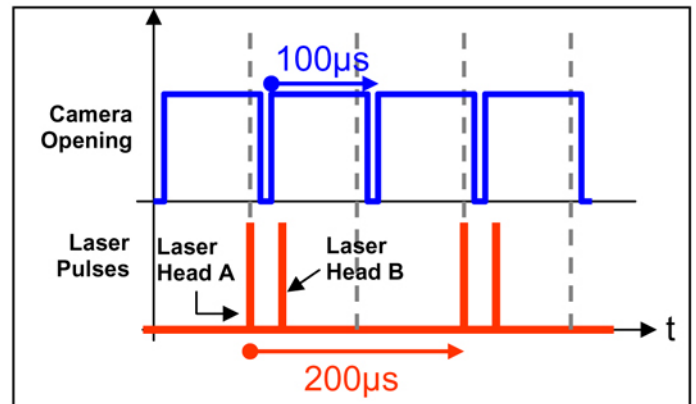


Figure 4. Chronogram of the synchronisation between the laser and the camera.

To obtain a focused image in the whole visualization field, it was necessary to align the focus plane with the laser sheet. This adjustment was performed by setting the aperture at its maximum in order to minimize the depth of field. The cell was then seeded with particles, illuminated with the laser sheet. The orientation of the camera was then adjusted until a focused image of the particles was obtained in the whole field of view, indicating that the focal plane and the visualization plane were parallel (Figure 5).

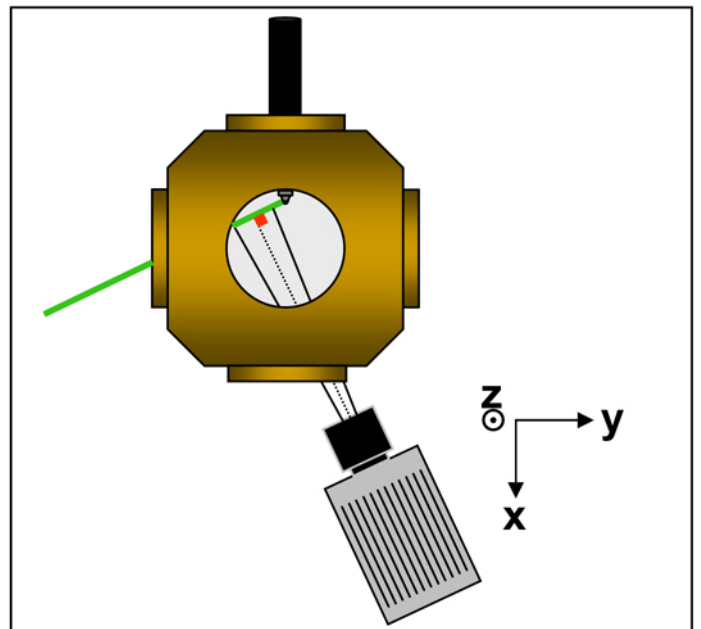


Figure 5. Relative position of the camera and the laser sheet. The camera CCD sensor is parallel to the visualization field. View from above the cell.

Once both the orientations of the laser sheet and the camera were set up and the focus adjusted, the focus was tuned once more by imaging the particles fields after a pre-combustion. This was necessary because local thermal gradients are generated during pre-combustion, affecting the air refractive index, and responsible for the presence of blurred zones in the focal plane, leading to errors in the PIV treatment. To overcome this problem, the depth of field was widened and the focus was adapted. This was performed by using a small lens aperture of $f/11$.

OPERATING CONDITIONS

Injection characteristics

For the analysis of the behaviour of air entrainment between two neighbouring jets, injections of 2 ms at a pressure of 1000 bar were carried out. For the study of the transient behaviour of the air entrainment after the EOI, an injection duration of $300\mu\text{s}$ was used, with the same injection pressure. The fuel was 99% dodecane.

Cell conditions

Cell conditions reproducing typical Diesel engine conditions at injection were chosen, with a density of 25kg/m^3 , and a pressure of 63 bar, corresponding to a temperature of 800K. A statistical study of the cell pressure at SOI shows that the injection condition are precise and repeatable (Figure 6). The oxygen concentration is null after the pre-combustion so that the Diesel spray can not burn.

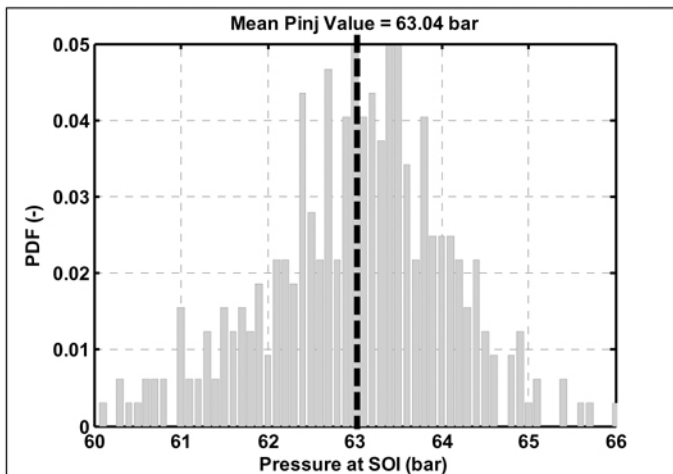


Figure 6. PDF of cell pressure at SOI and its mean value (dotted line).

MEASUREMENTS TECHNIQUES

Images acquisition

The measurement methodology consisted in realizing an injection under the cell conditions described above, and

acquiring PIV fields. 50 image pairs were obtained for each injection with the high-speed PIV (5kHz) system, each image pair being separated by $200\mu\text{s}$. The total acquisition time was thus 9.8ms. The temporal delay between two images of the same pair was set to $7\mu\text{s}$ for measuring the air flow surrounding the sprays ($2\mu\text{s}$ for the flow within the sprays). The camera, the laser and the injection were synchronized to obtain repeatable measurement timings. For each nozzle, about 50 injections were realized.

Images post-treatment

The image processing was carried out with Insight 3G. The PIV correlation windows had a surface of $64 \times 64 \text{pxls}^2$. The resulting flow fields were averaged using 50 instantaneous fields. A filter was applied to eliminate the vector with a norm higher than 10m/s for the surrounding air flow measurements, and 185m/s for the inner jets velocities measurements. An example of the surrounding air flow field obtained for the 6 holes nozzle (1 ms after the SOI) is represented in Figure 8. The vector field (black) is superimposed on the map of the vectors norm. The white zone in the centre of the sprays corresponds to the velocities that were not resolved by PIV with a $\Delta t = 7\mu\text{s}$.

Air entrainment measurements

Air entrainment is defined as the air mass flow rate entering into the fuel jets. Its determination therefore required to define the limits of the jet. Using axisymmetric hypothesis, this surface was considered to be a cone, illustrated in Figure 7, with the summit located at the centre of the injector's nozzle. To assess the influence of the value of θ on the air entrainment measurements, three different values have been used, 6.5° , 7.9° , and 9.5° , as illustrated in Figure 8 (more details concerning the influence of θ on air entrainment are available in Appendix A). These values were defined visually with the analysis of the flow patterns. Since no significant differences of cone angles θ were observed between the four nozzles, the same values were used in the calculation of air entrainment for the four nozzles. For the nozzles for which the two jets are in the visualization field (6, 8 and 12 holes nozzles), 6 values of air entrainment can be computed (3 angles and 2 jets). For the 4 holes nozzle, only one spray is visible, and therefore only 3 values of air entrainment are available (Figure 9). The total entrained air mass flow rate D_{tot} is obtained by integrating the local mass flow rate D over the whole control surface. The mass flow rate is positive when entering the spray. The control surface was divided into three zones, according to their distance to the nozzle: 2 to 3cm, 3 to 4cm, 4 to 5cm (Figure 7). Under 2cm and above 5cm, the jets are outside of the visualization fields, so that the air entrainment could not be computed.

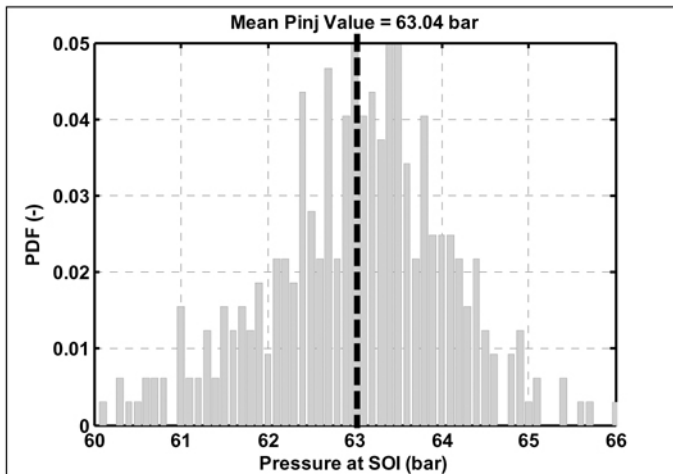


Figure 7. Definition of the integration zones for the computation of the air entrainment.

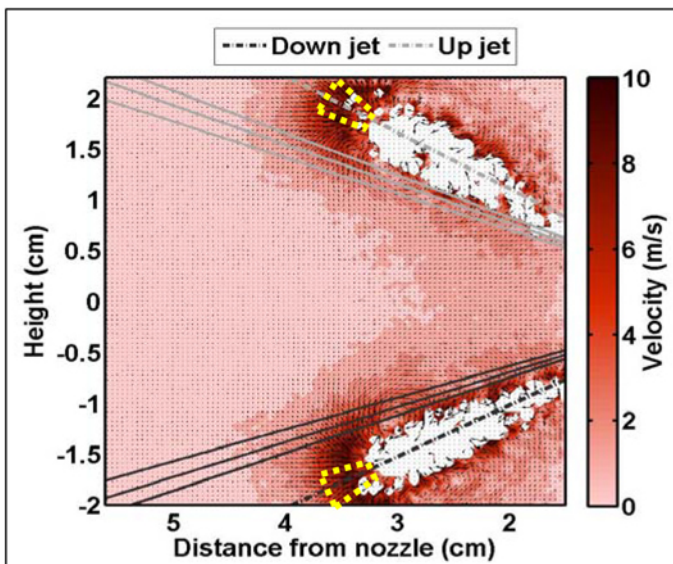


Figure 8. Instantaneous velocity field for the 6 holes nozzle (0.8ms after SOI), with the upper jet and lower jet limits corresponding to the 3 angles: 6.5°, 7.9° and 9.5°. The zones in yellow correspond to the limits used to compute the mean axial velocity of the jet tip.

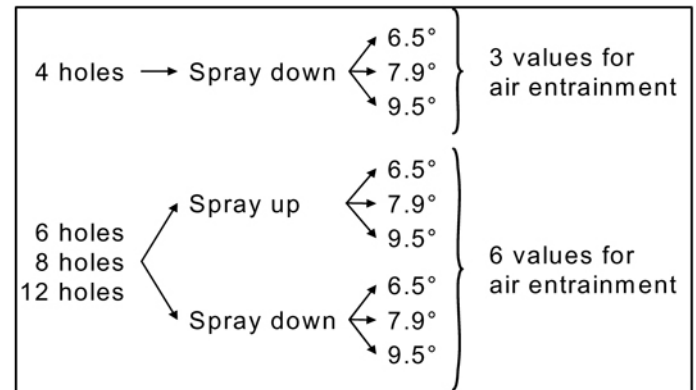


Figure 9. Summary of the air entrainment measurements available for the four nozzles.

RESULTS

INFLUENCE OF THE DISTANCE BETWEEN JETS ON AIR ENTRAINMENT

The aim of this study was to assess the influence of the distance between neighbouring jets on the air entrainment. For this purpose, a comparison of the air entrainment of the four nozzles was carried out.

Verification of the set-up

In order to compare the air entrainment of the different nozzles, it is necessary to make sure that the air entrainment calculations are comparable for all the cases. In particular it is necessary to make sure that the measurement plane (i.e. the laser sheet) is coplanar with the plane defined by the axis of the jets for which the air entrainment is measured. As explained before, the laser sheet position was precisely adjusted for this purpose using a sheet of paper. However, this adjustment was realized in cold conditions, with one sapphire window dismounted. Since temperature gradients in the cell during the pre-combustion cool down are likely to modify the laser path, and hence the laser sheet position, it was necessary to verify the alignment of this latter with the jet axis during the injection in high temperature conditions. This verification was done by measuring the jet velocities along the spray axis during the high temperature measurements. Indeed since the velocities are maximum on the spray axis, if the laser sheet is shifted away from the axis, a decrease of those velocities is expected. For the 4 hole nozzle, variations of the laser sheet position were carried out to maximize the mean axial velocities. When a maximum value was obtained, the laser sheet was considered to be aligned with the axis of the two jets. The same adjustment was used for the other nozzles. Table 1 shows the results of mean axial velocities along the sprays axis for the different nozzles. The jet tip mean axial velocity is the velocity