

Air Entrainment in Diesel-Like Gas Jet by Simultaneous Flow Velocity and Fuel Concentration Measurements, Comparison of Free and Wall Impinging Jet Configurations

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ABSTRACT

The air entrainment process of Diesel like gas jet was studied by simultaneous measurements of concentration and velocity fields. A high pressure gas jet was used to simulate Diesel injection conditions. The injection mass flow rate was similar to that of typical Diesel injection. The experiments were performed in a high pressure vessel at typical ambient gas density of Diesel engine during spray injection. The ambient gas density was varied from 25 to 30 kg/m³ and three nozzle diameters, 0.2, 0.35 and 0.5 mm were used. Both free and wall impinging jet configurations were investigated by combining Laser Induced Fluorescence (LIF) and Particle Image Velocimetry (PIV) to obtain simultaneous planar measurements of concentration and velocity. Fuel concentration fields were used to define the edges of the jet and allow an accurate determination of the air entrainment rate both in free and wall impinging configurations. The effects of ambient gas density, nozzle hole diameter and wall impingement on the air entrainment process were investigated. It was found that the presence of wall impingement results in a local increase of air entrainment, while the overall mass of air entrained in the jet is reduced. Also the effect of aerodynamic structures on the mixing process was investigated in details by local and statistical analysis to highlight the role of coherent structures on the air entrainment process.

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INTRODUCTION

Designing fuel efficient, low exhaust emission reciprocating engines requires a detailed understanding of the physical phenomena occurring in the combustion chamber. Among the various processes involved, the mixing of air and fuel is one of the most decisive since it also has consequences on combustion and pollutant formation. Therefore, an important part of the engine research aims at gaining more insights on the mechanisms involved [1,2,3], however the detailed mechanisms are still not yet completely understood, in particular that of air entrainment in Diesel jets. This is mainly due to the complexity of the processes involved, with a strong coupling between the contributing mechanisms (fuel evaporation, turbulence, small scale mixing...). As a consequence, the experimental investigation of these processes requires the simultaneous measurement of several

parameters such as flow velocities and mixing characteristics, with statistically reliable datasets. However, while laser based diagnostics techniques are widely used for such measurements [4,5,6], their application into the engine combustion chamber is limited by the harshness of the environment (high pressure and temperature, presence of liquid droplets...).

A way to bypass this difficulty is to study the air entrainment processes of a gas jet. Indeed, it was shown that the mixing rate of a gas jet is similar to that of a Diesel jet when injected into air of typical Diesel chamber density and with equivalent momentum injection rate [7]. A previous study [8] of the mixing processes of such gas jets has shown the validity of this approach. In this work the mixture structure of a gas jet was analyzed in detail showing similar mixing characteristics than a Diesel jet although significant differences in terms of injections characteristics could not be

avoided. In particular the injection pressure was significantly reduced (below 200bar). Nevertheless, operating at similar injection mass flow rate was shown to be sufficient to reproduce the mixing processes of Diesel injection. Recent numerical investigation further confirmed the validity of this approach [9]. Comparison of evaporating spray and gas jet characterized by similar injected mass and momentum flow rates were carried out and showed very similar mixing characteristics.

There are numerous advantages to this approach including that the absence of fuel droplets greatly facilitates the application of optical diagnostics and it is possible to study the mixing process at lower temperatures. Indeed chamber densities similar to that of the Diesel chambers can be obtained at a lower temperature without drawbacks associated with the presence of liquid droplets. All this facilitates optical diagnostics measurements since for instance it reduces the uncertainty associated with temperature effects on fluorescence yields for LIF applications and enables the use of liquid droplets for PIV seeding. In addition, since for most experimental apparatus reproducing high temperature conditions is time consuming, the use of lower temperature enables an increase in the number of measurements and consequently in the number of statistical samples. Finally, the comparison with numerical simulation for model validation is also easier in such simplified configuration [10].

The work presented in this paper is based on this simplified approach. A Diesel like single gas jet is studied in a high pressure cell by simultaneous LIF and PIV in order to get two-dimensional measurements of fuel concentration and velocity fields, respectively. The results are analyzed to further understand the entrainment and mixing processes.

EXPERIMENTAL SETUP

HIGH PRESSURE CELL

This work was conducted in a high temperature and high pressure cell which is comprehensively documented elsewhere [11,12]. Here only a brief introduction to the main capabilities of the cell is described. A schematic of the cell is displayed in Figure 1. The constant volume cell (1.37l) is equipped with four large sapphire windows offering large optical access (80mm) and sustaining elevated pressures. The cell was equipped with heating wires to regulate the chamber temperature up to 200°C.

For UV excitation in combustion applications, it is often convenient to employ the third (355 nm) and the fourth (266 nm) harmonic generation of an Nd:YAG laser. Quartz windows transmit both wavelengths efficiently but do not sustain high pressures as much as sapphire windows do. The drawback of using sapphire windows is the weak transmittance of the fourth harmonic wavelength making the use of the alternative wavelength at 355 nm mandatory and thus the choice of a suitable tracer difficult.

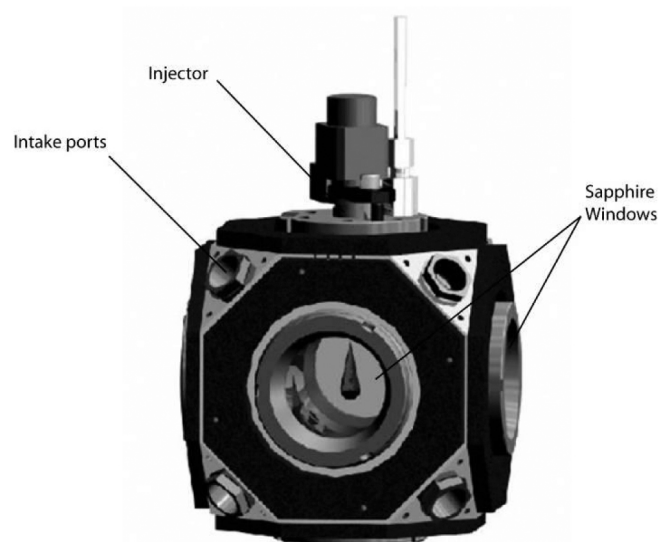


Figure 1. The high pressure and temperature chamber.

INJECTOR

A prototype gas injector, supplied by Hoerbigger and operating at pressures up to 200bar was used in the experiments. The injector was controlled with a power controller (booster), and three different nozzle diameters of 0.2, 0.35 and 0.5mm were used. The injector hosts a needle controlling the injection quantity. When the controller receives a trigger pulse, it sends a high current to quickly lift the needle and then decreases the current value in order to keep the needle fully open during injection. The delay between the trigger pulse and the start of the needle lift was 400μs. The injected gas was a mixture of 90% methane and 10% ethane. A gas compressor was used to maintain the injection pressure at 200bar during all the experiments.

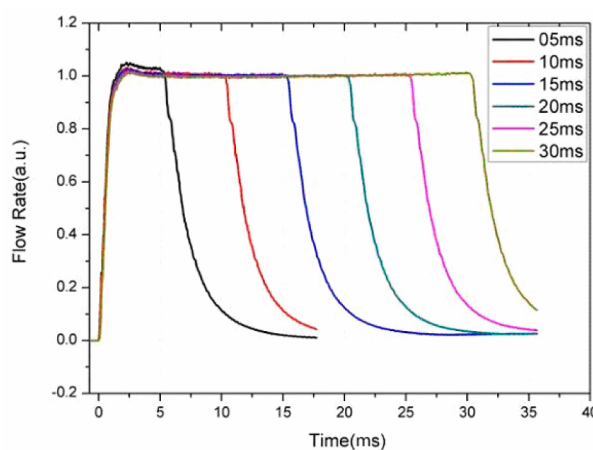


Figure 2. Flow rate at different injection times as measured by a piezoelectric sensor.

One of the advantages of using a gas injector is that the mass flow rate can easily be controlled and determined when sonic velocity is reached in the throat of a nozzle (venturi flow). Indeed, in such case the mass flow rate is only dependent of the upstream pressure and temperature. The mass flow rate at sonic conditions can then be given by the simplified isentropic flow equations:

$$\dot{m} = \text{Density(gas)} \times \text{Velocity} \times \text{Area} \quad \text{Eq. 1}$$

$$\dot{m} = \frac{A \cdot P}{\sqrt{T}} \sqrt{\frac{\gamma}{R}} \left(\frac{\gamma+1}{2} \right)^{\frac{-\gamma+1}{2(\gamma-1)}} \quad \text{Eq. 2}$$

Where, A is the flow area, P is pressure, T is temperature, Y is the specific heat ratio and R is the gas constant.

To verify that the flow is choked in the injector, series of measurements were performed for different injection pressures and injection durations using a piezoelectric sensor. The sensor was placed 3mm underneath the nozzle and the momentum induced by the injected jet was registered. In [Figure 2](#) the effect of different injection duration is displayed. When increasing the injection time, the flow rate remained constant as long as the injector was kept fully open. At the end of injection command, the injector took a significant time to close the needle. In [Figure 3](#) the effect of injection pressure is displayed. The mass flow rate increases with inlet injection pressure. Integrating the dashed area under each curve resulted in [Figure 4](#).

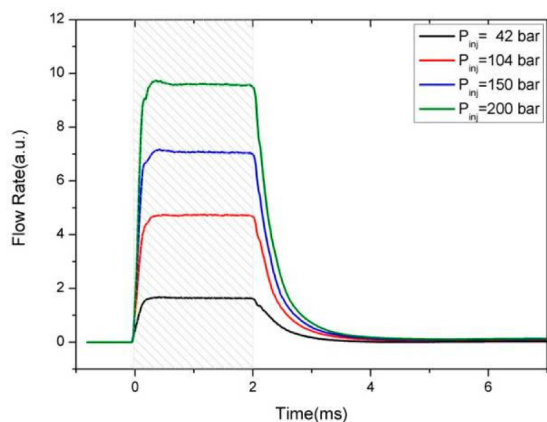


Figure 3. Flow rate at different injection pressures for an injection duration of 5ms.

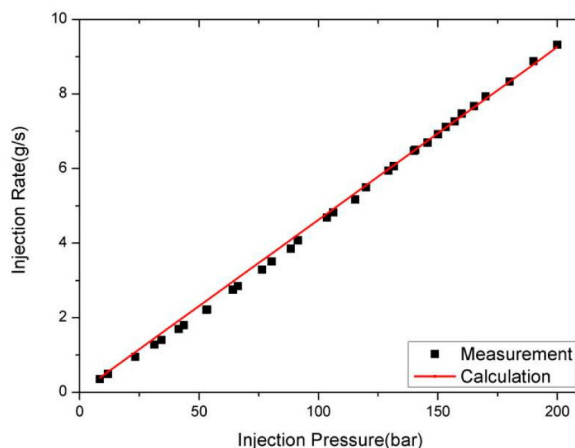


Figure 4. Injection rate as a function of injection pressure. Comparison between measurements and calculation.

In [Figure 4](#) a linear relation is found between inlet pressure and mass flow rate, which is consistent with venturi flow predictions. The measurement and calculation using sonic conditions seems to be in a good agreement. Thus a particular mass flow rate can be determined by applying the proper value of inlet pressure.

EXPERIMENTAL TECHNIQUES

Principle

In order to simultaneously measure the aerodynamic structures around the gas jet and the mixing characteristics, the flow field was measured by Particle Image Velocimetry (PIV) and the fuel mass concentration field was measured by Laser Induced Fluorescence (LIF).

PIV is a well established technique for mapping 2D velocity field with high spatial resolution [13,14,15]. PIV tracks groups of particles, “seeded” into the flow, within small regions of the image (interrogation areas) preferably at a high particle density, about 15 particles per 32×32 pixels. The correlation between the interrogation areas of two images taken successively with a given time interval is computed and the displacement is determined from the location of the strongest correlation peak.

The same methodology than that developed in ref[16] was used to obtain fuel mass concentration fields. A fluorescent tracer, biacetyl, was added to the injected gas to perform LIF imaging. The fluorescence signal was then normalized by the injected mass in order to obtain the fuel mass concentration field. This normalization is based on the following hypothesis: the effect of temperature variation on the fluorescence signal is supposed to be small in the operating range considered in this study, and the tracer is uniformly mixed with the fuel. As a consequence, the fluorescent signal is directly proportional to the tracer mass concentration and therefore to the fuel mass concentration. The uncertainty associated with this assumption was evaluated to be less than

$\pm 5\%$. This evaluation was based on temperature field estimations using adiabatic mixing hypothesis, showing that the temperature variation in the gas jet is less than 20K in the main area of interest (except in the very near region of the nozzle where the expansion effect lowers the temperature) then that the overall effect of temperature on the LIF signal in the jet is less than 10% according to the biacetyl LIF characterizations made in ref[17].

Experimental Set-Up

The experimental setup is shown in Figure 5. A pulsed double cavity Nd:YAG laser operating at 10 Hz and an energy of 80 mJ was used for both concentration and velocity measurements. For both experiments, only the third harmonic wavelength at 355 nm was used. A suitable time delay between the double pulses was used for particle velocity measurements while only the first laser pulse was used for concentration measurements. The laser beams were then transformed using suitable optical telescope resulting in 1mm thick and 60mm high coplanar laser sheets.

For concentration measurements, the mixture of gas was led into a bath of biacetyl, contained in a small high pressure cell, carrying with it a few percent of the tracer. The temperature of the tubes in which the gas mixture and tracer propagate was regulated to 383K which is superior to the boiling temperature of biacetyl. To avoid condensation of the biacetyl vapour in the injector, the high pressure cell and injector were also heated up to the same temperature as the biacetyl vapour. An increase of the quantum efficiency of biacetyl fluorescence was observed when increasing temperature to 383K, the same effect was observed when increasing pressure to 30 bar[17]. After injection, the laser sheet at 355nm was used to excite the biacetyl tracer and the subsequent fluorescence emission was detected by a 16-bit ICCD camera (Princeton Instruments) through a band-pass filter at 435nm and a 50mm (f/1.2) lens. The exposure time was set to 500ns to suppress biacetyl phosphorescence. The resulted fluorescence images were then subtracted from background and divided by a laser sheet profile.

Tracer or seeding particles are supposed to accurately follow the motion of the flow. Various seeding materials are available and the choice depends on the fluid properties and flow regime to study. In current experiments small droplet particles based on glycerol oil were introduced into the chamber at low pressure using a Lavision liquid atomizer. The introduced droplets had a mean diameter of $3\mu\text{m}$. When a reasonable seeding density was obtained, superior to 15 particles per interrogation window (32×32) corresponding to 2 to 3bars in the chamber, the non-seeded nitrogen gas was introduced into the high pressure cell to reach the required pressure and density. The Mie-scattering from the frequency tripled laser light of both lasers was then registered by a double frame TSI CCD detector.

PLIF and PIV experiments were controlled by pulse generators which drive and externally control the laser pulses, trigger the detectors and the injector. Due to hardware limitations the measurement frequency was set to 1Hz and the total number of acquired images in each run was set to 50. Between each series of 50 acquisition, the chamber was scavenged and filled up again. This limitation is caused by the accumulation of biacetyl after each injection. Only the first 15-20 concentration images were useful while the remaining ones served as a reference for the laser sheet profile.

In each test several measurement series were taken in order to collect 300 to 500 useful images.

LIF Normalization

The methodology used to obtain fuel mass concentration fields from LIF images is similar to that developed in ref. [16]. Each recorded intensity image is normalized by the injected mass in order to assess the calibration coefficient K_v . The later is determined by the ratio between the integrated volumetric intensity (I_v) in the jet and the injected mass M , where I_v is calculated from the LIF image according to Eq.3, and M is the injected mass derived from one dimensional isentropic flow theory as described in the injector section. This method implies that the jet is symmetric around the center axis.

$$I_v = 2\pi \int_{-\pi}^{+\pi} \int_{-\pi}^{+\pi} I(x,y) y dy dx$$

Eq. 3

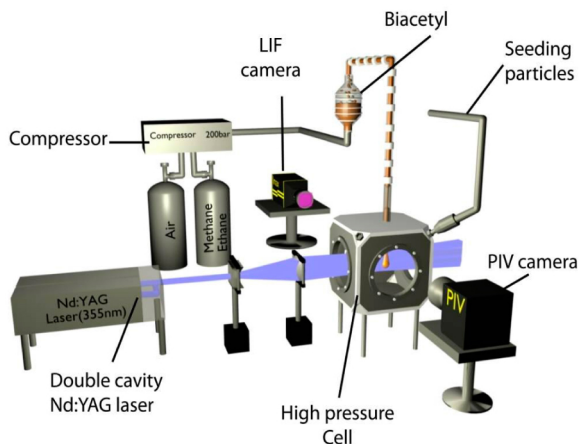


Figure 5. Experimental setup

In this work, the same procedure was applied to the acquired fluorescence images but slightly improved. For each injected mass, the fluorescence images were captured and averaged in order to get a symmetrical structure of the jet. Then the intensity of the averaged image was integrated in 3D coordinates as in Eq. 3. Using average images instead of instantaneous ones helps minimizing the uncertainties related to non-symmetrical jet structures.

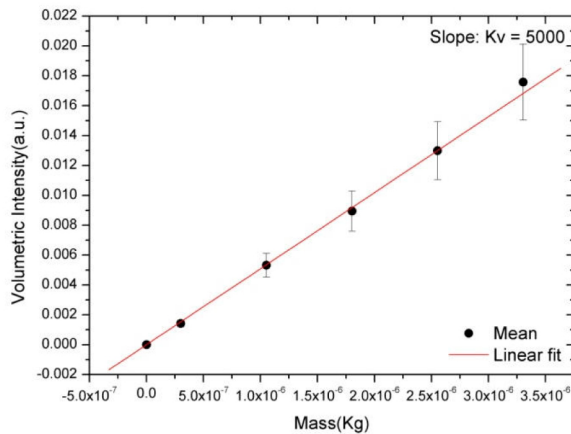


Figure 6. Volumetric intensity I_v as a function of the injected mass M .

The results in Figure 6 show a clear linear behaviour between the injected mass M and the volumetric intensity I_v , where the slope of the curve denotes the calibration coefficient. As expected when the injected mass increased, the volumetric intensity increased linearly as well.

RESULTS

OPERATING CONDITIONS

For the results presented in this paper a reference conditions was set consisting of an injection with the 0.35mm nozzle hole diameter in a 30kg/m³ ambient density and 383K ambient temperature. Parametric variations around this reference conditions were then performed with variations of nozzle hole diameter (0.2 and 0.5mm) and ambient density (25kg/m³). For the wall jet configuration the same parameters were used for the reference conditions, and in addition the distance between the nozzle and the wall was set to 30mm.

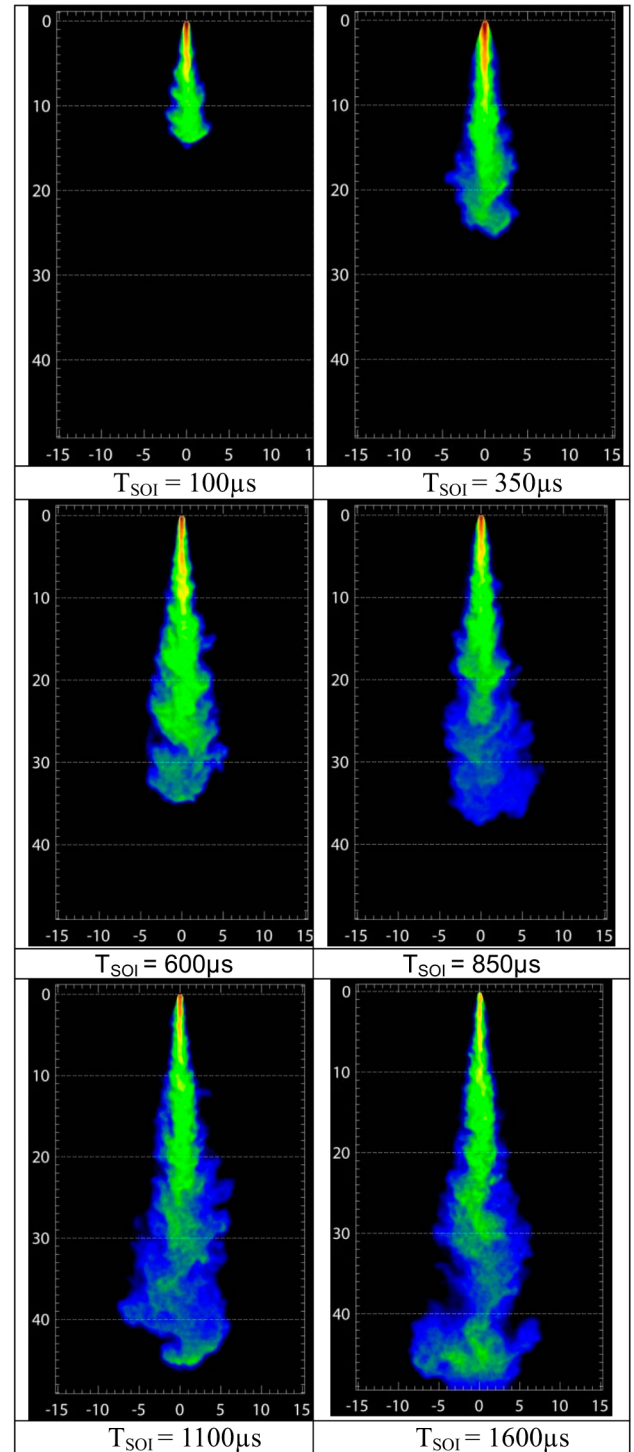


Figure 7. Single shot measurements at different times after SOI in the free jet configuration reference condition. Spatial scale indicated in mm. Color scale: 0 to 13kg/m³.

FUEL CONCENTRATION

Free Jet Configuration

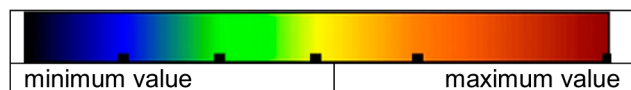


Figure 8. Color scale used for fuel mass concentration imaging.

The color scale used for all the fuel concentration images presented in this paper is displayed in Figure 8 for convenience. The image legend will systematically specify the minimum and maximum values used in the image when referring to this color scale.

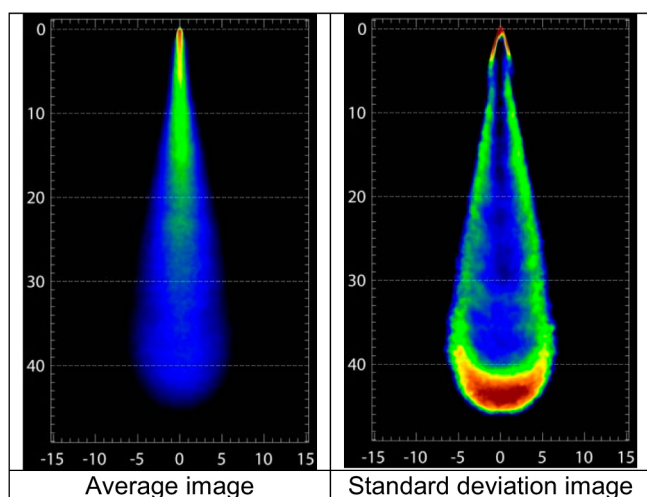


Figure 9. Average and standard deviation images at 1100 μ s in the free jet configuration reference condition. Color scale: 0 to 13kg/m³ for the average image and 0 to 1.6kg/m³ for the standard deviation image.

Figure 7 shows the time evolution of single shot images of fuel mass concentration during the injection process. The results are similar to those obtained in the literature [1,4,16]. The jet penetration increases during injection due to jet momentum. The jet edges are wrinkled as a result of the development of coherent structures formed by the shear between the stagnant ambient air and the high velocity jet. Consequently, low fuel concentration gradients are generated at the jet sides, indicating a relatively strong mixing process. The structure of the tip of the jet exhibits steeper gradients and lower wrinkling, as a consequence of reduced turbulence mixing compared to the sides of the jet. As time evolves, the size of the coherent structures increases towards the jet tip.

The average and standard deviation fuel concentration fields obtained from 400 instantaneous realizations at 1100 μ s after Start Of Injection (SOI) are displayed in Figure 9. High fluctuations are observed at the jet tip as a result of spatial fluctuations of the steep gradient jet frontier.

Wall Jet Configuration

Figure 10 displays the time evolution of instantaneous fuel concentration fields in a wall jet configuration where the wall is located 30mm from the nozzle. At 600 μ s, the jet structure is similar to that of the free jet except that the jet tip is just impinging the wall. At 1100 μ s and after, a typical jet wall structure is observed: a stagnation point is formed at the impingement location between the jet and the wall, and a radial jet expansion is observed with a structure corresponding to the formation of a jet wall vortex.

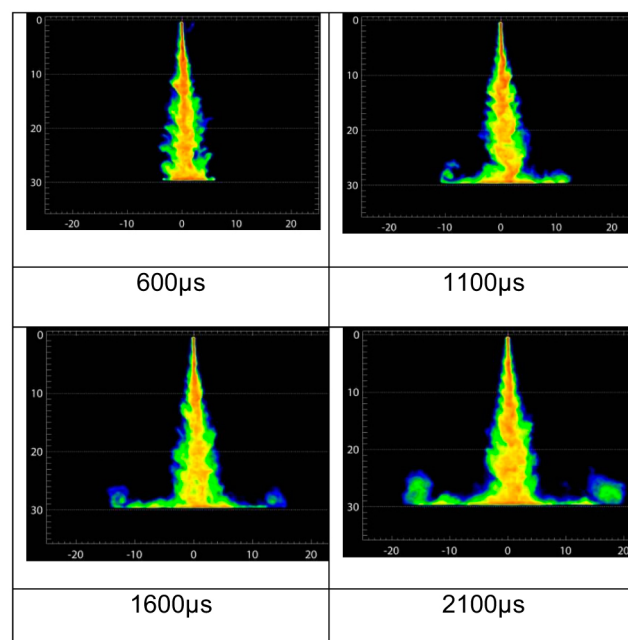


Figure 10. Single shot measurements at different times after SOI in the wall jet configuration reference condition. Color scale: 0 to 6kg/m³.

Average and standard deviation fuel concentration fields resulting from 400 instantaneous events obtained 1100 μ s after SOI are displayed in Figure 11. The jet wall structure characterized by a stagnation point and jet wall vortex formations is clearly visible and important fluctuations are observed at the jet edges as a consequence of significant mixing.