Experimental study of mixing and transport in a compressed vortex using PLIF and PIV

by

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ABSTRACT
This paper presents a model situation of mixing preparation in direct injection engines namely the compression and the breakdown of a tumbling motion after radial disruption. The experimental set up is a simple geometry with large optical access. The disruption is a round jet injection perpendicular to the vorticity tube. Injection parameters have been set in order to be representative of the direct-injection engine situation. The data presented here are obtained in the symmetry plane of the square chamber. The data have been obtained by using Particule Image Velocimetry and Laser Induced Fluorescence. The analysis of the injection stroke at BDC shows that the mean topology of the flow after both injections differs significantly and that injection induce large three dimensional flow in the chamber. A study of the evolution of the global in-plane mean and fluctuating kinetic energy in the symmetry plane shows that the perturbed tumble is weak and that no vortex breakdown occurs during the compression after injection. Therefore, the global fluctuating kinetic energy decreases strongly during the compression and is much lower at TDC when compared to the “free” tumbling motion. During the first half of the compression, a very inhomogeneous distribution of the jet fluid in the chamber is detected by the PLIF measurements. The transport of the jet fluid clearly results from both in-plane and out of plane motions triggered by the injection jet.

Fig. 1. Experimental overview with examples of PIV and PLIF results.

a) Compression chamber
b) Example of mean PIV field 6 ms after the beginning of injection.
c) Example of mean PLIF field 6 ms after the beginning of injection.
1. INTRODUCTION

The transient in-cylinder flow field that takes place during intake and compression strokes of an internal combustion engine cylinder is a key factor for the optimisation of the engine. For example in the case of GDI engine, a common strategy to raise the turbulence level at ignition uses the tumbling motion. The amount of turbulence at the end of compression drives the flame speed (Gruno et al 1994). The tumbling motion is a rotating flow whose axis is perpendicular to the cylinder axis and is a very efficient way to store the kinetic energy of the valve jet in a large scale rotating motion that becomes unstable as the piston rises toward top centre. The breakdown of this structure associated with energy transfer between large scale and turbulence was first addressed using computational fluid dynamics (CFD) (Gosman et al 1985, Haworth et al 1990) in simplified geometric configurations. However, very few detailed studies have been devoted to the interaction of this flow with the injection. If the spray-tumble interaction is significant, it is possible that transport properties of the large-scale rotating flows will be altered as well as the amount of turbulence at the end of compression.

These questions are addressed here by using a model square piston compression machine. This experiment is not designed to reproduce all the complexity of in-cylinder flows but to focus on the development of the compressed vortex after injection. Detailed particle image velocimetry (PIV) data following the injection phase will be discussed here. The analysis of the mixing process using Planar Laser Induced Fluorescence (PLIF) of acetone tracers will be used in order to provide additional data about mixing and flow organisation. A calibration has been performed to take into account the thermo-dynamical dependence of the tracer in the compression stroke. This calibration is described in the first part of the paper.

The paper is organised as follows. The experimental set-up and measurement techniques are presented first. Section 3 provides PIV measurements of injection phase. The modification of the tumbling flow by interaction with injection is analysed in section 4 using PIV (RANS averaging) and Fluorescence data.

2. EXPERIMENTAL METHOD and PROCEDURES

2.1 The compression chamber and injection system

This section is dedicated to give an overview of the experimental set up and the optical arrangement.

The compression chamber available for this study is a square cylinder. This chamber is equipped with a flat head square piston. For a complete description of the set up see Moreau (2003). A sketch of the square compression chamber is displayed figure 1. During the intake stroke, the bidimensional intake jet flow, tangential to the cylinder floor, is deflected by the moving piston and generates the tumbling vortex (Maurel 2001, Borée et al 1999, Borée et al 2002). A four-stroke cycle has been defined. The channel is closed during the compression/expansion strokes.

The goal is to mimic the effect of the injection on the dynamical behaviour of the tumbling motion during the cycle focusing on the spray momentum transmitted to the tumble structure. A model round jet is injected in the chamber respecting a non dimensional analysis in order to be representative of the real engine conditions. The ratio $A_b$ between angular momentum brought by the spray and initial angular momentum of the tumble was evaluated in Moreau et al (2003). Two configurations of injection have been set up corresponding to two different angles. The first configuration is a $30^\circ$ inclined jet located at 50 mm from the lower side of the chamber. The second one is a straight jet located at 62 mm from the lower side of the chamber. These two configurations have been chosen to compare inclined jet that will add angular momentum to the tumble and straight jet that will compete with tumble. We’ll focus in this paper only on the first inclined configuration (figure 2). For more details, see Moreau et al 2004. The phase of injection is a very important parameter that has to be chosen carefully. We decided to center the injection stroke around the Bottom Dead Center (BDC) since, at this phase, the rotating flow is quasi stationary because of the low speed of the piston. Furthermore, the tumbling flow is well known at this phase.
2.2 Experimental Techniques

a- Particle Image Velocimetry

The wide windows one each side of the domain associated with the upper and lower narrow windows are well adapted to Particle Image Velocimetry measurements. This non intrusive technique allows getting instantaneous velocity fields. Nowadays, the digital technology is the most significant way of progress for PIV as well as upgrade in camera acquisition rate, in the dynamic range or in pixels number. The technique used in this study to process the data is cross correlation. This technique has improved significantly this last years (Lecordier 1997, Fincham and Spedding 1997, Westerweel et al 1997). The algorithm used has been developed by Maurel (2001). This PIV algorithm uses iterative cell shifting. Lecordier (1997) has shown that both bias and random errors are significantly reduced when a sub-pixel cell shift is performed in order to obtain a zero displacement from the correlation peak when the process converges. The precision of the correlation is 0.05 pixels.

Velocity fields discussed in the present paper were acquired in the symmetry plane. The beam of a double pulsed Nd:Yag Laser (Quantel PIV 200) was focused through several optical components to produce a double light sheet in this symmetry plane (figure 1). The thickness of the light sheet at the beam waist was of the order of 500 µm. A Sensicam (12 bits, cooled) CCD sensor 1280*1024 pixels with full double frame has been used to collect images of 3 µm oil droplets. The Stokes Number of the seeding particles is \( St = \frac{\tau_p}{\tau_f} = 10^{-4} \). They are able to track accurately the turbulent flow in the present experiment. Synchronization of laser shots, camera acquisition and experiment was processed via several PC cards and specially developed softwares. It was possible to choose the repetition rate of the laser between 0 and 20Hz. However, for the case presented, the acquisition rate was limited by the camera at 4 Hz for a full resolution. Then authors decided for this study to synchronize the laser with the cycle signal of the piston thus corresponding to an acquisition rate of 1.7Hz. For more details about synchronization see Moreau (2003). One velocity field per cycle was then obtained. Pictures of tracer fields are analyzed using PIV algorithms on 32*32 pixels² cells at intervals of 16 pixels (i.e. with a 50% overlap). The spatial resolution is approximately 0.1mm/pixels inducing interrogation windows size about 3*3mm². The PIV is well adapted to the study of large scale motion but suffers from the limited resolution. Indeed, the scale smaller than the interrogation windows are not resolved. Then, in this paper, when discussing about fluctuating fields, authors will deal with filtered velocity field.
On most of the sets, the time interval separating the two laser shots was optimized to reduce out of cell and out of plane errors while keeping the dynamic range for velocity measurements as large as possible. Different thresholds based on predetermined signal to noise ratio, velocity vector amplitude and median filtering are systematically applied during post-processing of each PIV vector field. The number of spurious vectors is always very low (<2%). They were discarded and no interpolation was used to make-up for incomplete data.

b- Planar Laser Induced Fluorescence

Gaseous acetone has been used for the concentration measurement by PLIF to track the mixing process between jet and air during the injection and the compression stroke. Nowadays, acetone is commonly used due to its properties of fluorescence and its high saturation vapor pressure.

A pulsed laser beam (λ₀=266nm, Δt=10ns, E=40mJ) provided by the fourth harmonic of a Nd:Yag laser formed into a vertical light sheet (300µm thick) through the symmetry plane. The fluorescence emissions are imaged at 90° onto a gated intensified CCD camera (Sensicam 12Bit, 1376*1040 pixels coupled with a PCO SCI intensifier) with a 85mm f/1.4 objective lens equipped with a pass filter Schott BG25 (300nm<λ<500nm, 90%). The synchronization between the laser shot and the camera is performed by a magnetic rule signal and adapted developed software, thus enabling to position the measurement wherever in the cycle (Moreau 2003). In the following parts, we will use the variable \(x_p\) to represent the position of the piston and \(x_p=0\) corresponds with the Bottom Dead center i.e. \(x_p=100\)mm.

For quantitative measurements of acetone mass fraction, both the absorption coefficient and the fluorescence yield \(q(P,T)\) must be determined under reference conditions. The evolution of the fluorescence yield as a function of temperature, pressure, composition and excitation wavelength has been measured in previous studies (Lozano 1992, Thurber 1999). This calibration has been performed during the compression stroke in a homogeneous acetone mixture of concentration \(C_{ref}\) introduced in the chamber. For more detailed about calibration procedure see Moreau et al. (2004).

3. RESULTS AND DISCUSSION

3.1 Mean velocity field analysis

a) Injection phase

At the beginning of the injection, the ratio between the starting jet ejection velocity \(U_j\) and the maximum cross flow velocity \(U_{cf}\) due to the tumble is \(r = (U_j^2/U_{cf}^2)^{0.5} = 6\). The deflexion of the jet by the tumble is therefore very weak (Keffer & Baines 1967). A complex reorganisation of the vorticity in the chamber is expected during injection. Streamlines corresponding to the end of the injection phase are displayed in figure 4a and 4b. They are associated with the mean PIV fields after injection. Quasi-circular lines are obtained without injection. The topology of the mean flow in the injection plane clearly differs after injection. In the case of the inclined jet, the large eddy seems to be advected to the right bottom corner of the symmetry plane of the chamber. However, one always detects a large scale anti-clock wise rotation in the measurement plane on the lower part of the chamber. The second singular point corresponds to a sink region confirming the negative value of the transverse flow.

Quantitative understanding of the three dimensional character of the flow can be obtained because the divergence of the mean velocity is known. In the case of unsteady compressed flow, for piston velocities much smaller than the speed of sound, the density is only time dependant and one obtains \(1/\rho \frac{d\rho}{dt} + \frac{\partial(U)}{\partial x} + \frac{\partial(V)}{\partial y} + \frac{\partial(W)}{\partial z} = 0\). Just after BDC, at the very beginning of the compression stroke when the channel is closed, \(d\rho/dt\) is only associated with the mass flow of the injection and can be neglected when compared with the high value of other terms. Then, it is possible to compute the mean transverse velocity gradient \(\partial(W) / \partial z\) from our measurements.
Fig. 3. Comparison of the mean flow before and after injection at Bottom Dead Centre

a) Vector field before injection  

b) Vector field after injection  

c) \( \frac{\partial W}{\partial z} \) field before injection  

d) Streamlines after injection  

e) \( \frac{\partial W}{\partial z} \) field after injection
c) Streamlines before injection  f) $\partial W/\partial z$ field after injection

For example, after inclined injection, one can see in figure 3 that a high level of $\partial\langle W \rangle/\partial z$ is induced by the air jet. In the symmetry plane $\langle W \rangle$ is equal to zero but a positive value of $\partial\langle W \rangle/\partial z$ corresponds to a mean mass flux going away from the measurement plane. On the contrary, a negative value indicates a transverse back flow in the symmetry plane. The unsteady jet starting vortex leads to a high value of tri dimensional transverse flows. Converging regions are clearly detected under the jet on the left hand side and above the jet. Positive values of transverse flow correspond to jet expansion and to cross flow on the upper side of the jet. It is interesting to note that a wide region on the right hand side of the measurement plane corresponds to a negative value of $\partial\langle W \rangle/\partial z$.

The detailed study of this fully 3D flow with only one measurement plane in the middle of the box and only two velocity components is difficult. To get some lateral information about the effect of injection on the tumble structure, the injection location has been changed and the round jet was injected in the chamber out of the symmetry plane (two diameters from the symmetry plane). During the penetration of the jet in the chamber, it is assumed that this moderate dissymmetry does not induce a complete change of the flow during early injection. PIV fields obtained two-diameters apart from the injection plane show that the magnitude of the displacement of the tumble center is significantly lower than in the injection plane. The vortex core is mainly advected in the injection plane. Note that preliminary LES computations in a steady box are presented in Devesa et al (2004). These computations were obtained by using PIV velocity field of the motion before injection as initial conditions. The numerical results also confirm our experimental findings. Authors maintain that the evolution of these flows during the compression, to be presented in the next section, is so markedly different that useful conclusions can be drawn from this data.

b) Compression stroke

Fig. 4. Streamlines of the tumble during compression without and after injection
Without injection (a,b and c)
After injection (d,e and f)

In this section, in order to clarify we will call the flow that has not been injected in: the "unperturbed" vortex. The compression of unperturbed vortex leads to the formation of separation zones in the upper right corner and lower left corner due to strong adverse pressure gradient induced by the vortex along the wall of the chamber (Borée et al 2002). After the injection, we can note in the mean velocity fields the persistence of a rotating zone at the bottom of the chamber (figure 4). However, no more separation zone is observed. Furthermore, it has been showed that this remaining rotating zone does not correspond to a large value of vorticity. It can be shown that the maximum of the mean vorticity is 4 times less than without injection (Moreau et al 2004). A first important conclusion is thus that the injection of a significant amount of angular momentum flux in the centre plane of the chamber significantly perturbs the mean vorticity fields of the model tumbling flow. As no strong vortex core is detected any more, authors expect an important modification of the generation of turbulence during the compression. In particular, no tumble breakdown is expected to occur. The evolutions of the in-plane integrated mean and fluctuating kinetic energy during the compression after injection are plotted in figure 5 after injection. This kinetic energy comes from the following decomposition:

\[
\frac{1}{2} \int_S \left( U^2 + V^2 \right) ds = \frac{1}{2} \int_S \left( (U)^2 + (V)^2 \right) ds + \frac{1}{2} \int_S \left( (u^2) + (v^2) \right) ds = E + e
\]

The signature of the tumble breakdown is clearly observed for “unperturbed” compressed vortex. Injection provides fluctuating energy and turbulence is created by tumble destabilization due to injection and by the jet itself. However, we can note that the mean and fluctuating kinetic energy decrease all along the compression and that no signature of tumble breakdown is observed. The velocity field was not measured in other plane of the chamber. The final value of the turbulent kinetic energy is lower when in cylinder injection distorts the tumbling motion at BDC. This plot shows that the injection is responsible for a modification of the energy transfer during the compression. The turbulence evolution is then modified by the injection and a wide part of the energy is dissipated in the chamber during the compression.

![Fig. 5. Evolution of $E$ and $e$ during the whole cycle including intake and compression after inclined injection: *, $E$ after injection; o, $E$ without injection; ?, $e$ after injection; +, $e$ without injection](image-url)
3.2 Mean mass fraction field analysis

Figure 6 shows the evolution of the mass fraction during compression. The distribution of the injected fluid shows that the flow is 3D. Indeed, the amount of injected fluid detected in the symmetry plane at some phases is very weak. At a compression ratio of two, the jet fluid is detected in the lower half of the measurement plane. Looking at figure 6, one sees that a mean rotating flow remains in the symmetry plane after injection. This latter could be responsible of the mean transport of the injected fluid during compression. The transport of the jet fluid then results from both this in-plane motion and from out of plane motions triggered by the injection jet. At the end of the compression, we see that the mixing is quasi homogeneous in the whole chamber. Authors can compare the measured value at TDC to the ratio between injected mass and in cylinder air mass. This ratio is $Y_H = 4.2 \times 10^{-2}$ (Moreau$^{25}$) and corresponds to the horizontal line labelled "homogeneous mixture" in figure 7. One can notice that the measurements are 5% to 10% lower than $Y_H$. Owing to the complex calibration procedure, we believe that this comparison is representative of the accuracy of the PLIF measurements during the compression and that the mixing is homogeneous in the whole chamber.

![Fig. 6. Phased averaged mean injected fluid mass fraction field of the tumble at different step of compression stroke. (Comp’X’: X indicates the distance between piston and cylinder head in mm)](image-url)
Fig 7: Evolution of the x-averaged vertical profile of mass fraction of injected fluid after injection for:

- $O$, $x_p = 80\text{mm}$;
- $\wedge$, $x_p = 50\text{mm}$;
- $\wedge$, TDC.

Fig. 8. Evolution of the x-averaged vertical profile of $Y'/Y$ during the whole compression stroke: $O$, BDC; $+$, $x_p = 80\text{mm}$; $\wedge$, $x_p = 50\text{mm}$; $\wedge$, $x_p = 80\text{mm}$; $\wedge$, TDC. Where $x_p$ is the distance between piston and cylinder head.
Cycle to cycle variation is a key factor for the manufacturers. Figure 8 shows the distribution of the averaged (along x direction) ratio $Y'/Y$ (on the vertical direction y) during the compression. $Y'$ is the mass fraction variance. It is possible to note that the variance is maximal at the end of injection. The more the flow is compressed, the more the variance decreases. Then, injection involves very important cycle to cycle variations. This conclusion confirms that it is difficult to control cycle to cycle mixing variation in a real engine after direct injection.

4. SUMMARY

This paper presents data and analysis related to the compression and the breakdown of a tumbling motion after radial disturbance. The experimental set up is a simple geometry with large optical access. The disturbance is a round jet injection perpendicular to the vorticity tube. The parameters of the injection have been set in order to be representative of the direct-injection engine situation. The injection is performed at bottom dead centre in a well defined and well known tumbling motion.

The data presented here are obtained in the symmetry plane of the square chamber. The data have been obtained by using Particle Image Velocimetry and Laser Induced Fluorescence. A calibration of the fluorescence yield is proceeded in order to take into account the pressure and temperature dependence of acetone fluorescence during the compression.

The PIV data are analysed using Reynolds averaging decomposition. The analysis of the injection stroke at BDC shows that the mean topology of the flow after injection differs significantly. Extensive tests have shown that the vorticity tube is significantly distorted only in the vicinity of the injection plane. Strong transverse mean flows are detected by analysing the divergence of the mean velocity field.

The main observations of this work are obtained by comparing, during the compression, the mean and fluctuating velocity fields of the perturbed tumble with the previously documented evolution of the “free” tumbling motion. Although a mean rotation is still observed after injection during the compression phase, the mean vorticity field perpendicular to the symmetry plane shows that no strong vortex core is detected anymore. An important consequence of this finding, confirmed by studying the evolution of the global in-plane mean and fluctuating kinetic energy in the symmetry plane is that no vortex breakdown occurs during the compression after injection. Therefore, the global fluctuating kinetic energy at TDC is very much lower (4 times lower).

During the first half of the compression, a very inhomogeneous distribution of the jet fluid in the chamber is detected by the PLIF measurements. The transport of the jet fluid clearly results from both in-plane and out of plane motions triggered by the injection jet. It seems that it can be very difficult to control accurately from cycle to cycle variations in the direct injection engine technology. In our experiment, it is interesting to note that the mixture is more homogeneous at TDC with a moderate cycle to cycle variance.
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