Structure and in-cycle evolution of an in-cylinder tumbling flow

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Abstract The goal of this paper is to make use of PIV and high speed PIV in an optically accessible research engine in order to address both the spatial structure of an engine flow of moderate tumbling ratio and its temporal evolution during series of consecutive cycles. 2D-2C PIV phase averaged data acquired in selected in-cylinder planes are first used to understand the chain of events driving the generation of the three-dimensional mean tumbling motion. Spatial global indicators of the cycle to cycle stability of the flow are then introduced in symmetry or perpendicular planes. We finally concentrate on the “breakdown” phase. By applying phase invariant proper orthogonal decomposition and multi-time statistics on high speed PIV data in the second part of the compression phase, we propose to distinguish cycles according to their structure near top dead center and to use this decomposition to compute conditional statistics. This conditional analysis shows that the increase of the fluctuating kinetic energy is the largest for cycles that experience a loss of large scale coherence while no maximum is detected for cycles keeping their coherence.

1. Introduction

The large scale coherence of the turbulent flow generated inside the cylinder of an internal combustion engine critically affects the engine efficiency and pollutant emissions (Heywood 1988; Lumley 1999). This flow significantly influences the air-fuel mixing and mixture transport during the intake and compression stroke. Moreover, an order of magnitude analysis – see e.g. (Lumley 1999) – shows clearly that the turbulence generated by the induction process has decayed at the time of ignition. Therefore large scale motions and their evolution during the compression stroke determine the turbulence level in the chamber at ignition and the effective flame speed. Most direct injection (DI) gasoline engine use tumble. The tumbling motion is a rotating flow which axis is perpendicular to the cylinder axis (Arcoumanis et al. 1990; Hill and Zhang 1994; Borée et al. 2002). Tumble is interesting for a number of fluid-mechanical reasons. From a global point of view, tumble appears as a way to store the kinetic energy of the valve jets in a large scale motion and to transfer this kinetic energy to turbulence before the end of the compression stroke. Indeed, a literature survey of phase averaged statistics shows that the transfer of energy from the mean flow to the turbulence beyond a crank angle \( \theta \approx 300 \text{CAD} \) occurs at the turn-over time scale of the tumbling motion. The large scale flow is thus unstable near top dead center (TDC).

While Reynolds Averaged Navier Stokes (RANS) approach in turbulence modelling or data analysis is a very efficient and useful tool to study engine flow fields, one key challenge with present engine development is the modelling, understanding and ultimately control of cyclic variations. This cyclic variability is understood here as a large scale cycle to cycle variation that ultimately controls the gas motion and composition in the vicinity of the spark plug and at the time of ignition. The consequences of large cycle to cycle variations are particularly important for DI engines with stratified combustion. This industrial and environmental challenge has triggered a large amount of research work. On the experimental side, particle image velocimetry (PIV) pioneered by (Reuss et al. 1989) for in-cylinder flows provides, at low Laser repetition rates, the spatial structure of statistically uncorrelated realisations of the flow field in given planes. Recent developments in measurement technology now enables the study of both spatial and temporal coherence of in-cylinder flows using high speed PIV (Towers and Towers 2004; Cosadia et al. 2007; Muller et al. 2010). On the modelling side, large eddy simulation (LES) or hybrid RANS/LES methodologies (Vermorel et al. 2009; Hasse et al. 2010) are becoming attractive.
Our goal in this paper is to make use of both PIV and high speed PIV (HS-PIV) in an optically accessible research engine developed by Renault (Cosadia et al. 2006) in order to address both the spatial structure of an engine flow of moderate tumbling ratio and its temporal evolution during series of consecutive cycles. 2D-2C PIV phase averaged data acquired in selected in-cylinder planes will therefore be used to understand the chain of events driving the generation of the mean tumbling motion. Spatial global indicators of the cycle to cycle stability of the flow will then be introduced in symmetry or perpendicular planes. We will finally concentrate on the “breakdown” phase and use statistical tools to analyse both spatial and temporal coherence during this phase. Indeed, one may wonder if this phase corresponds to an effective transfer of kinetic energy to small scale turbulence or if what is called “breakdown” from a RANS approach is just the signature of an amplification of cycle to cycle unsteadiness.

2. Engine flow test bench and measurements techniques

The engine configuration is based on a spark ignition engine with a pent-roof chamber and 4 valves by cylinder. The Table 1 summarizes the dimension of the engine:

<p>| | | | |</p>
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<thead>
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<tbody>
<tr>
<td>Bore b</td>
<td>78mm</td>
<td>Maximum pressure at TDC</td>
<td>18 bars</td>
</tr>
<tr>
<td>Stroke S</td>
<td>73.1 mm</td>
<td>Pent-roof angle</td>
<td>28°</td>
</tr>
</tbody>
</table>

Table 1 : Engine characteristics

The cylinder is fully transparent in order to measure in several planes. For the vertical measurement planes (Figure 1), images are recorded through the cylinder and the vertical velocity fields are corrected for image distortion due to the cylinder shape. For the horizontal measurement planes, images are recorded via a mirror placed under the piston. A flat window in the pent-roof chamber (Figure 2) is present to allow visualisations at the end of the compression and near the position of the spark plug (no spark plug in the present experiments). The window’s size is of 12mm height and 40mm length. A flat crown piston is used instead of a real shape piston. Indeed, measurements through a real shape piston induce strong distortions that cannot be corrected. Moreover, the laser sheet is driven through the piston for the pent-roof measurements, and a flat piston shape guarantees a precise positioning of the laser sheet. Solid particle tracers are used to seed the flow. It was verified that their Stokes number is small and that the tracers are able to follow the structures during the intake and the compression phases of the engine – see discussion in (Cosadia et al. 2006). The data is acquired at a fixed engine rotation speed of 1200rpm, and an intake pressure close to the atmospheric pressure. Synchronization with engine angular information and operation frequencies allowed having one measurement, i.e. one instantaneous velocity field, at every engine cycle.

The flow will be described using a Cartesian coordinate system \((x, y, z)\), \(z\) is the ascendant axis, \(x\) is the axis between the two intake ports. In the horizontal plane, the origin is chosen in the middle of the cylinder. In vertical plane, it is chosen in the middle of the cylinder head (see Figure 1). The components of the instantaneous velocity field are denoted by \((U, V, W)\), respectively \(x\), \(y\) and \(z\) axis. The symbol <> indicates phase averaging operator. The components of the instantaneous fluctuating velocity are denoted \((u, v, w)\).
Two types of measurement are used. A standard PIV set-up from DANTEC is used to obtain one instantaneous velocity field every engine cycle for a large amount of realisations at a fixed crank angle degree (CAD). Data is stored for 500 consecutive cycles. Consequently, estimated statistical absolute errors for mean and rms values are respectively $\Delta <U> \approx 0.09u$' and $\Delta u' \approx 0.06u'$ with a 95% confidence level. The PIV system consists in a double pulsed Nd:Yag laser (100mJ per pulse). The thickness of the light sheet was adjusted to about 1 mm. The laser frequency is 10Hz. Images are recorded by a 1600 x 1200 pixels CCD camera Flowsense with an image pixel size of 0.073mm/pixel for the vertical planes. Adaptive cross-correlation is computed on 32 x 32 pixels-size final interrogation windows with 50% overlap. A widely accepted estimation of the absolute displacement error using these algorithms is 0.1 pixels. 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. Beyond 150° CAD, the time interval between two laser shots is fixed at 30 µs for vertical PIV planes and 20 µs for horizontal PIV planes. The maximum uncertainty on instantaneous velocity measurements are estimated at 0.3 m/s (displacement of 0.1 pixel). Spurious velocities are identified and replaced using both peak ratio and median filters. The average percentage of spurious vectors removed with the post-processing is approximately 1%.

Two different HS-PIV experiments are used here. For a large field of view through the cylinder, 38 consecutive cycles are acquired every 4 CAD in the symmetry plane (plane 1) from 40 to 310 CAD. For a smaller field of view in the pentroof chamber, 161 cycles are stored from 270 to 354 CAD in the symmetry plane. The measurement system consists in a LaVision synchronous system with a Litron LDY303 laser emitting two pulses of 10mJ (laser sheet thickness < 1 mm). The laser operates at 1.8 kHz. The resolution of the CMOS camera HSS6 is $1024 \times 1024$ pixels² with an image pixel size of 0.071mm/pixel for the symmetry plane and 0.055mm/pixel for the pentroof plane.
Cross-correlation is computed on 32 x 32 pixels-size final interrogation windows, with 50 % overlap. The time interval between two laser shots is fixed at 30 µs. The maximum uncertainty in instantaneous velocity measurements is estimated at 0.25 m/s for the symmetry plane and 0.2 m/s for the pentroof plane. The average percentage of spurious vectors removed with the post-processing is approximately 5% for the symmetry plane and 5% for the pentroof plane.


The Figure 3a, and Figure 3b show respectively the mean velocity field in the symmetry plane at CAD 120° and 180°. The confinement is very high at the beginning of the intake, the valve jets impact on the piston and no global coherence of the flow field is detected in the symmetry plane. Beyond 90 CAD not shown here for brevity, a tumbling jet structure develops along the wall of the cylinder, opposite to the intake valves, and interacts with the moving piston. This interaction is of course three-dimensional and fluctuates from cycle to cycle.

![Figure 3 : Phase averaged mean velocity field (<U>,<W>) (m/s) in plane 1, a. θ = 120CAD, b. θ = 180CAD](image)

Mean velocity vectors and turbulent “kinetic energy” $k_{2D} = \left( \langle u_1^2 \rangle + \langle u_2^2 \rangle \right) / 2$ $u_1$ and $u_2$ being the fluctuating velocity components measured in a given PIV plane – are shown at 120 CAD in the symmetry plane (Figure 4a) and in the perpendicular plane (Figure 4b). In the symmetry plane, we notice that the valve jet region is highly fluctuating. The global structure and intensity of the resulting tumbling motion is therefore expected to vary from cycle to cycle. The very clear ridge of $k_{2D}$ perpendicular to the piston at $x \approx -20mm$ in Figure 4a is believed to be the signature of this cycle to cycle variability. Indeed, this ridge is located at the front of the jet structure (see Figure 3a) and results from cycle to cycle variations of the propagation of the jet in the chamber. Such statement is confirmed by near-wall PIV data acquired along the piston. In the perpendicular plane (Figure 4b), we see that the jet-piston interaction induces a 3D coherence of the flow. Namely, an up-wash flow along the cylinder walls is detected. For a circular cylinder and a tumbling jet impacting the piston along one side of the cylinder, such 3D structure is expected because the downward momentum flux of the jet is deflected by the piston, spreads along the flat surface and interacts with the curved cylinder wall. The local maxima of fluctuating energy in the lowest part of
the cylinder are believed to be due to cycle to cycle variations of this up-wash motion. Again, a high level of turbulence is detected in the valve jet region.

A 3D display of the mean flow structure at BDC is proposed in Figure 5a. The sketch of Figure 5b describes our understanding of the non symmetrical impact of the combined valve jets on the flat piston and subsequent roll-up of the vorticity of the jet due to an interaction with the wall of the cylinder. Several flow regions are marked in Figure 5a. Region A surrounds a focal point in the symmetry plane. This focus is sometimes described as the center of the “tumbling vortex”, particularly if measurements are only taken in this symmetry plane. However, the tumbling vortex is not formed at BDC because the structure of the flow is dominated by the jet-piston interaction. Using the extended proper orthogonal decomposition (POD) methodology proposed in (Maurel et al. 2001; Borée 2003) and not detailed here, one shows (i) that the second and third POD modes, for a POD analysis restricted to region A, correspond to a global displacement of the structure and its focal point and (ii) that this displacement is strongly correlated to the intensity of the descending valve jet in the symmetry plane. The receptivity of the 3D structure at BDC to the development and merging of the valve jets is thus very clear. Line C in Figure 5a ($x = -10\text{mm}$) was selected on the horizontal PIV plane 2mm away from the piston wall at BDC, to compute the variations in intensity and direction of the momentum flux across C. Let’s call $T_U$, (resp. $T_V$), the integral of the transport of longitudinal (resp. transversal) momentum across line C. An angle $\beta$ of the momentum flux can be defined at each cycle with $\text{tg}(\beta) = T_V / T_U$. In the present set-up, the fluctuation intensity of $T_U$ is $\sigma_T_U / \langle T_U \rangle = 0,15\%$ while the root mean square value of $\beta$ is $\sigma_\beta = 7,2^\circ$. Coherent fluctuations of the momentum flux along the wall of the piston are thus evidenced. Contour B1 in Figure 5a surrounds the 3D motion detected in the perpendicular plane. B1 is used to compute the circulation on one side of the bottom half height of the cylinder while another contour B2, not visible in Figure 5a is used to compute the circulation on the other side of the symmetry plane. These circulations are obtained on each instantaneous velocity fields. One obtains $\langle \Gamma_{b1} \rangle / V_p b = -0,72$ and $\langle \Gamma_{b2} \rangle / V_p b = 0,63$. The absolute mean values are very close to each other, which proves the statistical symmetry of the set-up. Opposite signs are of course expected. Noting $\gamma = \Gamma - \langle \Gamma \rangle$ the fluctuating circulation, we find that both fluctuating intensities are large with $\sqrt{\langle \gamma^2 \rangle} / \Gamma \approx 30\%$. Interestingly, the correlation between both sides of the symmetry plane is quite
low with \( \langle Y_{b1} \cdot Y_{b2} \rangle \approx -0.1 \). Cycle to cycle variations of the strength and structure of the descending jet interacting with the piston does not result in a correlated 3D up-wash motion on both sides of the symmetry plane.

The early compression phase is characterized by the closure of the intake valves and a decrease of the intensity of the jet/piston interaction. The tumbling structure therefore gets organized. From PIV planes scanning the cylinder at mid-compression (270 CAD), it is obvious that the cylindrical shape deeply influences the development of the tumbling jet. The Figure 6a shows the mean velocity field in the symmetry plane at 270 CAD. The three-dimensional representation of Figure 6b displays the footprint of the mean 3D motion in horizontal planes respectively 2mm away from the piston wall and in the upper region of the cylinder \( \left( z = -10 \text{mm} \right) \), see lines in Figure 6a.

Figure 5 : a. Superposition of 2D 2C PIV plane inside the cylinder at BDC, b. Sketch of the three dimensional mean flow at BDC

Figure 6 : a. Phase averaged mean velocity field \( (<U>,<W>) \) (m/s) plane 1 at \( \theta = 270 \text{CAD} \), b. Superposition of 2C 2D PIV planes inside the cylinder at half compression stroke
We see that the flow along the piston diverges away from the jet impact region, rolls-up not only in the symmetry plane but also along the cylinder wall, focuses in the central region of the upper region of the cylinder and impacts the piston in a down-wash motion. The mean tumbling motion is therefore not symmetrical at all with respect to a “cross tumble” plane. Moreover, we see that the two “vortical structures” detected using two components of the velocity on an horizontal plane crossing the upper region are merely the signature of this 3D evolution and not the signature of the vortex breakdown as proposed by (Lumley 2001), following the conclusions of (Obukhov 2000), obtained in elliptical containers.

4. Statistical analysis of breakdown using phase invariant POD

At the end of the compression phase, a transfer of kinetic energy from the large scale tumbling motion to small scale turbulence is expected. One interest of the set-up used in this work is to be able to acquire PIV data in the pent-roof chamber at all CAD. We have seen in previous sections that the coherence of the tumbling motion can be studied by considering its footprint in the symmetry plane. We will therefore use in this section PIV and HS-PIV data, from 270 CAD to 360 CAD (TDC) in the symmetry plane and in the pent-roof chamber. Let’s recall that the height x width of the PIV window (see Figure 2) is 12mm x 40mm. This height corresponds to 22% and 92% of the combustion chamber at respectively 270 CAD and TDC. The mean velocity field in this plane at 270 CAD and TDC are shown in Figure 7a and b. The mean transport along the cylinder head is evidenced at 270 CAD but has significantly decreased at TDC. Note that two components mean velocity fields in a horizontal plane (not displayed here for brevity) still demonstrate the presence of two foci (see Figure 6b) discussed in the previous section at 270 and 330 CAD. The characteristics of a 3D mean tumbling motion is thus detected at these phases.

The evolution of the kinetic energy per unit mass is plotted in Figure 8a. 

\[ E_c = \frac{1}{2S} \int_{S} \left( \langle U \rangle^2 + \langle W \rangle^2 \right) dS \]

is the kinetic energy of the mean flow because the mean value of the transverse velocity \( \langle V \rangle \) is expected to be small in the symmetry plane.

\[ E_f = \frac{1}{2S} \int_{S} \left( \langle u^2 \rangle + \langle w^2 \rangle \right) dS \]

is not the kinetic energy of the turbulence because one component is missing. A very clear exponential decrease of \( E_c \) is detected beyond approximately 300 CAD. This exponential decrease takes place with a characteristic time scale of \( \tau_d \approx 2 ms \) (slope of the dashed line in Figure 8a). The turn-over time scale of the tumbling motion at 330 CAD can be expressed as \( \tau_r \approx L/U \) where \( L \) is the available height and \( U \) an order of magnitude of the mean velocity. With \( L \approx 16mm \) and \( U \approx 6 m/s \) (see Figure 7b), one obtains \( \tau_r \approx 2.7 ms \approx \tau_d \). This means that the rate of decay of the kinetic energy of the mean tumbling motion scales with its turn-
over time scale. This is usually interpreted as the signature of vortex breakdown (Lundgren and Mansour 1996; Borée et al. 2002).

Figure 8: a. Evolution of the kinetic energy of the mean flow and fluctuating kinetic energy, b. First normalized POD mode $\sqrt{\lambda^{(1)}} \Phi^{(1)}(x)$ of the global proper orthogonal decomposition

The previous section has however shown that large scale cycle to cycle variations of the tumbling jet and of the induced tumble occur in this engine. A natural question is then: are the integral evolutions of Figure 8a the signature of a breakdown to smaller scale turbulence or just the signature of an amplification of a large scale cycle to cycle unsteadiness? In order to address this question, our choice is to focus on the temporal evolution of the structure of the flow using proper orthogonal decomposition (POD) and a methodology proposed by (Fogleman et al. 2004). POD is applied using the direct method on a basis of 3542 velocity fields (161 cycles of 22 fields spanning from 270 CAD to 354 CAD) non dimensioned by their own kinetic energy. By grouping in this way all the realisations of the flow during the last part of the compression stroke in the POD analysis, it is clear that the POD decomposition addresses both the spatial and temporal coherence of the flow. Moreover, the normalisation step is an essential one when dealing with tumble flows. Indeed, a classical POD would focus on the large scale coherence of the events containing kinetic energy, namely on all the phases prior to 300 CAD as shown in Figure 8a.

Each instantaneous velocity field $U_n(x, \theta)$ is divided by the square root of its own energy $E_n$. The result is a normalized velocity field: $u_n(x, \theta) = U_n(x, \theta)/\sqrt{E_n(\theta)}$, corresponding to a new individual event having a normalised energy $e_n(\theta)=1$. The two-point correlation tensor is approximated by:

$$R(x,x') = \langle u_n(x)u_n(x') \rangle = \frac{1}{M} \sum_{n=1}^{M} u_n(x)u_n(x')$$

$M$ is the total number of independent events in the PIV statistical dataset. $N$ is the number of fields per phase ($N=161$) and $K$ is the number of phases acquired ($K=22$). The total number of fields is then $M = N \times K = 3542$. $M$ eigenfunctions $\Phi^{(k)}(x,y)$ and positive eigenvalues $\lambda^{(k)}$ ($k=1,\ldots,M$) of the two-point correlation tensor are obtained. $\Phi^{(k)}(x,y)$ are the POD modes associated to the eigenvalues $\lambda^{(k)}$. The eigenvalues are real and $\lambda^{(k)} > \lambda^{(k+1)}$. Each instantaneous flow field component belonging to the compression stroke can be projected onto the POD orthonormal basis to obtain:

$$u_n(x,z) = \sum_{k=1}^{M} a_n^{(k)} \Phi^{(k)}(x,z)$$

The coefficients $a_n^{(k)} = \langle u_n^{(k)} \Phi^{(k)} \rangle$ are the random reconstruction
coefficients and are uncorrelated. The normalization of each velocity field has an important consequence for the random coefficients $a_n^{(k)}$. Indeed, using the POD decomposition and the fact that $\left(\Phi^{(k)},\Phi^{(l)}\right) = \delta_{kl}$, it is easy to show that, for each instantaneous flow field:

$$1 = e_n(\theta) = (u_n, u_n) = \sum_{k=1}^{M} a_n^{(k)}(\theta)^2.$$ 

This specific property will be used in the conditional analysis presented in what follows. Averaging this relation at a specific CAD and introducing the phase averaged eigenvalue $\lambda^{(k)}(\theta) = \left\langle a_n^{(k)}(\theta) a_n^{(k)}(\theta) \right\rangle_{\theta}$, we also obtain $\sum_{k=1}^{M} \lambda^{(k)}(\theta) = 1$.

The first phase invariant POD mode is displayed in Figure 8b and corresponds to the footprint of a single large scale tumbling flow along the roof of the chamber. The analogy with the mean structure of the PIV field before tumble breakdown (Figure 7a) was expected. All the other POD modes have more complex structures and introduce vertical flow variations having a smaller length scale. The Table 2 shows that the convergence of the global eigenvalues is fast. Indeed, 5 modes contain more than 90% of the normalized kinetic energy. The physical interpretation of this global convergence is difficult and we rather propose to focus on the evolution of the phase averaged eigenvalues displayed in Figure 9a. We see in this figure that the convergence of the eigenvalues is very high before say 300 CAD but that the role of higher POD modes bursts during tumble breakdown. The relative evolution of the 10 first eigenvalues is plotted with a logarithmic scale in Figure 9b. Each $\lambda^{(k)}(\theta)$ is normalized by its averaged value in the CAD interval $[286^\circ,306^\circ]$. The transfer of energy from mode 1 to the higher modes appear very clearly in this figure and, at the precision of the present data, we can see that all eigenvalues for $k \geq 2$ burst at approximately the same exponential rate. A transfer from the large scale coherence (mode 1) to all higher orders modes is thus evidenced and is believed to correspond to the signature of tumble breakdown.

<table>
<thead>
<tr>
<th>Mode n°</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda^{(k)}$</td>
<td>0.819</td>
<td>0.04</td>
<td>0.023</td>
<td>0.015</td>
<td>0.011</td>
<td>0.009</td>
<td>0.007</td>
<td>0.006</td>
</tr>
<tr>
<td>$\sum \lambda^{(k)}$</td>
<td>0.819</td>
<td>0.859</td>
<td>0.882</td>
<td>0.897</td>
<td>0.908</td>
<td>0.917</td>
<td>0.924</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Table 2 : Eigenvalues of POD and associated convergence

The projection of each realization onto the first global POD mode being a good indicator of the level of tumble breakdown, a further step is to analyze the evolution of all the corresponding random coefficients. The quantity $\left(a_n^{(i)}(\theta)\right)^2$ is plotted in Figure 10a. The dispersion of $\left(a_n^{(i)}(\theta)\right)^2$ is low before 300 CAD and the first mode dominates each realization. However, the dispersion gets very high during tumble breakdown and it is obvious that some cycles keep a very coherent structure till TDC while others loose this structure very early in the compression phase. The pdf of $\left(a_n^{(i)}(\theta)\right)^2$ at 354 CAD is shown in Figure 10b. Having 161 cycles only, the main conclusion is that this pdf is rather “flat” for $\left(a_n^{(i)}(\theta)\right)^2 \in [0,0.9]$ with slightly higher probabilities of having a very low value in the interval $[0,0.1]$. These data show that the loss of large scale coherence is not observed in all cycles. In particular, this means that the increase of turbulent kinetic energy (Figure 8a) results both from a transfer to small scale turbulence and a large scale cycle to cycle variability.

Having HS-PIV data is interesting because the time evolution of $\left(a_n^{(i)}(\theta)\right)^2$ in a given cycle is known. Multi-time statistics can then be computed and a significant correlation is found between first
random coefficient during breakdown (for \( \theta \geq 300CAD \)). This result shows that, from the state of the flow at TDC, one can separate the breakdown phase into different families having very distinct behaviors correlated over the breakdown phase. Moreover, it is possible to show that statistically, flows having the largest kinetic energy in the symmetry plane before the breakdown phase are likely to transfer this kinetic energy to smaller scale fluctuations during the breakdown phase.

![Figure 9](image9.png)

**Figure 9**: a. Evolution of the phased averaged eigenvalues for the 10 first POD modes, b. Relative evolution of the phase average eigenvalues

![Figure 10](image10.png)

**Figure 10**: a. Evolution of \( (a_n^{(1)}(\theta))^2 \) for each cycle during compression, five groups spanning the pdf of \( (a_n^{(1)}(\theta))^2 \) at 354CAD, b. pdf of \( (a_n^{(1)}(\theta))^2 \) at 354CAD

Five groups spanning the pdf of \( (a_n^{(1)}(\theta))^2 \) in equal intervals of width 0.2 are selected in what follows (see Figure 10a) to perform a conditional analysis based on the structure of the flow near TDC. The statistical convergence in each group is of course not perfect with a total number of 161 cycles. However, the time evolution of the conditional kinetic energy of the mean and fluctuating flow in each group displayed respectively in Figure 11a and Figure 11b shows clear trends. Indeed, the increase of the fluctuating kinetic energy is the largest for cycles that experience a loss of large scale coherence (groups 5 and 4) while no maximum is detected for cycles keeping their coherence (group 1). The fact that the level of fluctuating kinetic energy at TDC is slightly smaller for group 5 than for group 4 is within the statistical error. However, previous experiments (Moreau et al. 2004) have shown that an early breakdown gives more time to turbulent dissipation and results in a lower level of fluctuation near TDC. This may be a physical reason for the present observation. One also
observes that the maximum kinetic energy of the mean flow is larger for groups 4 and 5. This illustrates further the level of statistical correlation between the kinetic energy of the flow before breakdown and the level of breakdown.

5. Conclusion

The goal of this paper was to make use of both PIV and high speed PIV (HS-PIV) in an optically accessible research engine in order to address both the spatial structure of an engine flow of moderate tumbling ratio and its temporal evolution during series of consecutive cycles. 2D-2C PIV phase averaged data acquired in selected in-cylinder planes have therefore been used to understand the chain of events driving the generation of the mean tumbling motion. Beyond 90 CAD, a tumbling jet structure develops along the wall of the cylinder, opposite to the intake valves, and interacts with the moving piston. An up-wash flow along the cylinder walls is detected. For a circular cylinder and a tumbling jet impacting the piston along one side of the cylinder, such 3D structure is expected because the downward momentum flux of the jet is deflected by the piston, spreads along the flat surface and interacts with the curved cylinder wall. Spatial integral indicators – namely circulation, momentum fluxes and POD analysis restricted to the focus regions and extended to the jet region – were introduced in order to quantify the cycle to cycle stability of the flow. The variations in structure and intensity of the 3D flow at BDC are shown to be very high and believed to be strongly correlated with the development and merging of the intake jets.

During the early compression phase, the flow along the piston diverges away from the jet impact region, rolls-up not only in the symmetry plane but also along the cylinder wall, focuses in the central region of the upper region of the cylinder and impacts the piston in a down-wash motion. One key progress in the understanding of the cycle to cycle large scale fluctuations of the tumbling motion lie in the characterization of the in-cycle properties of the tumbling jet.

The breakdown phase was studied by considering the signature of the tumbling motion in the symmetry plane and in the pent roof chamber. From a classical RANS treatment of the data, we first show that the rate of decay of the kinetic energy of the mean tumbling motion scales with its turnover time scale. This is usually interpreted as the signature of vortex breakdown. The increase of turbulent kinetic energy results both from a transfer to small scale turbulence and a large scale cycle to cycle variability. By applying phase invariant proper orthogonal decomposition and multi-time statistics on high speed PIV data in the second part of the compression phase, \( \theta \in [270^\circ,360^\circ] \), we have proposed to distinguish cycles according to their structure and to use this decomposition to compute conditional statistics. Indeed, the phase invariant POD guarantees to determine a large
scale structure (mode 1) keeping in an optimal way the spatial and temporal coherence of the flow in the measurement domain. This conditional analysis shows that the increase of the fluctuating kinetic energy is the largest for cycles that experience a loss of large scale coherence while no maximum is detected for cycles keeping their coherence.

6. References


