Pulsatile turbulent flow through pipe bends at high Dean and Womersley numbers

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Abstract. Turbulent pulsatile flows through pipe bends are prevalent in internal combustion engine components which consist of bent pipe sections and branching conduits. Nonetheless, most of the studies related to pulsatile flows in pipe bends focus on incompressible, low Womersley and low Dean number flows, primarily because they aim in modeling blood flow, while internal combustion engine related flows have mainly been addressed in terms of integral quantities and consist of single point measurements. The present study aims at bridging the gap between these two fields by means of time-resolved stereoscopic particle image velocimetry measurements in a pipe bend with conditions that are close to those encountered in exhaust manifolds. The time/phase-resolved three-dimensional cross-sectional flow-field 3 pipe diameters downstream the pipe bend is captured and the interplay between different secondary motions throughout a pulse cycle is discussed.

1. Introduction

1.1. Background

The study of fluid flow through pipe bends is often associated with Dean (1927), who provided an analytical solution to this problem under steady and laminar conditions. His study revealed the existence of two symmetrical counter-rotating vortices located in the upper and lower half of the pipe. These unique structures, that have become the driving force for many research studies, are nowadays widely known as Dean vortices. While Dean’s study as well as those following (McConalogue & Srivastava, 1968; Greenspan, 1973) were dealing with laminar and steady flows, the question whether the vortical picture found in steady flows would remain under more practical, i.e. unsteady or turbulent, conditions remained to a large extent untouched. Almost five decades after the seminal work by Dean, the problem of unsteadiness of a viscous fluid motion in a curved pipe was addressed by Lyne (1971), who revealed that the flow pattern can change drastically depending on the frequency of the oscillations. A series of studies, which confirmed and extended Lyne’s work followed (Zalosh & Nelson, 1973; Bertelsen, 1975), but were still limited to smaller parameter values than those met for example in the internal combustion engine environment, for which this study is aimed at. A great interest in pulsating flow through pipe bends was also shown by a number of authors due to its relevance to physiological mechanisms...
such as the causes of atherosclerosis and the blood flow in the aortic arch (Chandran & Yearwood, 1981; Hamakiotes & Berger, 1990) and consequently did not extend their investigation to high values of the parameters.

Up to now, the interest for pulsating flow through pipe bends remains vibrantly alive while no clear conclusion has been made yet on the structural picture of the flow field under turbulent, pulsating flow conditions. The most important parameters that control the flow under turbulent, pulsating conditions through pipe bends are the Dean and Womersley (or frequency parameter) number, which are defined respectively as: $De = \sqrt{\gamma} Re$ and $\alpha = D / 2 \sqrt{\omega \rho / \mu}$, where $Re$ denotes the Reynolds number based on the pipe diameter $D$, $\gamma$ the curvature ratio, $\omega$ the angular frequency, $\rho$ the density and $\mu$ the dynamic viscosity of the fluid. The Reynolds number itself is of course also of importance, here we assume that it is high enough so that the flow is fully turbulent. The Womersley number can be said to be the ratio of the oscillatory inertial forces related to the pulsations and the viscous forces. Recently, Timité et al. (2010) performed both simulations and experiments in developing laminar pulsating flow, adding information on the evolution of the secondary flow under the effect of different, but low, Reynolds numbers and a wide range of the frequency parameter. In the same kind of flow, but for a slightly different parameter range, Jarrahi et al. (2010) performed Particle Image Velocimetry (PIV) measurements, revealing secondary flow patterns varying from a single dominating vortex to more complex constellations with up to four vortices.

1.2. Motivation

The aforementioned studies show that increasing the Dean and Womersley number has a large effect on the strength of the secondary motions and makes the flow field more complicated, varying between multiple vortex patterns at certain instances and no vortex patterns at other instances. Our motivation to study high Dean and Womersley number flows in curved pipes stems from the fact that such flows are widely met in internal combustion engines (for example in the exhaust manifold) and can strongly affect the engine performance, especially for turbocharged engines.

Studies focusing on engine research often regard single point measurements (Szymko et al., 2005; Capobianco et al., 1993) which do not provide a full picture of the nature and structures of the turbulent pulsating flow field. The way for example the Dean vortices behave under harsh engine flow conditions (reportably of the $10^2$ and $10^5$ order for the Womersley and Dean number respectively) and how the three dimensional velocity field looks during the phases is to a large extent unknown. Some efforts have been reported in more recent years to show how the vortices behave under high Dean number conditions. Rütten et al. (2005) performed Large Eddy Simulation (LES) and comparing results with these from PIV measurements by Brücker (1998), confirmed the existence of the so-called “swirl switching” phenomenon first observed by Tunstall & Harvey (1968). This phenomenon exhibits one vortex that alternatively dominates the two different sides of the pipe, “switching” between the two positions with varying strength. The same phenomenon was depicted in the results from Stereoscopic PIV measurements by Sakakibara et al. (2010) at a Reynolds number of $Re = 1.2 \times 10^5$. Sudo et al. (1998) on the other hand, presented results from hot-wire measurements providing information on the velocity field and Reynolds stresses distribution in a $90^\circ$ pipe bend with long straight upstream and downstream pipes at $Re = 6 \times 10^4$. These studies, addressing the effect of the pipe bend, considered only steady flow conditions. Hellström & Fuchs (2007) computed the turbulent steady and pulsatile flow field by LES and Reynolds Averaged Navier-Stokes (RANS). The steady turbulent case at $De = 3 \times 10^3$ was computed in a single pipe bend while the pulsating case at $De = 6.3 \times 10^2$ and $\alpha = 8$ was calculated for the case of a double bended pipe revealing very complex secondary patterns during a cycle.

It is now made clear that studies need to be performed on high Dean and Womersley number
flows in order to investigate the parameters that affect the performance of the engine but also to
give useful information on the limitations of classical experimental techniques in highly unsteady,
turbulent and three dimensional flows, as well as to provide a unique data base for the CFD
community. Above all, these studies will give new insight into the complex flow field, during a
cycle and its vortical structures.

2. Experimental set-up

2.1. Pulsating pipe flow rig
The experiments were conducted in a newly developed flow rig in the CICERO Laboratory at
KTH CCGEx. The rig can be operated both under steady and pulsating flow conditions and the
air is supplied through a compressor installation facility that can deliver up to 500 g/s at 6 bar.
The pulses are obtained from a rotating valve located upstream of the pipe test section and its
rotation rate can be set by a frequency controlled AC motor. The insert in Figure 1 depicts the
relative open area change caused by the rotating valve as function of the revolution angle. The
flow rate is monitored for accuracy by means of a hot-film type mass flow meter (ABB Thermal
Mass Flowmeter FMT500-IG) which is located around 10 m upstream from the measurement
site. For details on the CICERO rig the reader is referred to Laurantzon et al. (2010).

For the present measurements, a 90° pipe bend of inner diameter $D = 40.5$ mm and curvature
radius $R_c = 51$ mm was connected to the downstream end of a straight pipe section which
provided a total entrance length of 20 $D$ downstream of the pulse generator. All measurements
were taken at the exit of an extension pipe with the same inner diameter and length 3 $D$
downstream of the bend as depicted in Figure 1.

2.2. Measurement technique
Time-Resolved Stereoscopic Particle Image Velocimetry (TS-PIV) was employed in order to
capture snapshots of the instantaneous in-plane velocity components as well as the streamwise
velocity across the pipe cross-section. Two high-speed C-MOS cameras (Fastcam APX RS,
3000 fps at full resolution, 1024 × 1024 px, Photron) were positioned in backward-forward scattering mode at an angle of approximately 70° between the observation axes (see figure 1). The 105 mm camera lenses (Nikon Nikkor) mounted on the cameras were adjusted by means of a Scheimpflug adapter. The raw images from the measurements had a resolution of 1024 × 1024 px and a 10-bit dynamic range. For the steady flow measurements the images were taken at a sampling frequency of 1 kHz and for the pulsating flow measurements images were acquired at 1.5 kHz while the laser was additionally triggered externally by the valve rotation in order to enable phase averaging of the snapshots.

A laser light sheet of 1 mm thickness was produced by a Nd-YLF laser (Pegasus PIV-Laser, 10 kHz maximum frequency, New Wave) which was aligned 1 mm downstream from the exit of the pipe and oriented perpendicular to the main flow direction. For the in-situ calibration of the cameras, images were taken of a two-level calibration plate (#20, LaVision GmbH).

A water-based solution (Jem Pro Smoke Super ZR-Mix) was atomized using a high volume liquid seeding generator (10F03 Seeding Generator, DANTEC Dynamics). Smoke was injected homogeneously through 4 holes drilled symmetrically around a steel pipe section which was mounted upstream of the pulse generator in order to avoid effects on the smoke distribution from the valve rotation. The post-processing of the PIV data was performed using a commercial software (DaVis 7.2, LaVision GmbH). The vector fields were calculated by a multi-pass iteration procedure starting with a 64 × 64 px interrogation window and decreasing down to 16 × 16 px interrogation window with 50 % area overlapping.

3. Results & Discussion

3.1. Steady Turbulent Flow

Steady turbulent flow measurements were performed by means of TS-PIV at a downstream position of 3 D from the bend. Figure 2 shows snapshots of the streamwise velocity field and the in-plane velocity components. Nearly symmetrical structures at the upper and lower section of the pipe are observed at certain instances (left figure) while at other instances the vortices are seen to move either in clockwise (middle figure) or anti-clockwise (right figure) direction in varying strength. Similar observations were also made by Hellström & Fuchs (2007) who

![Figure 2. Left, Middle & Right: Snapshots of the streamwise and in-plane velocity field from TS-PIV measurements 3 D downstream the 90° pipe bend. Streamwise (W) and in-plane (U and V) velocities are depicted through the contour map as well as vector field, respectively. The asterisk denotes scaling by the bulk velocity obtained from the ABB mass flow meter.](image-url)
performed simulations on the experimental set-up by Sudo et al. (1998) in a 90° pipe bend, for $De = 3 \times 10^4$. Even though no direct comparison can be made due to the different flow and geometrical parameters between the two studies, the instantaneous results from the simulations show a behaviour of the vortical structures that can also be seen in the present study.

Figure 3 depicts the time-averaged flow field computed over 500 snapshots acquired at a sampling frequency of 1 kHz, which corresponds to about 400 integral time scales. In principle the figure should be symmetric around the centreline, however the difference between the lower and upper half is probably due to an insufficient number of independent snapshots.

The vortex structure is clearly illustrated by the streamlines in Figure 3, though the upper vortex is not captured entirely. Note also that the region $r/R > 0.95$ is excluded here due to reflections which cause spurious vectors. One observation in our study is that the streamwise velocity maxima is not at the outer wall but two maxima are found along the upper and lower sides, respectively. A similar effect was seen by Sudo et al. (1998) where the evolution of the flow field at different stations after the bend showed a tendency of the higher speed side slowly moving from the outer wall until the flow profile becomes fully symmetrical. Contour maps featuring the highest velocity located closer to the inner wall at downstream locations after the bend was also shown in Enayet et al. (1982), who studied developing turbulent flow by means of Laser-Doppler Velocimetry (LDV) in a 90° pipe bend at $Re = 43000$. For the present experimental configurations, additional measurements at further upstream locations (not presented here), showed the maximum velocity located closer to the outer wall revealing a tendency of the velocity maxima to move from the outer wall towards the centre while under the effect of the secondary motions exhibiting a slight “overshoot” towards the inner wall at 3 $D$ distance from the bend.

3.2. Time/Phase-Resolved results: Pulsating turbulent flow
For a high Womerlel number the unsteady inertia forces dominate in comparison with the viscous forces while interacting with the centrifugal forces under one cycle, providing more complicated and varying secondary flow structures than those seen in the steady flow case. TS-PIV measurements under pulsatile conditions were performed at $De = 1.5 \times 10^4$ and $\alpha = 72$. Snapshots of the streamwise and in-plane velocities are shown in Figure 4 for different phases.
of the pulse cycle. The phase averaged velocity at the centreline of the pipe is also shown as an indication of what instance during the pulse cycle each one of the figures represent. At the end of the first acceleration phase the highest velocity reaches 3.5 times the bulk speed, while at the end of the deceleration phase back flow with a magnitude of the bulk speed sets in.

During the whole acceleration phase (top of Figure 4) no clear cross flow structures can be seen, and at the beginning of the phase shown the highest streamwise velocity is at the inner half of the pipe whereas the flow becomes more uniform with time. Timité et al. (2010) showed that for laminar flow, as the frequency parameter increases, the secondary flow intensity decreases which can also be seen here for a large value of $\alpha$, even though for a completely different type of flow.

![Figure 4.](image)

**Figure 4.** Left: Snapshots of the streamwise velocity and in-plane vector field at subsequent instances $3D$ downstream the 90° pipe bend at $De = 1.5 \times 10^4$ at a pulsating frequency of 30 Hz corresponding to $\alpha = 72$. Right: Instantaneous streamwise velocity (thin black line) and its phase average (thick red line) at the centreline of the pipe. The phase angle corresponding to the shown snapshots is indicated through the vertical dashed lines. Top: Acceleration phase, middle: Deceleration phase, Bottom: Back flow.
A completely different vortical picture is shown during the deceleration phase (centre of Figure 4) where almost symmetrical vortical structures are seen and the position of the maximum streamwise velocity has switched to the outer wall, thereby resembling a C-shaped velocity distribution similar to those observed in steady flows in the vicinity of the pipe bend.

Reversed flow is an often observed phenomenon under pulsating flow conditions (Timité et al., 2010; Hellström & Fuchs, 2007). As the deceleration phase ends and back flow sets in (bottom of Figure 4), a pair of vortical structures can be distinguished which are seen later on being almost “squeezed” inside the back flow region until they are completely vanished.

The phase averaged streamwise and in-plane velocities are shown as contour and vector plots respectively in Figure 5 depicting a similar and smoother structural picture as in the instantaneous figures, as expected. During the acceleration phase, no vortical structures can be recognized even here, due probably to the dominant inertial forces. The almost symmetrical vortices observed in the instantaneous figures during the deceleration phase appear smoother.

Figure 5. Left: Phase averaged streamwise velocity and in-plane vector field for the same case as in Figure 4. Right: Phase averaged streamwise velocity (thick red line) at the centreline of the pipe. The phase angle corresponding to the shown phase averages is indicated through the vertical dashed lines. Top: Acceleration phase, middle: Deceleration phase, Bottom: Back flow.
Figure 6. Contour plots of the probability density function of the streamwise velocity along the horizontal axis at 3 $D$ downstream distance from the pipe bend exit, plotted together with its mean value (thick black line) at $De = 1.5 \times 10^4$. Left: Steady flow Right: Pulsating flow ($\alpha = 72$). Note that the PDFs have been scaled to unity in order to ease comparison between the steady and pulsating flow case.

Figure 6 shows the probability density function (PDF) of the streamwise velocity component for both the steady and the pulsating flow case together with its mean value along the horizontal axis. The time-averaged profiles between the two flow cases do not differ considerably from each other; i.e. both exhibit a “saddle”-like profile with a slightly larger amplitude on the inner side of the pipe (see also Section 3.1). It is interesting to note, that for the steady flow case the PDF looks as expected, i.e. with the most frequent velocity appearing around its time-average value, while for the pulsating flow it is accumulated around zero velocity. The bimodal behaviour of the PDF (Left Figure) caused by the pulsatile motion, is apparent from the phase averaged signal at the centreline (thick red line) shown in Figure 5.

4. Summary & Conclusions

The present investigation aims at understanding the behaviour of the secondary motions and the distribution of the axial velocity under the effect of the pipe bend in a parameter range that is relevant to the flow environment for internal combustion engines. TS-PIV measurements have been conducted in a high Dean and Womersley number flow, through a 90° pipe bend.

It was shown that the flow has started to recover from the bend at a downstream distance of 3 $D$, depicting the highest axial velocity located close to the inner wall. Measurements conducted in highly pulsating flow revealed that the secondary flow appeared to be very weak during the acceleration phase while the highest velocity reached 3.5 times the bulk speed. A different vortical picture was observed during the deceleration phase, where symmetrical structures were present at certain instances. The streamwise velocity was observed to have moved its maximum from the inner wall during the acceleration phase to the outer wall during deceleration. The almost symmetrical vortices were observed at the beginning of back flow, being quickly “squeezed” into the centre of the pipe until vanishing in the peak of the reversed flow region.
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