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Vortical patterns in turbulent flow downstream a 90° curved pipe at high Womersley numbers

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ABSTRACT

The present experimental work focuses on highly pulsatile, *i.e.* inertia dominated, turbulent flow downstream a curved pipe and aims at investigating the vortical characteristics of such a flow. The flow parameters (Dean and Womersley number) investigated are of the same order as those met in the internal combustion engine environment. The technique employed is time-resolved stereoscopic particle image velocimetry at different cross-sections downstream the pipe bend. These measurements allow the large-scale structures that are formed to be analyzed by means of proper orthogonal decomposition. The flow field changes drastically during a pulsatile cycle, varying from a uniform flow direction across the pipe section from the inside to the outside of the bend to vortical patterns consisting of two counter-rotating cells. This study characterizes and describes pulsatile curved pipe flow at Womersley numbers much higher than previously reported in the literature. Furthermore, the oscillatory behaviour of the Dean cells for the steady flow – the so-called 'swirl switching' – is investigated for different downstream stations from the bend exit and it is shown that this motion does not appear in the immediate vicinity of the bend, but only further downstream.

1. Introduction

Studies on the fundamentals of pulsatile flows started truly in the mid 1950s (Womersley, 1955) focusing mainly on biological flows (McDonald, 1955; Helps and McDonald, 1954; Hale et al., 1955). These studies revealed some of the main characteristics that contribute to its complex nature, such as partial flow reversals. The complexity of pulsatile flow in its own comes also from the fact that it can be met not only in different Reynolds number regimes (laminar, transitional, turbulent) similar to steady flow, but can additionally be divided into three other categories (quasi-steady, intermediate and inertia-dominant) depending on the ratio between the unsteady inertia and viscous forces (Çarpinlioglu and Gündogdu, 2001). When the inertia forces are dominating, *i.e.* are much larger than the viscous forces, it is known that the turbulent structures can no longer respond to the rapid changes, hence turbulence becomes independent of the phase angle of the pulsations. The interested reader is referred to Ramaprian and Tu (1983), Shemer and Kit (1984), Shemer et al. (1985), Iguchi et al. (1985), Çarpinlioglu and Gündogdu (2001), Scotti and Piomelli (2001), He and Jackson (2009) for further details on pulsatile flow in internal geometries.

Turbulent flow through curved pipes occurs in a number of various industrial applications and has recently attracted new attention both from a fundamental (Rütten et al., 2005; Sakakibara and Machida, 2012) and applied point of view (Ono et al., 2010). One of the attractors for this interest is the oscillatory character of the Dean vortices (Dean, 1927), which are formed in the pipe bend due to the imbalance of the centrifugal force and an adverse pressure gradient. This phenomenon, known in the literature as *swirl switching* (Tunstall and Harvey, 1968; Brücker, 1998; Rütten et al., 2005; Sakakibara et al., 2010; Sakakibara and Machida, 2012; Kalpakli et al., 2012; Kalpakli and Örlü, 2013), depicts the two characteristic cells to alternatively dominate the turbulent flow field rotating in the clockwise and anti-clockwise directions. This motion – occurring at relatively low frequencies, *i.e.* large time scales – might cause fatigue in piping systems (Rütten et al., 2005; Yuki et al., 2011) and it is therefore important to investigate the exact mechanism that causes such a quasi-periodic vortical motion.

In many technical applications where a fluid or gas is transported in a piping system, turbulence is not fully developed and co-exists with a superposed pulsatile motion. The pulsations often act at a different (larger) time scale than the energetic turbulent time scales. This kind of flow is for example prevalent in different components of the Internal Combustion Engine (ICE) such as the exhaust manifold. Numerical simulations of such complex flow systems can give detailed knowledge of the flow (for an example see Hellström (2010)). To assess the accuracy and limitations of

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such simulations they need to be validated against experiments to make sure that the main physical features of interest are captured qualitatively as well as quantitatively. However, also experimental studies on pulsatile flow related to the engine flow environment are complex and mainly provide integral quantities (Szymko et al., 2005; Piscaglia et al., 2007; Capobianco and Marelli, 2010).

Detailed experiments for understanding the flow physics and to get experimental data for validation of simulations are therefore preferably carried out in idealized situations. As part of understanding the flow in an exhaust manifold, an idealized model case is the pulsatile flow through a curved pipe. For instance, studies based on quantitative and qualitative visualisation of laminar curved pipe flow (Sumida et al., 1989; Jarrahi et al., 2011; Timité et al., 2010; Glenn et al., 2012), show that there exist various vortical patterns within the fraction of a pulse cycle, differing from the vortical pattern known for steady curved pipe flow. However the relevance for an exhaust manifold may be limited since the flow in the real system is highly turbulent.

Therefore the present work aims at investigating both a steady and inertia-dominant flow (*i.e.* highly pulsatile, see also Section 2.1) at high Reynolds numbers in a curved pipe by means of two dimensional, three component (2D3C) measurements and extract information for the most energetic, large-scale structures present in such a flow through proper orthogonal decomposition (POD). The swirl switching phenomenon is studied for different stations downstream the bend whereas the various vortical patterns being formed under the acceleration and deceleration phases of a highly pulsatile flow are presented and discussed. This is believed to cast light onto the main characteristics of a flow related to the ICE environment from a more fundamental point of view and for flow parameters which have been missing from the literature.

2. Experimental set up and techniques

The experiments were conducted in the CICERO laboratory at KTH where a compressor installation facility delivers air at a maximum mass flow rate of 500 g/s at 6 bar, under steady or pulsatile flow conditions. The pulsatile motion is created by rotating a valve with its rotation rate being set by a frequency controlled AC motor. In order to ensure steady flow conditions, the mass flow rate is additionally monitored by a hot-film type mass flow meter (ABB Thermal Mass Flow meter FMT500-IG), that is mounted 10 m upstream the rotating valve. For details on the CICERO rig and related instrumentation the reader is referred to Laurantzon et al. (2012).

A 90° pipe bend of inner diameter D = 40.5 mm and curvature radius of R_c = 51 mm was mounted downstream a 20D long straight pipe. The data were acquired at two distances of 0.2 and 2D downstream the curved pipe (see Fig. 1).

The technique used to obtain the three dimensional flow field downstream the pipe bend was time-resolved stereoscopic particle image velocimetry (TS-PIV). To seed the flow an alcohol-based solution (Jem Pro Smoke Super ZR-Mix) was atomized using a high volume liquid seeding generator (10F03 Seeding Generator, DANTEC Dynamics). The resulting smoke was injected homogeneously through 4 holes drilled symmetrically around a steel pipe section mounted upstream of the pulse generator in order to avoid effects on the flow distribution from the smoke injection.

A laser light sheet of 1 mm thickness was produced by a Nd-YLF laser (Pegasus, 10 kHz maximum frequency, New Wave Research). The laser was externally triggered by the valve rotation in order to enable phase averaging of the snapshots. It should be noted here that due to technical restrictions the laser light sheet was not 'cutting' through the pipe, but instead positioned directly after the pipe exit. Such a configuration has – through comparison with hot-wire measurements obtained within the pipe – been shown to provide representative data of flow measured within the pipe, for the purposes of the current study (Kalpakli and Örlü, 2013).

Two high-speed C-MOS cameras (Fastcam APX RS, Photron, 3000 fps at full resolution 1024 × 1024 pixels, 10 bit) were positioned at an angle of approximately 70° between their viewing axes (Fig. 1) in backward-forward scatter. The 105 mm Nikon Nikkor lenses of the cameras were adjusted using a Scheimpflug adapter according to the synonymous principle (Prasad and Jensen, 1995). For the in situ calibration of the cameras, images were taken of a two-level calibration plate (#20, LaVision, GmbH). Small discrepancies between the object and image planes due to vibrations during the measurements were eliminated by means of self-calibration (Wieneke, 2005).

The number of acquired images was 1000 and they were taken with a sampling frequency of 1 kHz and 1.5 kHz for the steady and pulsatile flow cases, respectively. The post-processing of the data was performed with the commercial software DaVis 7.2, LaVision GmbH. The vector fields were calculated with a multi-pass iteration procedure for increased resolution starting with an interrogation window of 64 × 64 pixels and decreasing to 16 × 16 pixels with an overlapping area of 50%. Outliers were detected by a median test (Westerweel, 1994) and replaced by a linear interpolation scheme. It should be kept in mind that the data acquisition and evaluation parameters have been chosen with the aim to resolve the large-scale structures of the flow under focus while obviously the small dissipative scales are not resolved and are beyond the scope of this paper. Any further data analysis (statistical and modal) was performed in MATLAB (MathWorks®).

Complementary Laser-Doppler Velocimetry (LDV) measurements were also performed at the exit of the bend in order to compare with the PIV measurements. This was thought necessary, since the large-scale pulsatile character of the imposed flow

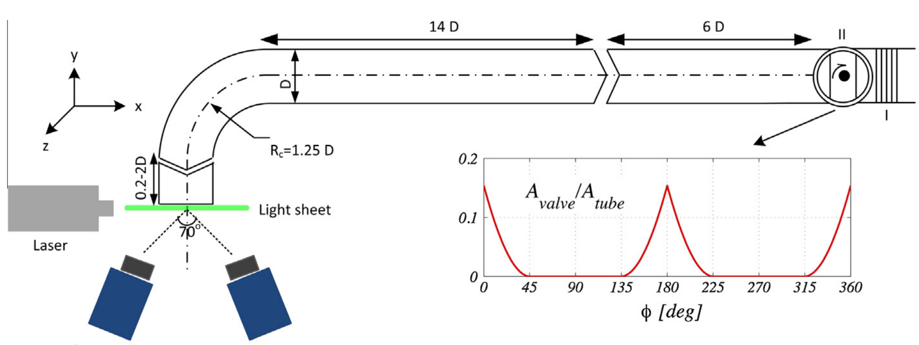

Fig. 1. Geometrical configuration used in the experiments and camera set up for the TS-PIV measurements *(top view)*. D = 40.5 mm, R_c = 51 mm, (I) smoke injection inlet, (II) rotating valve. The insert depicts the relative open valve area change as function of the revolution angle.