COHERENT MOTIONS IN TURBULENT FLOWS THROUGH CURVED PIPES

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Abstract

Turbulent flow in curved pipes occurs in a variety of industrial applications such as heat exchangers, nuclear reactors and components of internal combustion engines (*e.g.* exhaust manifolds), and has attracted the interest of the fluid-dynamics community both from a fundamental [1] and an applied point of view [2]. One of the main characteristics of this flow case is the imbalance between the cross-stream pressure gradient and the centrifugal force induced from the bend which causes a secondary motion in the form of a pair of counter-rotating vortices, so-called Dean vortices (Fig. 1). The observable turbulent structures are pushed towards the outer side of the curved pipe due to the centrifugal force, correspondingly the turbulence on the inner side is highly reduced. Moreover, the Dean vortices may reorganise the near-wall turbulence and yield a more complex system compared to the straight pipe configuration. In the present work, direct numerical simulations (DNS) are combined –for the first time– with experiments in order to obtain a proper understanding of the coherent motions and large-scale structure dynamics of the turbulent flow in a curved pipe.

Data generation: Curved pipe geometries can be classified as (a) spatially developing bends such as U-bends or elbows where a fully developed flow from a straight pipe enters the bend and (b) coiled tubes where the flow is developed inside the curved geometry. Even though the two cases exhibit different flow characteristics they also share some common features. As a first approach, the turbulent flow through an infinitely curved pipe (toroidal pipe with periodic boundaries) and a 90° bend are studied by means of DNS and Time-resolved Stereoscopic Particle Image Velocimetry (TS-PIV), respectively, complementing each other (see Fig. 1).

The numerical approach consists of the spectrally accurate representation of the turbulent field in an infinitely curved pipe solving for the fully developed, statistically steady flow in various configurations. The incompressible flow is expressed in Cartesian coordinates and solved by a spectral-element method on Gauss–Lobatto–Legendre nodes. The method has been developed and implemented by Fischer *et al.* [3] as the massively parallel code `nek5000`. A comparative study of turbulent characteristics in straight and curved pipes at different Reynolds numbers and various curvature ratios has recently been conducted by Noorani *et al.* [4]. This effort already provided the statistical data up to fourth-order moments in curved pipe configuration. A relevant parameter in curved pipes is the curvature ratio, also denoted κ. This dimensionless parameter distinguishes between mild curvature ($\kappa \approx 0.01$) and strong curvature ($\kappa \gg 0.01$) and is defined as $\kappa = R_a/R_c$; R_a being the radius of a generic cross-section of the pipe and R_c is the radius of curvature at the pipe centreline. Cross-sectional views of streamwise velocity, along with a section of equatorial mid-plane view of this quantity for a set of mildly curved ($\kappa = 0.01$), and strongly curved pipe ($\kappa = 0.1$) with bulk Reynolds number 11700 (based on pipe section diameter and bulk velocity) are presented in Fig. 2 along with 3D rendering of the isosurfaces of negative λ_2 [5] for each configuration. It is interesting to note that in the fully developed bend partial relaminarisation at the inner side is obvious from the figures; it is expected that the flow would be fully laminar at lower Reynolds numbers. To what extent turbulence can be maintained at higher curvatures and what its characteristics would be, is yet unknown and shall be studied.

The experimental data, on the other hand, were obtained 0.67 D (where $D = 60.3$ mm, the diameter of the pipe) downstream a 90° pipe bend of $\kappa = 0.31$. The air flow entering the bend from a straight pipe section of 100 D length was fully developed turbulent pipe flow. The Reynolds numbers based on the bulk velocity and pipe diameter which have been examined are $Re = 14000$, 24000 and 34000. Previous work [6, 7] examined the unsteady behaviour of the Dean vortices (Fig. 3) and also the effect of the curvature on the large-scale structures by means of Proper Orthogonal Decomposition (POD). However, the origin of the so-called 'swirl-switching' phenomenon [1] is not yet fully understood.

Future work and aim: DNSs are ongoing to match the experimental flow parameters (*i.e.* $Re = 14000$ and $\kappa = 0.31$) and results with both turbulent statistics and modal decomposition (POD) will be presented in the final paper. The available data sets will be assessed, and the influence of the two different setups will be discussed in detail. An interesting aspect which will be examined, is to what extent developed conditions can be obtained in the 90° bend compared to an infinite pipe. Specifically, the question of the origin of the swirl-switching will be addressed, carefully comparing the two setups (90° bend versus periodic, developed curved pipe flow). For this purpose, the four-dimensional DNS data is deemed to be particularly helpful, allowing POD and DMD decompositions to be performed and extract low and high frequencies present in the flow. This is believed to constitute a unique study which will provide for the first time, complementary and matching (fully resolved) simulations and experimental data in extracting coherent structures in turbulent curved pipe flows.

References

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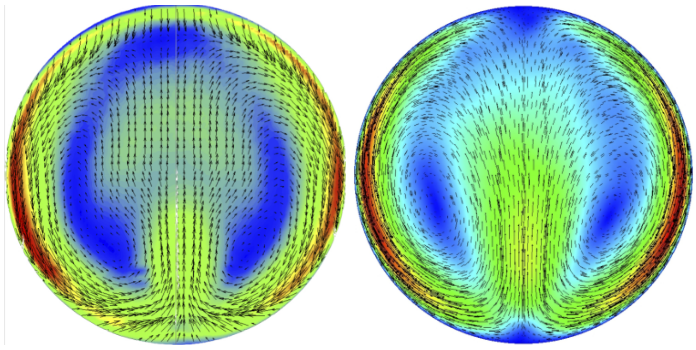

Figure 1. Time-averaged velocity field across a pipe cross-section from PIV (*left*) at $Re = 34000, \kappa = 0.31$ and DNS (*right*) at $Re = 11700, \kappa = 0.01$. The background contour map denotes the magnitude of the in-plane velocity components scaled by the bulk speed and the in-plane components are shown as vectors. Note the maximum mean value is indicated with red colour and for the DNS it reaches up to $0.05 \times U_b$ whereas for the PIV it reaches up to $0.5 \times U_b$ (where U_b denotes the bulk velocity).

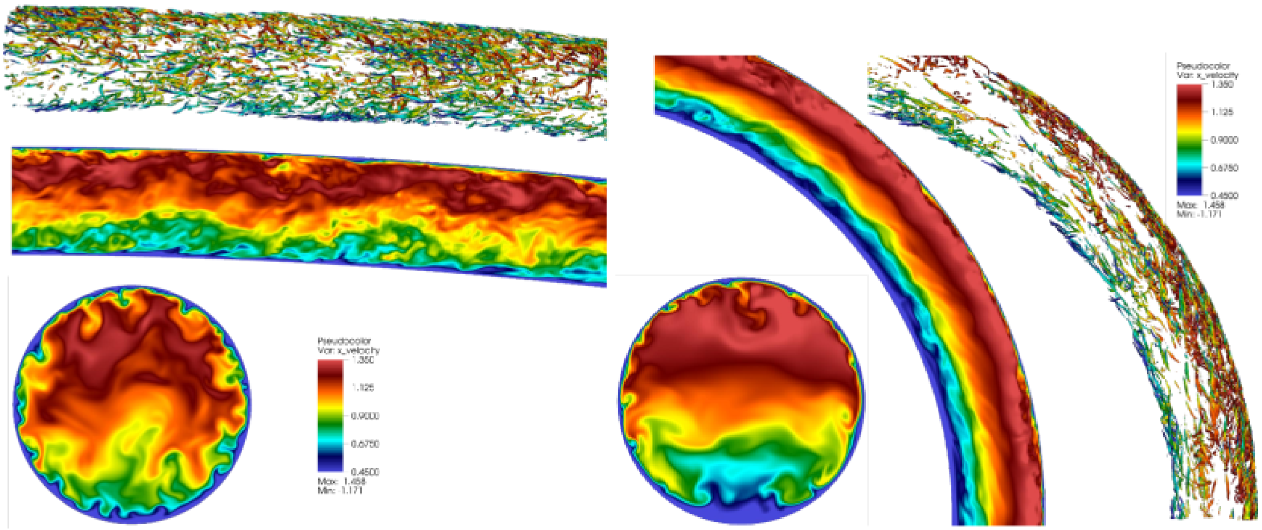

Figure 2. *(Left)*: 3D rendering of isosurfaces of negative λ_2 *(top)* coloured by the velocity magnitude, equatorial mid-plane view of streamwise velocity *(middle)*, and cross-sectional view of the same quantity *(bottom)* of the turbulent flow at mildly curved ($\kappa = 0.01$) pipe and bulk Reynolds number 11700. *(Right)*: Same quantities as left figure but for a strongly curved pipe ($\kappa = 0.1$) with similar flow rate (Data from DNS [4]).

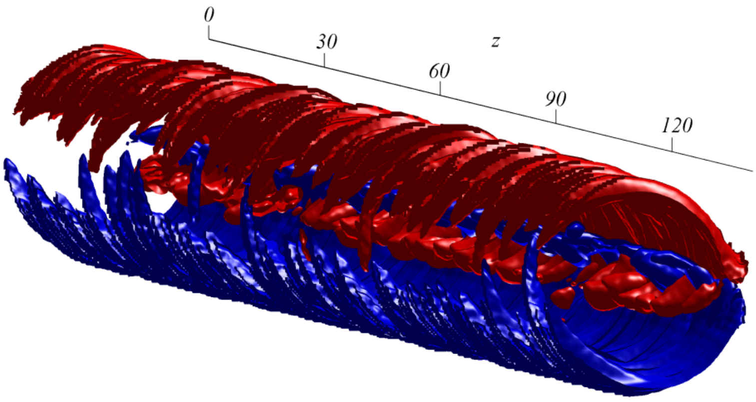

Figure 3. Spatial evolution of the POD reconstructed tangential velocity component (using the first 6 modes) for $Re = 34000$ and $\kappa = 0.31$, obtained by applying Taylor's hypothesis. The time-space transformation is done by assuming the bulk velocity and pipe diameter as convection velocity and characteristic length scale, respectively. The contours denote clock-wise (red) and anti-clockwise (blue) tangential velocities exceeding 40% of the bulk velocity (Data from PIV [7]).