Transitional and Turbulent Bent Pipes

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Abstract We review a number of aspects of the transitional and turbulent flow in bent pipes, obtained at KTH using the spectral-element code Nek5000. This flow, sometimes also called Dean flow, is characterised by the appearance of Dean vortices, which arise due to the action of the centrifugal force in the bend. We start with reviewing recent stability analysis in the toroidal flow, and conclude that for all curvatures $\delta > 0$ an exponential instability is present at a bulk Reynolds number of about 4000. Further increasing the Reynolds number lets the flow go through a region with potential sub straight and sublaminar drag. An analysis using proper orthogonal decomposition (POD) reveals that wave-like motions are still present in the otherwise turbulent flow. Upon further increasing Re, the in-plane Dean vortices lead to a modulation of turbulence depending on the azimuthal position. The flow is then dominated by low-frequency so-called swirl-switching motion. This motion is studied in both a periodic and spatially developing framework. Finally, the effect of Dean vortices on Lagrangian inertial particles is studied.

1 Introduction

The flow in bent pipes is an important natural extension of straight pipe flow, however, significantly less studies are devoted to bent pipes as compared to their straight counterparts. Due to the curvature, the azimuthal symmetry of the flow is broken, and centrifugal forces lead to the appearance of a secondary flow, i.e. an in-plane flow which manifests itself in the formation of two so-called Dean vortices. This secondary flow is skew-induced, and appears for both laminar and turbulent flow. The strength of these Dean vortices depends on the (bulk) Reynolds number Re_D, the curvature δ (usually defined as the ratio of pipe radius to the radius of the curvature), and also the streamwise extent of the bend. The latter parameter distinguishes the

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flow in a torus (see e.g. [1]) from the one in spatially developing pipes, as for instance the 90° bend [2]. A recent review of both experiments and simulations in bent pipe configuration is provided in [3].

2 Numerical Setup

The fully resolved direct numerical simulations (DNS) are performed using Nek5000 [5], a high-order spectral-element code, in a similar way as discussed in e.g. [4, 6]. Special care has been taken to assure that the somewhat unusual spectral-element discretisation with its non-equidistant point distribution even in homogeneous (periodic) directions does not lead to any visible artifacts in the results. As an example, Fig. 1 shows an in-plane cut of the streamwise vorticity at moderate Reynolds number $Re_\tau = 1000$ [4]; in this case the Reynolds number is based on the friction velocity and pipe radius. The spectral-element mesh is Cartesian over the shown section, and involves curved elements. Nevertheless, no discontinuities at the elemental boundaries are present in the solution, which is completely continuous even for the vorticity which involves derivatives of the primary flow variables. This indicates that both the chosen resolution (fixed in inner units for the various Reynolds numbers considered) and the other details of the solver are suitable for accurate DNS of turbulent flows.

The diameter $D = 2R$ is used to define the bulk Reynolds number Re_D, which is set to $Re_D = 11,700$ for most cases reported in this article, which corresponds in the straight section to a friction Reynolds number of $Re_\tau \approx 360$. To assure that no non-

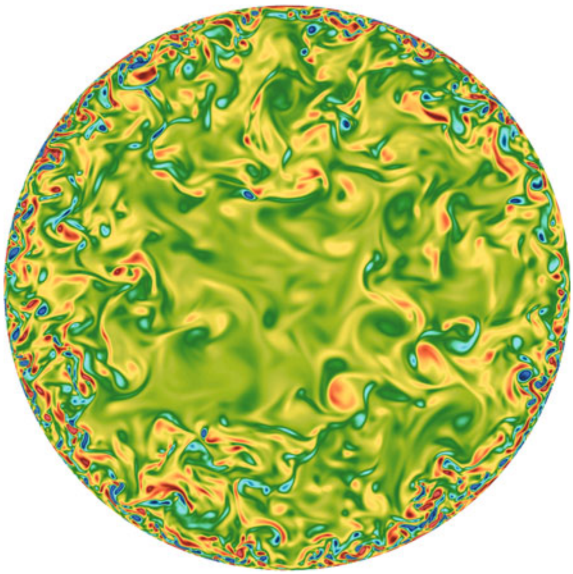

Fig. 1 Colour visualisation of the streamwise vorticity ω_z in a straight pipe at $Re_\tau = 1000$ [4]. Even though the mesh is non-uniform across the shown cut, no artifacts are visible even in the flow derivatives

physical effects are incurred throughout the simulation via the artificial periodicity, all shown torus simulations were performed in a pipe of total length of approximately $25R$. The spatially developing bend is even longer with a total length of $25D$.

The steady solutions and the stability analysis have been computed with PaStA, an in-house developed software code written in primitive variables and based on the finite element method (FEM, for details see [7]).

3 Stability and Transition

It has been known for a long time that the laminar flow in straight pipes does not exhibit a linear instability at any "relevant" Reynolds number (even though there is no formal proof as opposed to Couette flow). However, a similar analysis has not been performed for pipes with curvature, even though some recent experiments and simulations suggest a wave-like instability. Therefore, we started studying the laminar flow in bent pipes [8], and confirmed that indeed the curvature and the Reynolds number need to be considered independent parameters, and cannot be collapsed into a single Dean number. In [9] we provide a complete linear stability analysis, and found that for any pipe with curvature larger than zero exhibits a linear instability at $Re \approx 4000$; the corresponding stability diagram is shown in Fig. 2, and is composed of a multitude of modes grouped in different families. Note that for lower curvatures also subcritical transition, as observed in straight pipes, has been observed, but is not shown in the diagram.

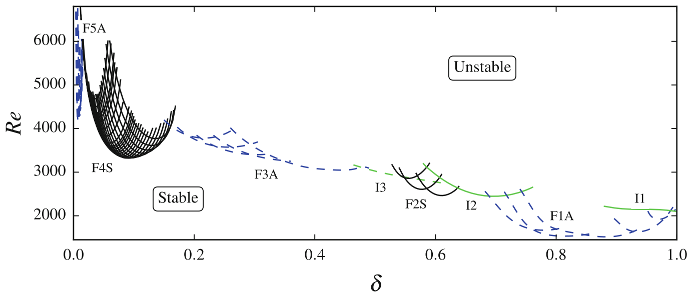

Fig. 2 Neutral curve in the $\delta - Re$ plane for $\delta \in [0.002, 1]$, see [9]. Each line corresponds to the neutral curve of one mode. The neutral curve for the flow is formed by the envelope of the lines. Five families *(black and blue)* and three isolated modes *(green)* are marked by labels. Symmetric modes are indicated with *continuous lines* while antisymmetric modes are represented with *dashed lines*. Note that the curves are not interpolated, i.e. they are segments connecting computed solutions with $\Delta\delta = \mathcal{O}(10^{-3})$. The uncertainty on the Reynolds number is $\pm 10^{-4}$

Fig. 3 Turbulence in a bent pipe: The pictures show from *left to right*: Vortical structures in the near-wall region, coloured with the streamwise velocity [6]; the wall-shear stress indicating partial laminarisation at the inner bend [12]; particle distribution for inertial particles [11]. For all simulations $Re_\tau = 360$, curvature $\delta = 0.1$

4 Turbulent Flow in Bent Pipes

After the flow has undergone transition, a turbulent flow is established [6] which is modulated by the in-plane Dean flow. This means that the turbulence at the outer side of the bend is enhanced, and partial laminarisation is observed at the inner side of the bend. A typical snapshot of such a turbulent flow at intermediate curvature is shown in Fig. 3, showing the azimuthal dependence of turbulence. Motivated by this inhomogeneity, we also studied inertial Lagrangian particles in bent pipes, and concluded that a bend may have a crucial impact on the spatial distribution of particles, see [10, 11]. For specific conditions there are regions, located in the centre of the Dean vortices, that are never visited by any particle. This knowledge may be important when designing probes that measure e.g. concentration.

It is intuitively clear that the drag induced by the flow in a bent pipe is generally larger than in the straight counterpart at the same mass flux. However, there exists a regime at comparably low Reynolds number and curvature, where this is not the case: both sub-straight drag and sub-laminar drag could be established using our numerical simulations [12]. It turns out that in these configurations the bend induces comparably strong wave-like motion in the flow, which transports the energetic near-wall flow towards the centre of the Dean vortices, thereby reducing the wall gradient.

5 Swirl Switching

The flow in bent pipes at high Reynolds number and sufficiently large curvatures has been known to exhibit low-frequency oscillations, which may contribute to fatigue of the structure [13]. This so-called swirl switching is the periodic dominance of one

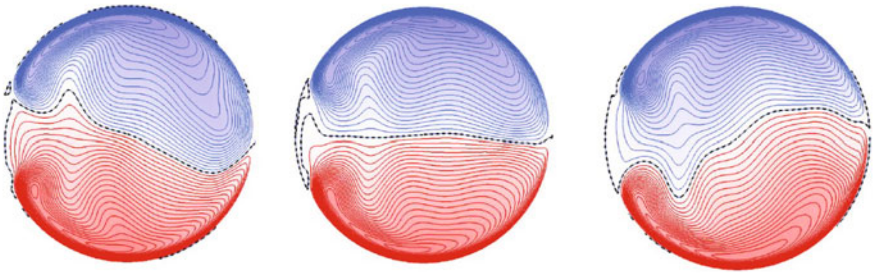

Fig. 4 Illustration of the swirl switching as an alternate dominance of one Dean vortex over the other; shown are contours of the in-plane stream function for three time instants. The *inner side* of the bend is on the *left-hand side* [1]

Dean cell over the other, and has been the subject of a number of recent (experimental) papers. Using our simulation setup we wanted to study this so-called swirl-switching phenomenon as well. We consider two different geometries, i.e. a toroidal pipe [1] and a spatially developing pipe [2].

For the torus simulations, an analysis using proper orthogonal decomposition (POD) revealed that the low-frequency oscillations characteristic of swirl switching could be detected in the flow [1]; Fig. 4 shows a low-order reconstruction with the 50 most energetic modes. This result indicates that in order for swirl switching to happen, no upstream straight section of the pipe is necessary, and only the bent part is sufficient. However, in experiments only spatially developing bends are considered, therefore we aimed at setting up a similar case in order to perform POD analysis on a spatial bend as well, see Fig. 5. In order to generate a turbulent inflow for the spatially developing bend, the synthetic eddy method [14] has been adapted to the current setup. This choice was particularly important in order to avoid spurious frequencies in the flow that would arise when using recycling conditions. Our experience with the current inflow method is very good, and the flow can be considered a canonical turbulent pipe flow already after 5 diameters downstream of the inflow. The POD analysis performed on the DNS data is classical; the only noteworthy aspect is that the symmetry of the flow (mirror symmetry) is exploited in our decomposition. In order to be able to compare to experiments, we have performed both 2D-POD (in cross-flow planes) and 3D-POD. It turns out that we could exactly reproduce all modes found in experiments using the 2D-POD technique. The fully three-dimensional POD modes reveal that the swirl switching is essentially one travelling mode, originating in the bend without connection to the inflowing turbulent flow. This finding highlights the importance of using the full three-dimensional velocity snapshots in order to extract correct modes, and thus an accurate low-order description of the phenomenon.

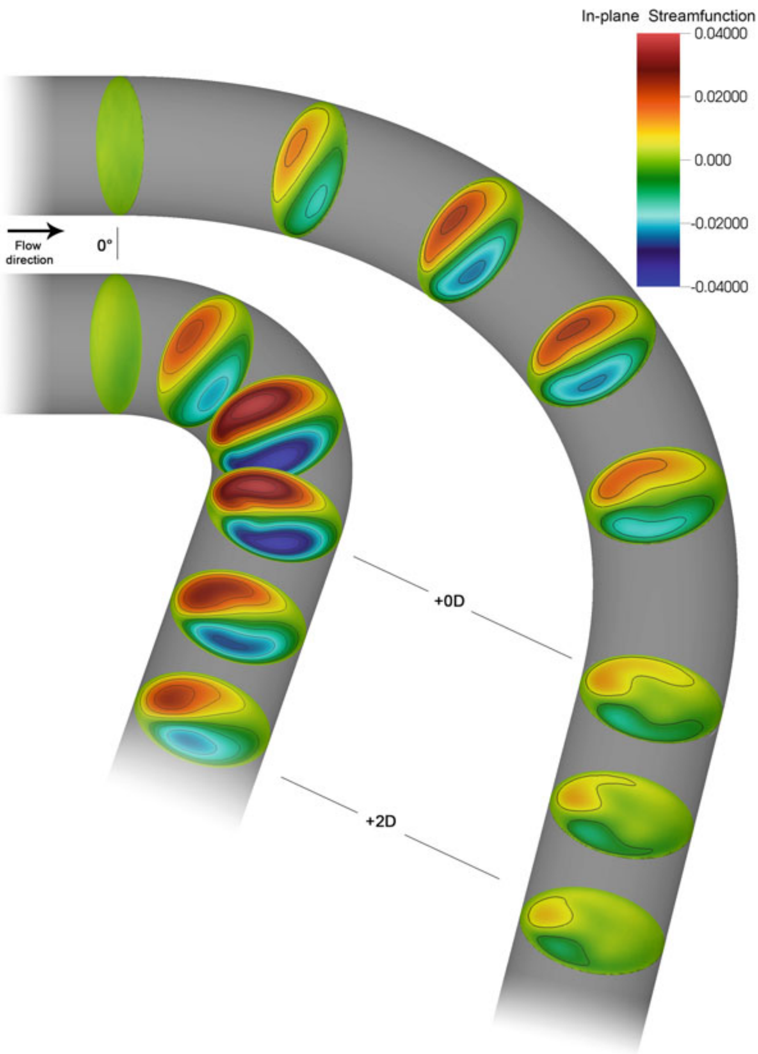

Fig. 5 Setup of the spatially varying bent pipe for studying the swirl switching: The flow enters on the top left, and is curved by 90° with curvature $\delta = 0.1$ and 0.3. The colours indicate the amplitude of the inplane streamfunction. The appearance of Dean vortices in the bend, and their subsequent decay can clearly be appreciated

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