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Evolution of turbulence characteristics from straight to curved pipes

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ABSTRACT

Fully developed, statistically steady turbulent flow in straight and curved pipes at moderate Reynolds numbers is studied in detail using direct numerical simulations (DNS) based on a spectral element discretisation. After the validation of data and setup against existing DNS results, a comparative study of turbulent characteristics at different bulk Reynolds numbers $Re_b = 5300$ and 11,700, and various curvature parameters $\kappa = 0$, 0.01, 0.1 is presented. In particular, complete Reynolds-stress budgets are reported for the first time. Instantaneous visualisations reveal partial relaminarisation along the inner surface of the curved pipe at the highest curvature, whereas developed turbulence is always maintained at the outer side. The mean flow shows asymmetry in the axial velocity profile and distinct Dean vortices as secondary motions. For strong curvature a distinct bulge appears close to the pipe centre, which has previously been observed in laminar and transitional curved pipes at lower Re_b only. On the other hand, mild curvature allows the interesting observation of a friction factor which is lower than in a straight pipe for the same flow rate.

All statistical data, including mean profile, fluctuations and the Reynolds-stress budgets, is available for development and validation of turbulence models in curved geometries.

1. Introduction

Turbulent flow in curved pipes is frequently occurring in a variety of industrial applications. Typical prominent examples are heat and mass transfer systems where straight, bent and helically coiled pipes are encountered in heat exchangers, chemical reactors, pipeline systems as well as components of internal combustion engines (e.g. exhaust manifolds). Similarly, biological systems such as the blood flow in arteries or the air flow in the respiratory system, are also occurring mostly in bent geometries. A better understanding of the physical mechanisms in action and improved ability to accurately model the specific fluid phenomena would help to improve the performance of such devices; e.g. improved heat and mass transfer coefficients and enhanced cross-sectional mixing, and reduced axial dispersion, as for instance discussed by Vashisth et al. (2008).

Compared with other (canonical) internal flows such as flow in straight pipes and ducts, the curved pipe configuration has been studied in detail mainly for laminar flow. In general, the curvature causes the appearance of centrifugal forces which deflects the axial maximum velocity away from the centre towards the outer side of the curved pipe. At the same time, the curvature gives rise to a secondary motion in the cross-section of the bent pipe, essentially due to the imbalance between the cross-stream pressure gradient and centrifugal force. This inviscid process is usually referred to as Prandtl's secondary flow of first kind, which by itself leads to the formation of a pair of counter-rotating, axially-oriented vortices, so-called Dean vortices. These vortices are skew-induced, and as such appear both in laminar and turbulent flow. Alternatively, mean streamwise vortices can also be formed as a result of local variation of the Reynolds stresses. These are then referred to as Prandtl's secondary flow of second kind (or stress-induced vortices) and are observed, for instance, in the turbulent flow in straight ducts with non-circular cross-section (see Bradshaw, 1987).

Curved pipe geometries can be classified into two major types: (i) spatially developing bends and (ii) coiled tubes/conduits. In spatially developing bends such as U-bends or elbows (90° bends), the entry flow passes through a straight inlet section before it reaches the bend, whereas in coiled tubes, the fluid flow is totally confined within the curved geometry. An extensive literature review of early research activities on flow in curved pipes has been carried out by Berger et al. (1983) and later also by Ito (1987). In addition, a more recent survey by Naphon and Wongwises (2006) also includes aspects of heat transfer.

It is a common approach among experimentalists to use helically coiled pipes in order to study the effect of curvature in bent pipes. In this case, the pitch of the resulting coil induces an additional *torsion* force acting alongside the centrifugal force on the fluid flow. However, in most practical applications, the pitch angle

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is small compared to the coil diameter and thus the influence of torsion becomes negligible with respect to curvature; see for instance the discussions on that topic in Manlapaz and Churchill (1980), Germano (1982), and Yamamoto et al. (1995). The idealised configuration is then reduced to that of a torus; i.e. an infinitely long bent pipe. This flow case provides a unique opportunity to isolate the effect of curvature on pipe turbulence, and also to study the influence of centrifugal forces and secondary motion on near-wall features.

In order to perform numerical simulations of fluid flow in curved pipes, on the other hand, the Navier–Stokes equation have to be expressed in curvilinear or body-fitted coordinates. Germano (1982) proposed local orthogonal helical coordinate system to study the laminar flow in a helical pipe. Despite these efforts, very few data bases regarding turbulence statistics and near-wall mechanisms in bent pipes are available from simulations. Boersma and Nieuwstadt (1996), Hüttl and Friedrich (2000), and Hüttl and Friedrich (2001) applied Germano's coordinates system in order to perform large-eddy simulation (LES) and direct numerical simulation (DNS) of the turbulent flow in curved pipes, respectively. In both references infinitely bent pipes using periodic boundary conditions were considered. Boersma and Nieuwstadt (1996) investigated the influence of curvature on the mean flow and rms (root-mean-square) fluctuations, and also tested the influence of different initial conditions. Hüttl and Friedrich (2000) employed DNS and studied the influence of curvature and torsion on turbulence at friction Reynolds number $Re_\tau = 230$; based on azimuthally averaged friction velocity and pipe radius. In their follow-up study, Hüttl and Friedrich (2001) observed that the turbulent fluctuations in curved pipe are drastically reduced compared to flow in straight configuration and also provided a useful database, albeit at low Reynolds number, for flow modelling for a variety of configurations, including data for few selected terms of the Reynolds stresses.

From an engineering point of view, one of the most crucial aspects of internal flow in pipes has always been the accurate determination and prediction of the relation between wall friction and flow rate. A customary way to parameterise this relation in pipe flow is given by the so-called Fanning friction factor (f) which non-dimensionalises the wall shear stress τ_w, expressed as friction velocity $u_\tau = (\tau_w/\rho)^{(1/2)}$, using the bulk velocity u_b and the fluid density ρ. Alternatively, the hydraulic head-loss (i.e. pressure drop) can be used as basis, yielding the Darcy–Weisbach friction factor (λ). It can be simply deduced that the two factors are related by $\lambda = 4f$. Determining concrete values for either of the two coefficients in various flow configurations has been the subjects of many studies: Regarding bent pipes, in the early part of the twentieth century Grindley and Gibson (1908) examined the viscosity of air in helically coiled pipes to measure the pressure drop. Since then there have several reports been published on refinements of the friction-factor diagram. For instance, Ito (1959) presented a series of experiments to find the correlation between λ and the flow rate for many curvature configurations. He also provided an empirical equation indicating the critical Reynolds number for transition to turbulence at each curvature configuration. It is generally accepted that the flow in curved pipes has a higher pressure drop than the straight ones at similar flow rates, which is believed to be related to the existence of the mentioned secondary motion. Cioncolini and Santini (2006) conducted a set of experiments in a wider range of the curvature parameter to obtain the Fanning friction coefficient, and they confirmed, in general terms, the validity of Ito's data. In their work, Cioncolini and Santini (2006) observed an additional interesting behaviour in the changeover from the laminar and turbulent flow for mildly curved pipes: When the flow rate is increased (parametrised by the Reynolds number), the friction factor does not monotonously increase away from the laminar value. Rather, it first reaches a minimum which is *below* the laminar Ito correlation. After an inflection point, the friction factor increases, and finally settles on friction values pertaining to developed turbulent flow in bent pipes. In addition, Cioncolini and Santini (2006) identified a small range of Reynolds numbers in which the flow at mildly curved pipes showed a lower hydraulic resistance compared to the straight pipe flow with the same flow rate. The authors suggested that the smoothing effect of curvature on turbulence may have balanced the effect of the secondary motion, however no real explanation or confirmation has been given yet.

As already discussed by e.g. Sreenivasan and Strykowski (1983), curved pipes tend to have a higher critical Reynolds number for transition to turbulence than straight pipes. A recent numerical study of flow in the transitional regime in highly curved tori (with radii of the pipe being 0.1 and 0.3 times the major radius of torus) by Di Piazza and Ciofalo (2011) revealed an intermediate state between laminar and fully turbulent flow, denoted as the quasi-periodic state: When increasing the Reynolds number, the flow would first reach a chaotic state along the pipe centreline (see also Hüttl and Friedrich, 2000), however without near-wall features characteristic of pipe turbulence. With a further increase of Re, these features appear and co-exist with the strong chaotic motion in the pipe centre. Based on Ito's correlation for the critical Reynolds number in curved pipes, Di Piazza and Ciofalo (2011) further presented a tentative flow regime map in the form of Reynolds number against curvature parameter.

Even though the direct numerical simulation is the most accurate way of computing a solution of a given flow, the range of relevant (length and time) scales increases dramatically with the Reynolds number. This makes DNS impractical for most engineering applications which occur at substantially high Reynolds numbers. Therefore, well validated turbulence models, be it for LES or the Reynolds-averaged Navier–Stokes (RANS) equations, are necessary. In curved pipes, the presence of centrifugal forces due to the inevitable streamline curvature affects not only the bulk flow around the centre of the pipe but also the near-wall regions. The resulting strong anisotropy makes the flow to be away from quasi-equilibrium suitable for traditional turbulence modelling (e.g. via eddy-viscosity models) and has been a major issue for the Reynolds stress transport modelling community (see Wallin and Johansson, 2002). Recently, Di Piazza and Ciofalo (2010) conducted a number of marginally resolved DNS of turbulent flow in helically coiled pipes with heat transfer. By comparing their DNS results, the authors found that the SST k–ω and RSM-ω performed reasonably well in computing the friction and heat-transfer coefficient of the flow even at high curvature. However, a more detailed analysis, including comparison of the individual modelled terms in the budgets, seems appropriate for various curvatures and Re.

The present DNS study is aimed at investigating the evolution of selected characteristics of the turbulent flow in straight to bent pipes over a limited range of Reynolds numbers and curvatures. The main purpose is to provide a validation of our simulation setup and the specific way our statistics are extracted, together with a documentation of the various simulation parameters and the respective results. In a first step we validate our data against existing DNS results by Hüttl and Friedrich (2001). Our newly obtained results at higher Reynolds number and higher curvature will be introduced later. The obtained statistical data (mainly Reynolds stresses and turbulent kinetic energy budgets) will serve to investigate the observed near-wall and pipe-core turbulent features. The performance of traditional eddy-viscosity models in capturing turbulent flow in curved pipes will be put to test applying the present DNS data. Finally, the friction factor as an integral quantity will be computed and compared to existing experimental results. Further studies aiming at a deeper physical understanding of the various findings are certainly necessary.