PARTICLE DISPERSION IN TURBULENT CURVED PIPES

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Abstract
Particle laden turbulent flow in a curved pipe is studied using direct numerical simulation (DNS). The near-wall accumulation of the inertial particles with different Stokes number is examined in the presence of the secondary motion and geometry-induced centrifugal force at low volume fractions. It is observed that in a highly curved pipe the secondary motion plays a dominant role in particle dispersion along with the centrifugal force. Near-wall streaks of the particles are formed as a result of their turbophoretic motion. An inclination of particle streaks due to the secondary motion effect is observed. At the same time, the core of the stable Dean vortices is fully depleted of the particulate phase.

INTRODUCTION: Turbulent flow in curved pipes is frequently occurring in a variety of industrial applications. Typical examples are heat and mass transfer systems where straight, curved and helically coiled pipes are encountered, as in heat exchangers, chemical reactors, pipeline systems and components of internal combustion engines (*e.g.* exhaust manifolds). In addition, biological flows such as blood flow in veins or that of air in the human respiratory systems are also usually curved. The various types of 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 completely developed inside the curved geometry. Although both configurations share similar characteristics, the focus of the current study is on the second type. Due to the influence of the curvature, the imbalance between the cross-stream pressure gradient and centrifugal force causes a secondary motion. The fluid particles located closer to the inner side are pushed outwards by centrifugal forces. At the same time, because of a decrease in the axial velocity due to the friction at the wall, the fluid elements near the outer side of the curve are less affected by these forces. This leads to the formation of a pair of counter-rotating vortices, so–called Dean vortices. Most of the industrial processes involving this configuration include two-phase flows. Here the particulate phase is subjected to the inertial motion of the near-wall turbulence of the carrier phase, its secondary motion and volumetric centrifugal force. Owing to the complexity of the Eulerian turbulent field published investigations on two-phase phenomena in curved pipe geometries are rare. Hence an in-depth study of the effect of the curvature on turbophoresis and particle accumulation is certainly timely and relevant for various applications.

The interaction between dispersed phase with the carrier phase are defined by the volume fraction ($\Phi_p = NV_p/V$), and Stokes number (St) as the ratio between the particle relaxation time and a flow time scale (τ_p/τ_f). Here N stands for number of particles, V_p is the volume of individual particles and V denotes volume of fluid and particles in total. A Dispersed phase with sub-Kolmogorov-scale diameter can be considered as small Lagrangian spheres, *i.e.* point particles. According to Elghobashi [1] considering heavy point particles with small volume fraction the influence of the particles on the continuoues phase and also the inter-particle collisions can be neglected. This so–called one-way coupling model is thus considered in the present study. Maxey and Riley [2] derived detailed equations of motion for spherical rigid particle immersed in a non-uniform flow. Based on Elghobashi and Truesdell [3] the only significant forces to drive the heavy point particles are the Stokes drag and buoyancy. The other terms can be usually neglected. This reduces the formulation to describe the particle motion to a set of ordinary differential equations to be solved along with the fluid flow equations.

PRESENT SIMULATIONS: A spectrally accurate representation of the Eulerian field is obtained performing DNS of fully developed, statistically steady turbulent flow. The incompressible flow is expressed in Cartesian coordinates and solved by a spectral element method (SEM) on Gauss–Lobatto–Legendre (GLL) nodes. The method has been developed and implemented by Fischer *et al.* [4] as the massively parallel code `nek5000`. As a first validation step, turbulent flow in straight channel at low Reynolds number is simulated. Lagrangian evolution of particles is computed using a spectrally accurate interpolation scheme in each time-step to obtain the fluid velocity at the particle positions. Starting from an initial condition of randomly distributed particles, a statistical steady-state for the particle distribution is reached. The accumulation of the particles at the wall, so called turbophoresis, is observed where particles preferentially sample low-speed regions [5]. A visualisation of the instantaneous near-wall particle streaks close to the wall is shown in Fig. 1 *(left)*. The Eulerian statistics of the Lagrangian particles is validated against the data by Marchioli *et al.* [6]. Fig. 1 *(right)* shows the instantaneous particle concentration normalised by the initial distribution in each slab.

A comparative study of turbulent characteristics in straight and curved pipes at different Reynolds numbers and various curvature configurations has been conducted by Noorani *et al.* [7]. This effort provided the statistical data up to fourth-order moments for the first time. A relevant parameter in this configuration is the curvature parameter κ defined as R_a/R_c; R_a being the radius of a cross-section of the pipe and R_c is the radius of curvature at the pipe centreline. This dimensionless parameter distinguishes between mild curvature ($\kappa \approx 0.01$) and strong curvature ($\kappa \gg 0.01$). Cross-sectional views of streamwise velocity, along with equatorial mid-plane views of this quantity for a set of straight ($\kappa = 0$), mildly curved ($\kappa = 0.01$), and strongly curved pipes ($\kappa = 0.1$) with bulk Reynolds number 11700 is presented in Fig. 2 *(right)*. Due to the centrifugal force the turbulent structures are pushed towards the outer side of the pipe, correspondingly the inner side is partially relaminarised. A cut–away view of the instantaneous particle aggregation for the curved pipe geometry with $\kappa = 0.1$ and bulk Reynolds number of 11700 is shown at Fig. 2 *(left)*. Forming elongated streaky near-wall particle accumulation caused by turbophoretic motion of the solid phase is still evident in this case; however, they are helicoidal in shape. Correspondingly, an inclination of the particle streaks at the sides of the pipe can be seen. A strong secondary motion of the carrier phase is likely to cause such a behaviour.

OUTLOOK: In the final paper we will investigate the effect of the secondary motion and Dean vortices on the accumulation of solid inertial particulate phase at nominal friction Reynolds numbers 400 of the curved pipe. This paper thus describes a first step towards studying Lagrangian particles in moderately complex geometries, using a spectrally-accurate Navier-Stokes solver capable of dealing with general geometries. As a prototype, we have chosen the bent pipe, both because of its industrial relevance, but also due to the interesting physical phenomena: An interesting aspect which will be examined is to what extent secondary motion dominates the particle dispersion compared to the centrifugal and turbophoretic effects. Also small-scale clustering of the particle in particular shall be quantified. In addition, particle accumulation in the intermittent relaminarised region near the inner-side of the toroidal pipe will be discussed.

References

[1] S. Elghobashi. On predicting particle-laden turbulent flows. *Appl. Sci. Res.*, **52**(4):309–329, 1994.

[2] M. R. Maxey and J. J. Riley. Equation of motion for a small rigid sphere in a nonuniform flow. *Phys. Fluids*, **26**:883, 1983.

[3] S. Elghobashi and G. C. Truesdell. Direct simulation of particle dispersion in a decaying isotropic turbulence. *J. Fluid Mech.*, **242**(3):655–700, 1992.

[4] P. F. Fischer, W. J. Lottes, and S. G. Kerkemeier. nek5000 Web page:http://nek5000.mcs.anl.gov, 2008.

[5] G. Sardina, P. Schlatter, L. Brandt, F. Picano, and C. M. Casciola. Wall accumulation and spatial localization in particle-laden wall flows. *J. Fluid Mech.*, **1**:1–29, 2012.

[6] C. Marchioli, A. Soldati, J.G.M. Kuerten, B. Arcen, A. Taniere, G. Goldensoph, K.D. Squires, M.F. Cargnelutti, and L.M. Portela. Statistics of particle dispersion in direct numerical simulations of wall-bounded turbulence: Results of an international collaborative benchmark test. *Int. J. Multiphase Flow*, **34**(9):879–893, 2008.

[7] A. Noorani, G. K. El Khoury, and P. Schlatter. Evolution of turbulence characteristics from straight to curved pipes. *Submitted to: Int. J. Heat Fluid Flow*, 2012.

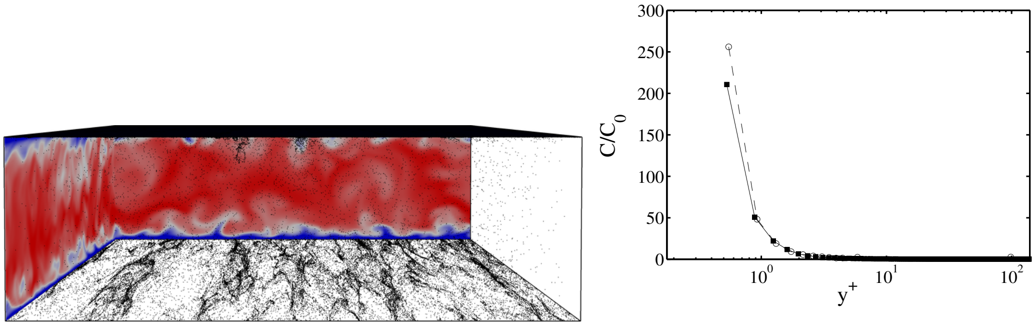

Figure 1: *(left)* Instantaneous snapshot of the particle aggregation at the walls of a turbulent channel due to turbophoresis. Particles form a clear near-wall streaky patterns. *(right)* Instantaneous particle concentration profile (C/C_0) plotted against *Ref.* [6] at $St = 25$; with C being the normalised particle density number at each wall-normal position. ∘ literature data, ■ present simulation data using `nek5000`.

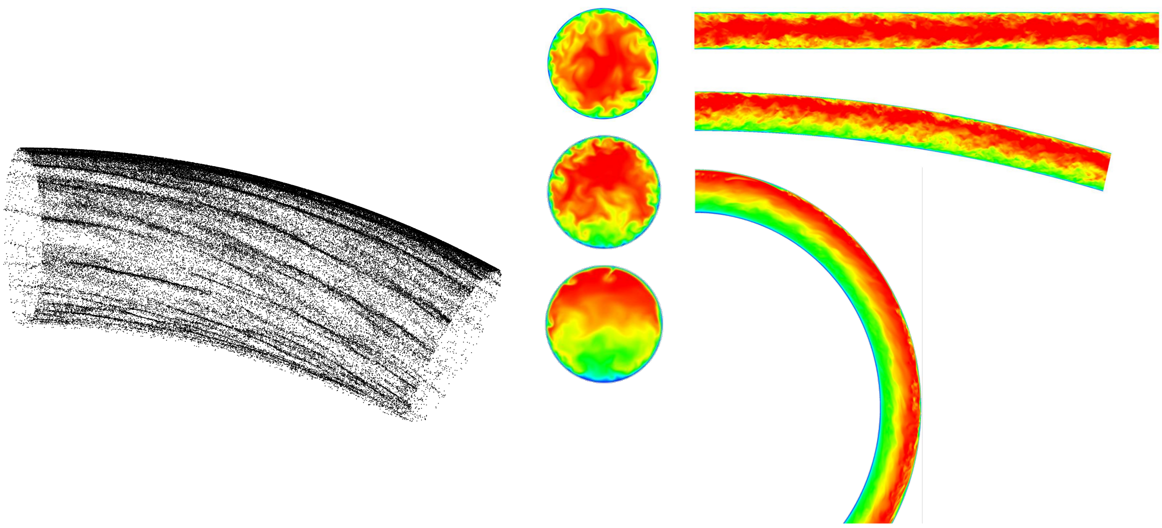

Figure 2: *(left)* Instantaneous snapshot of the particle dispersion in a cut–away view of the curved pipe with $\kappa = 0.1$ and bulk Reynolds number 11700. *(right)* Cross-sectional view of streamwise velocity, along with equatorial mid-plane view of this quantity for straight, mildly curved, and strongly curved pipes with bulk Reynolds number 11700.