TURBULENCE MODULATION IN PARTICLE LADEN PIPE FLOW: EXACT REGULARIZED POINT PARTICLE METHOD

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Abstract Many technological applications are characterized by turbulent bounded flows with dispersed particles. For high mass load (particle/fluid mass ratio) a significant inter-phase momentum exchange occurs (two-way coupling regime), inducing a significant alteration of the turbulent field which, in turn, modifies the dynamics of the suspended phase. Aim of the present study is exploring the potentially of recently developed momentum coupling method, dubbed the Exact Regularized Point Particle (ERPP) method, in reproducing via Direct Numerical Simulation (DNS) the detailed dynamics of a particles laden turbulent pipe flow. The comparison with available experimental and numerical data confirms the ability of the new approach in reproducing the relevant dynamics also in parameter ranges which are unaccessible to standard techniques.

INTRODUCTION

Particle laden turbulent flows occur in many technological applications where the carrier flow is confined by solid walls, e.g. cyclonic separators or pipelines. In particular a high mass load (particle/fluid mass ratio) produces a significant inter-phase momentum exchange (two-way coupling regime) which leads to a substantial alteration of the wall turbulence and a modification of the particle dynamics.

The alteration of the fields induced by the coupling is a rather dedicate process which is difficult to asses both experimentally and numerically, and different phenomenologies are observed changing the numerous control parameters, e.g. mass loading, density ratio and particle Reynolds number, to mention just a few. Indeed, relatively few experimental and numerical studies which address these topics are available, see [7, 6] and [10, 8] respectively. In [7] experimental data of a channel flow documenting the turbulence modification are presented. Data show turbulence attenuation for the different mass loading in presence of particles with a diameter comparable with the wall unit. For heavy particles, the preferential accumulation in the near wall region (turbophoresis) in correspondence with low speed streaks ([6], channel flow data) leads to an alteration of the turbulence production mechanisms and to an overall decrease of the mean velocity. Lighter particles, instead, ([9], pipe flow data) show that the turbulence intensity increases close to the center of the pipe while the fluctuations are depleted in the near wall region.

Concerning numerical simulations, results are available for the turbulent channel flow ([10, 8], DNS). The data in [8] show the increase of the turbulence intensities for small mass loading and its decrease for the higher mass loadings. Unexpectedly, an overall drag decrease is observed in the DNS reported in [10]. All the above numerical simulations employed the classical Particle In Cell (PIC) approach to account for the inter-phase momentum coupling [2], see [1, 5, 4] for a critical discussions of the methodology.

Overall, the available data present a significant scatter presumably due to the difficulty in controlling the experimental conditions and to the lack of a clear cut modeling of the momentum coupling in the numerics. Our aim is to address the particle laden turbulent pipe flow in the two-way coupling regime exploiting a novel momentum coupling method named Exact Regularized Point Particle (ERPP) approach [3] which overcomes the typical difficulties of the PIC.

RESULTS & DISCUSSION

In the limit of small heavy particles, the dimensionless parameters which control the particle laden pipe flow are the Stokes number $St_+ = \tau_p/\tau_+$, with τ_p the Stokes time and τ_+ the wall-unit time-scale, the mass loading ϕ_m, the number of particles N_p, and the friction Reynolds number Re_*. The simulation dataset is summarized in table 1 and typical results

Case	St_+	ϕ_m	St_0	N_p	Coupling
A	5	0.15	0.375	375000	2-way
B	10	0.15	0.75	130000	2-way
C	10	0.3	0.75	265000	2-way
D	50	0.15	3.75	12000	2-way
E	50	0.3	3.75	24000	2-way
F	50	0.6	3.75	48000	2-way
G	5	–	0.375	300000	1-way
H	10	–	0.75	300000	1-way
I	50	–	3.75	300000	1-way

Table 1. Summary of computational cases considered. The Stokes number is defined as $St_+ = \tau_p/\tau_+$ where τ_p is the Stokes response time-scale and τ_+ is the wall-unit based time-scale. ϕ_m denotes the mass loading, $St_0 = \tau_p U_0/R_0$ where U_0 is the centerline velocity and R_0 is the pipe's radius. N_p is the number of particles used to achieve the desired mass loading. In all cases the density ratio is fixed to $\rho_p/\rho_f = 50$ and the friction Reynolds number is $Re_* = 200$.

are presented in figure 1. The plots show the semi-logarithmic profiles of the mean velocity in wall units, $u^+ = \langle u_z \rangle / u_\tau$, being u_τ the friction velocity (top panels), and profiles of the turbulent shear stress $\langle u'_r u'_z \rangle^+$ (bottom panels). The left column concerns the Stokes number effect at fixed mass loading while the right column reports the data at changing mass loading for fixes Stokes number.

Concerning the mean axial velocity of the carrier fluid, the particles affect both the buffer and the log-layer. Significant effects are visible in the turbulent shear stress, bottom panels, where turbulent fluctuations decrease with increasing mass load, right panel, with a non monotone dependence on the Stokes number, left panel.

The talk will address the turbulence modulation in more details. e.g. by discussing the turbulent kinetic energy budget. A detailed discussion of the present results with those available in literature, of both numerical and experimental origin, will highlight the potentiality of the proposed ERPP method in dealing with particle laden turbulent flows in the two way coupling regime.

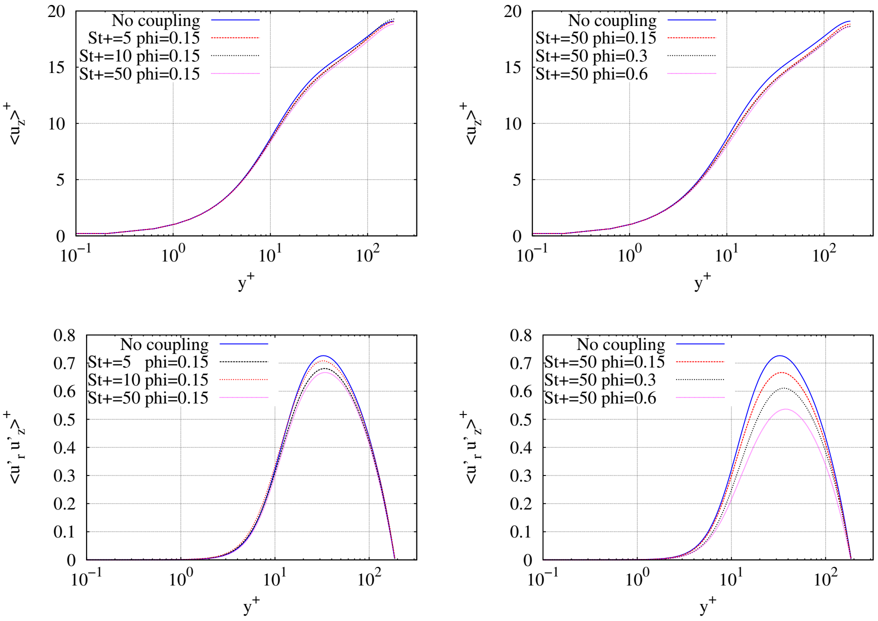

Figure 1. Semi-logarithmic plots of the normalised mean axial velocity, $u^+ = \langle u_z \rangle / u_\tau$ with $u_\tau = \sqrt{\tau_w / \rho}$ the friction velocity, as a function of the normalise wall distance $y^+ = (1 - r)/y^*$ being $y^* = \nu / u_\tau$, top plots. Semi-logarithmic plots of the Reynolds stress $\langle u'_r u'_z \rangle^+$ component normalized with the friction velocity as a function of the radial distance, bottom plots. Left column: Stokes number dependency. Right panel: mass load dependency.

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