TURBULENCE MODULATION IN PARTICLE LADEN HOMOGENEOUS SHEAR FLOW: EXACT REGULARIZED POINT PARTICLE METHOD

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Abstract This contribution presents a first evaluation of a new approach, dubbed the Exact Regularized Point Particle (ERPP) method [4], designed to model the modulation of turbulence by hundred thousands of small inertial particles. The approach overcomes some intrinsic difficulties which arise in some circumstances in available approaches like, e.g., the Particle In Cell (PIC) method introduced by Crowe and coworkers since 1977.

Numerical results concerning a homogeneous shear flow at moderate values of the Reynolds number laden with hundred thousand of small inertial particles are discussed documenting the turbulence modification in the so-called two-way coupling regime, in a range of control parameters unaccessible to the available approaches.

INTRODUCTION

Turbulent multiphase flows consist in a carrier fluid transporting a disperse phase typically represented by solid particles, small liquid droplets or gas bubbles. Our understanding of these flows basically concerns the so-called one-way coupling regime where the mass (or throughput) of the transported phase is much smaller than the mass (or throughput) of the carrier fluid so that the particles cannot modify the carrier flow.

The one-way coupling assumption oversimplifies reality when the suspension load is large and modifies the turbulence. Indeed, in many applications the inter-phase momentum exchange cannot be neglected due a large solid/fluid density ratio ρ_p/ρ_f while, at the same time, the dispersed phase can still be modeled as a diluted ensemble of small spheres (diameter d_p much smaller than the Kolmogorov dissipative scale η). In this so-called two-way coupling regime the dispersed phase back-reacts on the carrier fluid altering its velocity fluctuations which, in turns, produce a modified advection of the dispersed phase, see e.g. [3, 1] for a clear-cut discussion of the different transport regimes.

The numerical modeling of the inter-phase momentum coupling is a major concern in numerical simulations of particle laden flows when the transported phase is disperse and formed by a number of tiny particles. In fact, the sparse and relatively small ($d_p \ll \eta$) particles must be followed by a classic Lagrangian, point-wise approach. However the particles are localized sources of momentum for the fluid and the carrier phase is stirred by such concentrated, highly singular forces that need being suitably regularized to be represented in the Eulerian grid. In this spirit, the Particle In Cell (PIC) method introduced in [2] exploits spatial averaging across the computational cell occupied by the particles to smooth the back-reaction field out. There are drawbacks, however, since this averaging procedure lacks a clear physical interpretation and is strongly grid dependent, see [5]. The issue becomes particularly crucial for highly uneven distributions of particles, as occurring in turbulent sprays [6].

In this context, the present contribution reports about the use of an alternative method, dubbed the Exact Regularized Point Particle (ERPP) method, recently developed by the authors for the Direct Numerical Simulation of particle laden turbulent flows in the two-way coupling regime [4].

SHORT OVERVIEW ABOUT THE ERPP

In the ERPP method the actual equations for the suspension formed by the fluid endowed with the particles are exploited in an asymptotic form for small particles. This allows a splitting strategy to advance the solution during one time step whereby the equation for the background flow is advanced in sequence with the equation for the correction field due to the disturbance flow produced by the particles. The disperse phase is followed along their Lagrangian trajectories by solving the Newton equation of motion forced by the hydrodynamic drag. The correction field has been rigorously shown in [4] to obey the unsteady Stokes flow. It is indeed the time dependence of the viscous Stokes operator that endows the ERPP with most of its favorable characteristics, namely: 1) It naturally provides a physically based regularization associated with viscous diffusion of the vorticity generated at the particle surface during the time step; 2) It determines a natural cut-off length scale associated with the time required by diffusion to reach neighboring grid points; 3) It allows to recover the entire amount of generated vorticity, thereby enforcing exact momentum conservation in the fluid-particle interaction; 4) The vorticity generated by the particles is continuously transferred to the Eulerian grid, where it evolves according to the full Navier-Stokes operator, including full nonlinear advection by the turbulent field.

Additionally, in the ERRP method the regularized pseudo-velocity field is known in closed analytical form. This feature is important in the overall design of the method, since it allows depriving the flow investing the particle of the its own self-induction effect, paving the way to the exact exploitation of known formulae for the hydrodynamic force.

In conclusion the ERPP as originally described in [4] seems to be potentially equipped with a number of favorable features in view of the accurate simulation of particle-laden turbulent flows in the two-way coupling regime. The original paper [4] where the ERPP was first presented was devoted to the illustration of the basic theory and only a few preliminary results were discussed. Here we challenge this new and potentially promising approach by addressing a canonical particle laden turbulent flows, namely a turbulent homogenous shear flow as a prototype of shear dominated configuration.

RESULTS & DISCUSSION

The left panel of figure 1 addresses an instantaneous snapshot of the particles configuration and of the ensuing Eulerian feedback field on the fluid. The data reported in the figure refers to a turbulent simulation operated at $Re_\lambda = 70$, laden with $N_p = 2.200.000$ small inertial particles whose Stokes number based on the Kolmogorov timescale is $St_\eta = 1$. The mass load, i.e. the ratio between the mass of the disperse phase and the mass of the fluid, is $\Phi = 0.4$. Note that the instantaneous Eulerian feedback field on the fluid is a continuos smooth field which retains the same geometrical features of the particle clusters, i.e. the back-reaction on the fluid is expected to be a multi-scale field which pumps turbulent fluctuation in a wide range of temporal and spatial scales.

The central panel of figure 1 reports the turbulent kinetic energy k against the mass loading Φ. The data in the plot have been normalized with the corresponding value k_0 in the unladen case. As the mass load increases the turbulent fluctuations are progressively attenuated. In the figure two sets of data obtained with few particles per computational cell $N_p/N_c < 1$ and $N_p/N_c = 1$ are also compared. From the plot it emerges that the physical result does not depend, within statistical error, on the average number of particles per cell. In fact, in the context of the ERPP approach, the back-reaction operated by the particles on the on the fluid is a smooth field even in presence of few particles. This overcomes the drawbacks of the PIC approach where the back-reaction field is grid depended and the results are physically reasonable only if $N_p/N_c \geq 1$.

The right panel of figure 1 documents the energy spectrum for different mass loading. As expected for particles of unitary Stokes number turbulent fluctuations result attenuated at the largest scales while they are augmented at the smallest ones due to the presence of the small-scale particle clusters. Note the convergence of the spectrum when the average number of particles per cell is changed.

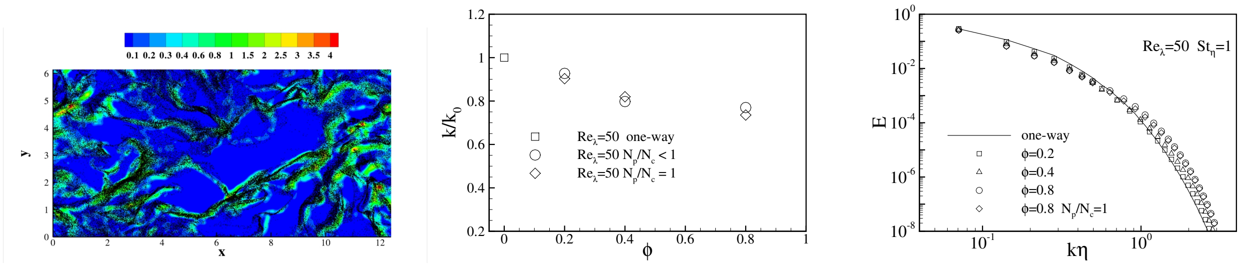

Figure 1. Left panel: snapshot of the instantaneous particle configuration (scatter plot) and of the ensuing Eulerian intensity of the force feedback field operated by the particles on the fluid (contour plot). The slice in the $x - y$ is of the order of few Kolmogorov scales. The mean flow $U(y) = Sy$ is in the $x - y$ plane from left to right. Central panel: Normalized turbulent kinetic energy versus the mass loading Φ. Data obtained for few particles per cell $N_p/N_c < 1$ are compared against data with $N_p/N_c = 1$. Right panel: Energy spectrum at different values of the mass loading, namely $\Phi = 0.2$, 0.4, 0.8 and at different values of the number of particles per cell.

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