Direct Numerical Simulation of Particle Turbulence Interaction in Forced Turbulence

J.C. Brändle de Motta, J.-L. Estivalezes, E. Climent, and S. Vincent

Abstract. Usually, numerical simulations of two-phase particle dispersed flow both with Eulerian or Lagrangian approaches assume particle size to be smaller than the smallest scales of the carrier fluid, which is not the case for most two-phase dispersed flows. The present work aims at giving a detailed analysis of particle behaviour by performing fully resolved of finite size particle simulations in the case of forced homogeneous isotropic turbulence

1 Introduction

Turbulent particle-laden flows in nature and industrial applications are ubiquitous like spray combustion, liquid atomization, fluidized bed combustion or aerosol transport. Hence, it is of major importance to clearly understand the effect of particles on turbulence. Recently Balachandar et al [1] has given an exhaustive review on that topic. Experimentally, it is often difficult to obtain some relevant data concerning the local particle and flow characteristics, so the numerical simulation becomes mandatory. Moreover, in numerical methods, it is possible to perform either Large Eddy Simulation (LES) or Direct Numerical Simulation (DNS). DNS can be seen as a real numerical experiment. However, in order to be fully resolved for turbulent flows, the spatial resolution must be lower than the Kolmogorov scale. A lot of works have been published about DNS of two-phases flow with particles smaller than this scale with point particle approximation [2, 3] for example. In this work,

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we are interested in particles larger than the Kolmogorov scales, typically thirty times the initial Kolmogorov scale. Simulations performed are four way coupling, this means that the presence of particles influences the carrier fluid and vice versa, and furthermore the interaction particle-particle is taken into account by a repulsive force. Moreover, the turbulence is isotropic and so the computational domain is a periodic cubic box.

2 Numerical Method

The present approach is based on one fluid formulation for particulate disperse two-phase flows. A fictitious domain approach on a Cartesian fixed grid has been chosen as a computational framework. An implicit tensorial penalty method allows to account for solid behavior, while, the incompressibility constraint is tackled with an augmented Lagrangian method [4]. The originality of this method is to split the stress tensor in order to increase the space order. The solid constraint is enforced by high viscosity. The resolved particles are tracked in a Lagrangian way. To avoid deformations, the solid fraction in each cell are updated taking into account the analytical spherical shape. This solid fraction indicator is introduced in the fictitious domain model similarly as in the Volume of Fluid method. Particle-particle collision or wall-particle collision are taken into account thanks to an improved model [5]. A detailed presentation of the finite size particle simulations and their validations are presented in [6].

3 Parameters of the Simulation

3.1 Turbulence Forcing

Numerical simulations of forced isotropic turbulence are most often formulated in Fourier space, where a forcing is applied to low wave number modes. As we use finite volume method and to avoid extra cpu time consuming by the Fast Fourier Transform calling, we implement linear forcing in physical space as proposed by Lundgren [7]. Rosales [8] has shown that linear forcing is a useful alternative method and can be easily integrated into finite volume based codes. The forcing is insured by keeping constant total kinetic energy in the computational domain.

3.2 Parameters

The non dimensional domain is a square box of $L_b = 2\pi$, the ratio of box size over Taylor micro-scale is $L_b/\lambda = 27$ the ratio of Taylor micro-scale over Kolgomorov scale is $\lambda/\eta = 17$, $\eta/\Delta x = 0.56$, and finally the ratio of particle diameter over Kolmogorov scale is $D_p/\eta = 20$. The Taylor micro-scale Reynolds number is $Re_\lambda = \lambda u'/\nu_f = 73$. Three density ratio (particle density over fluid density) have been simulated $\rho_p/\rho_f = \{1,2,4\}$. With these parameters, we can define particle Stokes number based on eddy turnover time, which can be written as a function of density ratio: $St_E = 1.5\rho_p/\rho_f$ giving the following Stokes numbers $St_E = \{1.5, 3, 6\}$. The particle volume fraction is $\phi_v = 0.03$ which corresponds to $N_p = 512$ particles. The simulations have been done on 256^3 grid points with 512 processors. The cpu time is about 10 hours per processor for one eddy turnover time. In figure 1 is plotted the initial kinetic energy spectrum. The vertical dotted line gives the particle radius.

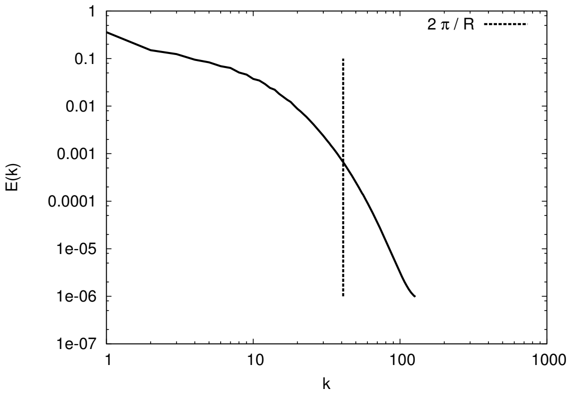

Fig. 1 Initial kinetic energy spectrum

4 Results

We present influence of particles on turbulent kinetic energy spectra in figure 2. The first comment that can be drawn for this figure, is the quite weak influence of particle phase on the spectra except for high wave numbers. We can see that this difference, which seems to increase the energy at the high wave numbers, increase as density ratio does. The small oscillations at high wave numbers are due to Fourier Transform through the particule, see [9].

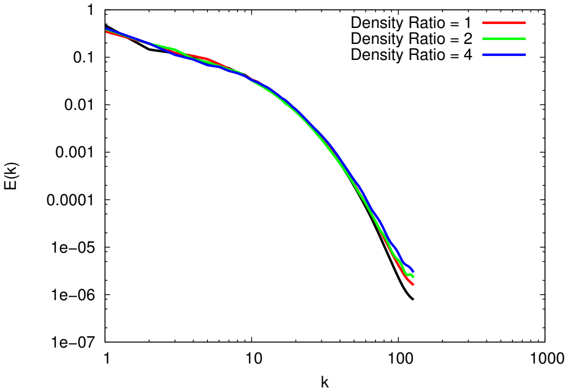

Fig. 2 Comparison of energy kinetic spectra, black line is single phase flow

A more significant modification by increasing particle volume fraction should be expected, which is here quite low. Next figure 3 depicts Lagrangian autocorrelation coefficients for both single and two-phase flows. In this figure time variable is made non dimensional by using the carrier fluid integral Lagrangian time scale. Single phase Lagrangian autocorrelation has been obtained by seeding the fluid with 20000 massless point tracers and following their trajectory. The same procedure has been applied for finite size particles. As in the previous figure, increase of density ratio causes deviation from single phase case. However, one would expect a more important difference at least for $T/T_l < 1$. One explanation is that even for quite low particle volume fraction collisions are quite frequent, whatever the density ratio is.

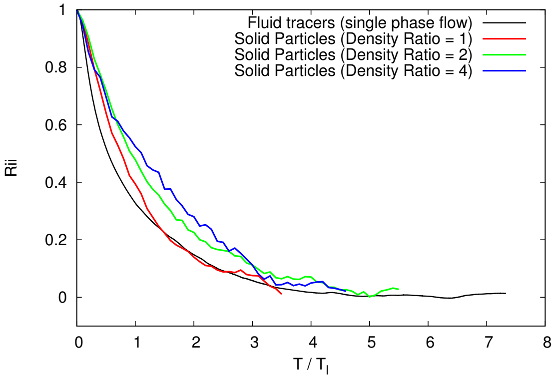

Fig. 3 Comparison of autocorrelation coefficients

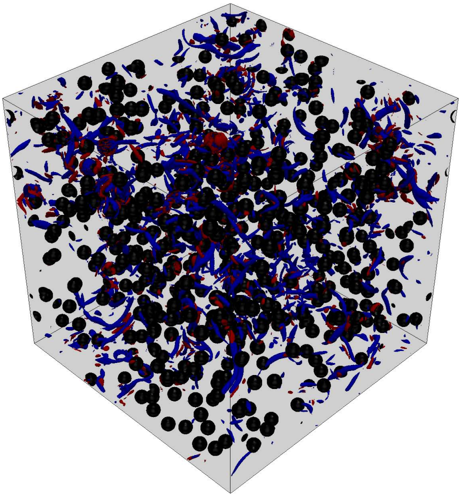

Fig. 4 Snapshot of particules and Q criterium - blue value corresponds to negative value and red to positive

Figure 4 gives an overview of the flow field with the particles at a selected time step. It can be seen in this figure although the volume fraction is low, particle-particle collision could occur relatively often.

In order to get more insight in the particles motion, we try to extract averaged property over the whole particle phase. To do that, we define a local mesh around each particle as depicted in figure 5.

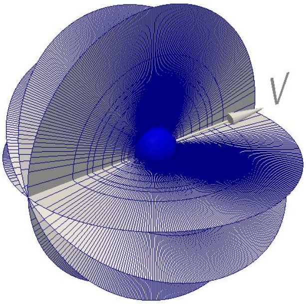

Fig. 5 Local mesh around a particle

For each particle, its center of mass velocity is subtracted and then average is performed for all particles and all time step. Finally one obtains the mean carrier fluid velocity seen by the particle which by symmetry is contained in a particle diametral plane. Figure 6 shows the mean streamlines around the particles superimposed on the carrier fluid pressure field.

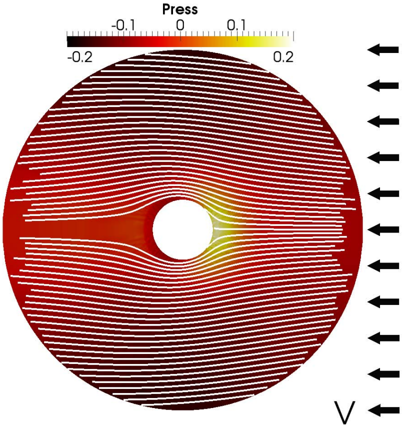

Fig. 6 Mean streamlines around particles and pressure field

From the streamlines, one can deduce that the flow seen by the particle seems to correspond to a low Reynolds number flow as the wake is very thin, and close to a Stokes flow as can be compared with the next figure 7, where are plotted the streamlines and the pressure field for a Stokes flow.

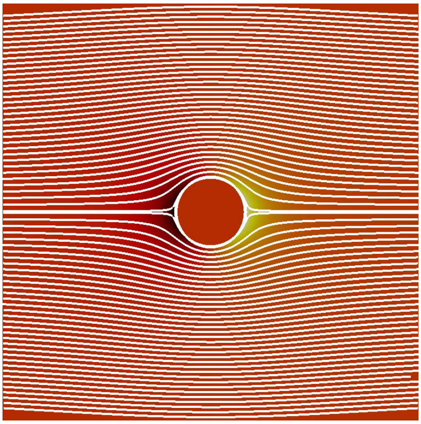

Fig. 7 Mean streamlines around particles and pressure field for a Stokes flow

In figure 8 is plotted the mean vorticity field around the particle. This figure emphasizes the fact that field is quite close to the vorticity field induced by a Stokes flow where the vorticity maxima appear to the top and the bottom of the particle whereas mimina are located upstream and downstream.

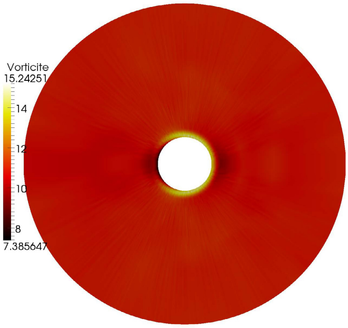

Fig. 8 Mean vorticity field around particles

5 Conclusion

Finite size resolved particle simulations in forced homogeneous turbulence have been performed for low volume fraction value. Parametric study on Stokes numbers based on eddy turnover time has been conducted. Analysis on kinetic energy spectrum have shown that Stokes number increase raises energy density at high wave numbers compared to single phase flow. However this increase stays moderate, most probably due to low volume fraction. Temporal evolution of Lagrangian autocorrelation coefficient have demonstrated Stokes number effect, but early time behaviours seem to indicate collision effect. That has to be more deeply investigated. Finally, mean pressure, vorticity and streamlines values seen by particle show nearly Stokes flow behaviour. This fact demonstrates the the particle phase experiences nearly equilibrium with carrier fluid.

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