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NUMERICAL STUDY OF PARTICLE-LADEN TURBULENT CHANNEL FLOW

Marek Jaszczur
Department of Fundamental Research in Energy Engineering
Faculty of Energy and Fuels, AGH University of Science and Technology
E-mail: Marek.Jaszczur@agh.edu.pl

Abstract

In this paper Eulerian-Lagrangian approach combined with Large Eddy Simulation of turbulent flow laden with large number of solid heavy particles has been investigated for three subgrid models and tested for three Stokes numbers. The objective of this work was the analysis of influence of the sub-filter models on the flow and particles. The influence of the models were tested with the comparison to the Direct Numerical Simulations. Some statistics of the dispersed phase show good agreement with the DNS data. Phenomena like clustering and concentration was not possible to reproduce properly with LES. It was notice that, even though the models reproduces accurately results for the continuous phase the properties of the dispersed phase computed using LES do not match with the DNS results. The particles tend to be highly concentrated in the region close to the wall but concentration is always lower than for DNS. Sensitivity of the LES models on the grid resolutions has been also tested. As the result of using SGS model and different grid resolutions in some cases fluid fluctuation has been enhanced. Moreover, the particles concentrations and particle velocity fluctuation do not show any major improvement. One of the reason can be the particle velocity interpolation which act as an additional filter and in the case of coarse grid smooth results too much.

Key words:LES, particle channel flow

INTRODUCTION

Flow laden with large number of solid particles, droplets or bubbles are important in various industrial processes including coal and spray combustion, chemical reactors, droplets and dust deposition, environmental (pollution in air and water, sedimentation) and engineering processes. Such flows are almost always physically very complex due to turbulence, phase changes, chemical reaction or particle dispersion.

On the way of understanding particle-turbulence interactions two approaches are mainly used, direct numerical simulation DNS and large eddy simulation LES. Accurate prediction of the behavior of particles in a turbulent flow can be obtained using Direct Numerical Simulation but this approach is the computational very expensive and restricts its application to a range of small Reynolds number values that are far from those found in practical application. To avoid this restriction, LES with much coarser grid has been used. Recently some progress has been achieved in Computational Fluid Dynamics of multiphase flow, but there is still a need for model developments, for both fundamental and industrial applications. So far most of turbulent flow computations still base on RANS modeling. Recently some research has been done using LES modeling where only large flow structure are resolved, also many papers can be found in literature for full scale resolved flow computations. LES seems to be very promising to model particle laden flows because particle motions usually depend on large scales existing in turbulent flows which are well resolved with LES. Several important aspects of particle-turbulence interactions have been analyzed by Maxey and Riley [1], Kulick [2], Fessler and Eaton [3], Chung [4], and Portela [5] among others.

In the most study DNS has been used to overcome problem of additional numerical modeling but Large Eddy Simulation method has been also used for particle-laden flows and several work have been published over the last years [6-10]. One of the several available models in LES is the Smagorinsky model, which has been widely applied to many different situations. However the main problem of this model is the dependence on a model coefficient, which has to be determined a priori. Unless LES has increasing its popularity and much more complex wall-bounded flows can be modeled with available computer resources benefit compromise between cost and accuracy this type of modeling still needs developments and the issue is still perceived as open and further work is needed to understand the effect of sub grid-scale fluid flow on particle motion and vice versa. In particular, seems to be very important to model properly the carrier flow.

In this paper Eulerian-Lagrangian approach combined with Large Eddy Simulation of turbulent flow laden with large number of solid heavy particles has been investigated for three subgrid models and tested for three Stokes numbers. The focus is on the accuracy of the subgrid models with respect to particle behavior, particle concentration and particle properties (mean velocity, fluctuations). To compare results of the computations using sub-filter models first Direct Numerical Simulations has been performed for the same conditions as LES. Comparison of the fluid statistics and particle statistics shows in some detail the prediction of increased particle concentration near a solid wall through turbophoresis, as a function of the quality of the small-scale reconstruction of turbulent motion.

PHYSICAL PROBLEM AND NUMERICAL METHODOLOGY

For current studies of wall-bounded fully developed isothermal turbulent particle-laden flow sketched in Fig.1 the Eulerian-Lagrangian point-particle [5] approach has been used.

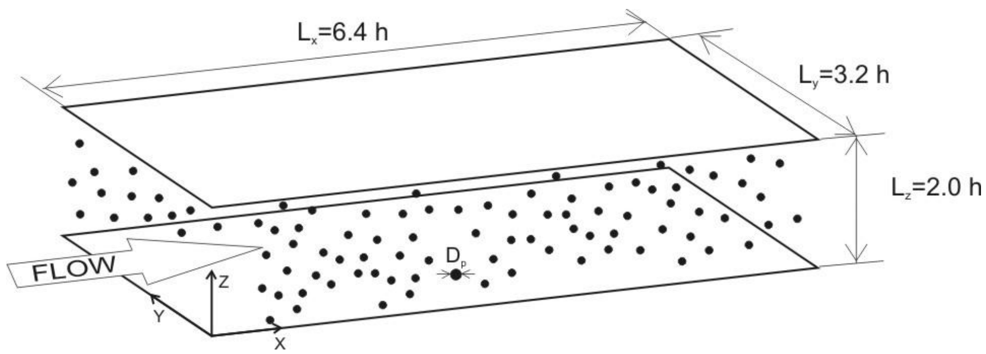

Figure 1. Computational domain of channel flow.

The continuous-phase is solved using direct numerical simulation and large eddy simulation techniques for incompressible flow together with the tracking of the individual particles. The transfer of momentum between the particle and the fluid is considered through a force located at the particle center, which is determined from the velocities of the particle and of the surrounding fluid. Detailed information of wall-bounded turbulent particle-laden flow based on the Euler-Lagrange point-particle approach can be found in [5]. Particles are dispersed in a pressure-driven fluid flow which is assumed to be incompressible, isothermal and Newtonian. Simulation has been restricted to very small volume fractions and assumed that the size of the particles is considerably smaller than the local Kolmogorov length-scale in the turbulent flow. In such situations the particles have a negligible feedback coupling on the turbulence and the one-way coupling formulation for the particle phase can be employed [5].

In general the forces acting on the particle immersed in a flow are described properly by Maxey and Riley equations[1]. But in the case of the small heavy particles considered here, the dominant forces acting on the particles are the drag force and gravity force (in order to study fluid particle interactions gravity force was neglected). With the above assumption the equation of motion for the particle for the location *x* and velocity *v* can be written as:

$$\frac{dx(t)}{dt} = v(t) \qquad \frac{dv}{dt} = C_d \frac{Re_p}{24}\frac{1}{\tau_v}\left(u(x(t),t) - v(t)\right) \tag{1}$$

where $u(x(t),t)$ is the velocity of the fluid interpolated using tri-linear interpolation to the geometrical center of the particle. The particle Reynolds number Re_p, particle drag coefficient C_d and the particle relaxation time τ_v, are defined as follow:

$$Re_p = \frac{|(u-v)|\, D_p}{\upsilon} \;\; ; \;\; \tau_v = \frac{\rho_p}{\rho_f}\frac{D_p^2}{18\upsilon} \;\; ; \;\; C_d = \frac{24}{Re_p} \tag{2}$$

where ρ_p, ρ_f are the density of the dispersed phase (particle) and the continuous phase (fluid) and D_p is the diameter of the particles.

The fluid phase is model using the conservation of mass and momentum, and is solved with DNS and LES technique[7]. For DNS model equations can be written as:

$$\nabla \cdot \mathrm{u} = 0 \tag{3}$$

$$\frac{D\mathrm{u}}{Dt} = -\frac{\nabla P}{\rho_f} + \frac{1}{Re}\nabla^2 \mathrm{u} \tag{4}$$

The filtered continuity and Navier-Stokes equations (3)-(4), that are the basis for LES of the continuous phase are:

$$\nabla \cdot \overline{\mathrm{u}} = 0 \tag{5}$$

$$\frac{D\overline{\mathrm{u}}}{Dt} = -\frac{\nabla \overline{P}}{\rho_f} + \frac{1}{Re}\nabla^2 \overline{\mathrm{u}} + \nabla \cdot \tau \tag{6}$$

where $\overline{u}$ and $\overline{P}$ are the filtered fluid velocity and pressure, ρ_f is the fluid density, R*e* is the fluid Reynolds number. The stress-tensor τ in eq. (6) represents the influence of the sub grid scales on the resolved fluid-velocity. One of the most popular sub grid scale (SGS) stress model is the Smagorinsky model [13]. Even though this relatively easy model has been successfully applied to many different turbulent flows. In the standard model, the residual stress tensor τ is defined as follows:

$$\tau_{ij} = \overline{u_i u_j} - \overline{u}_i \overline{u}_j \tag{7}$$

This tensor τ is parameterized by an eddy viscosity model, as follows:

$$\tau_{ij} - \frac{\delta_{ij}}{3}\tau_{kk} = -2\nu_t \overline{S_{ij}} \tag{8}$$

This is incorporated in the pressure term and the coefficient of proportionally to ν_t. In the Smagorinsky model the turbulent eddy viscosity is modeled by analogy to the mixing length hypothesis as:

$$\nu_t = C_S \Delta^2 \left|\overline{S}\right| \tag{9}$$

where C_s is the Smagorinsky constant, Δ is the filter width, and $\left|\overline{S}\right|$ is the magnitude of the large scale strain rate tensor $\overline{S}_{ij}$:

$$|\bar{S}| = \left(2\bar{S}_{ij}\bar{S}_{ij}\right)^{1/2} \quad ; \quad \overline{S}_{ij} = \frac{1}{2}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) \tag{10}$$

For this type of numerical simulations recommended value of the Smagorinsky constant is C_S=0.1. Near the solid walls of the channel this model exaggerate the dissipation [19]. To counteract this tendency, the turbulent eddy-viscosity ν_t has to be damped near the walls. Van Driest wall-damping model was used in present work replacing constant C_s by $C_s(1-exp(-z^+/A))$, with parameter A=25.

In the present paper alternative approach has been also used. It based on the Germano identity which relates the turbulent sub-filter tensor τ and its "tested filtered" analog to a resolved stress tensor. Instead of assuming a fixed or a damping model of C_s near a wall, the dynamic procedure yields a self-adaptive dynamic eddy-viscosity coefficient. With this procedure eddy-viscosity reduces to zero near a solid wall. More details about this procedure can be find in Germano et al. paper [14].

The position, flow, and particle quantities considered in this study are reported in dimensionless form, represented by the superscript + and expressed in wall units. Wall units are obtained combining channel half-width *h*, friction velocity u_τ, ν and ρ. To solve the governing equations (5)-(6) with SGS model in case of LES, a finite-volume method on a staggered grid was employed, together with a two-step predictor-corrector method for incompressible flow. The convective and diffusive terms in all the equations are discretized using a second-order central scheme. For time-advancement a second-order Adams-Bashforth scheme is used, with the time-step determined by the Courant criterion. The Poisson equation is solved applying a Fast Fourier Solver in the two periodic directions and a tri-diagonal solver for the remaining direction. The equations of the particle motion (1) are solved using a second-order Adams-Bashforth scheme for the time-advancement. To force the fluid motion, a constant pressure-gradient is imposed along the streamwise direction. Periodic boundary conditions are imposed in both streamwise and spanwise directions.

NUMERICAL RESULTS

Starting from arbitrary conditions - random flow - flow field has been time advanced to get a statistically-steady state for fluid velocity. After that small solid particles are assigned uniformly to the channel with initial velocity to be the same as the fluid in the center of particles location. Other initial conditions have been also tested for example injection of initial particles only in the center of the channel but finally the same results have been obtained but usually with much longer computational time. After some time the particles get into statistically-steady state conditions independent from the initial velocity and position. The statistics for the fluid and particles were averaged for $200h/u_\tau$ at Re_τ=150. The simulations were performed with the computational grids ($N_xN_yN_z$) equal to 128x128x64 for DNS and from 63^3 down to 32^3 for LES uniform in the streamwise and spanwise directions, and with an hyperbolic-tangent stretching γ=1.7 in the normalwise direction. Some computations has been also performed for the domain two times larger in comparision to domain presented in Fig.1.

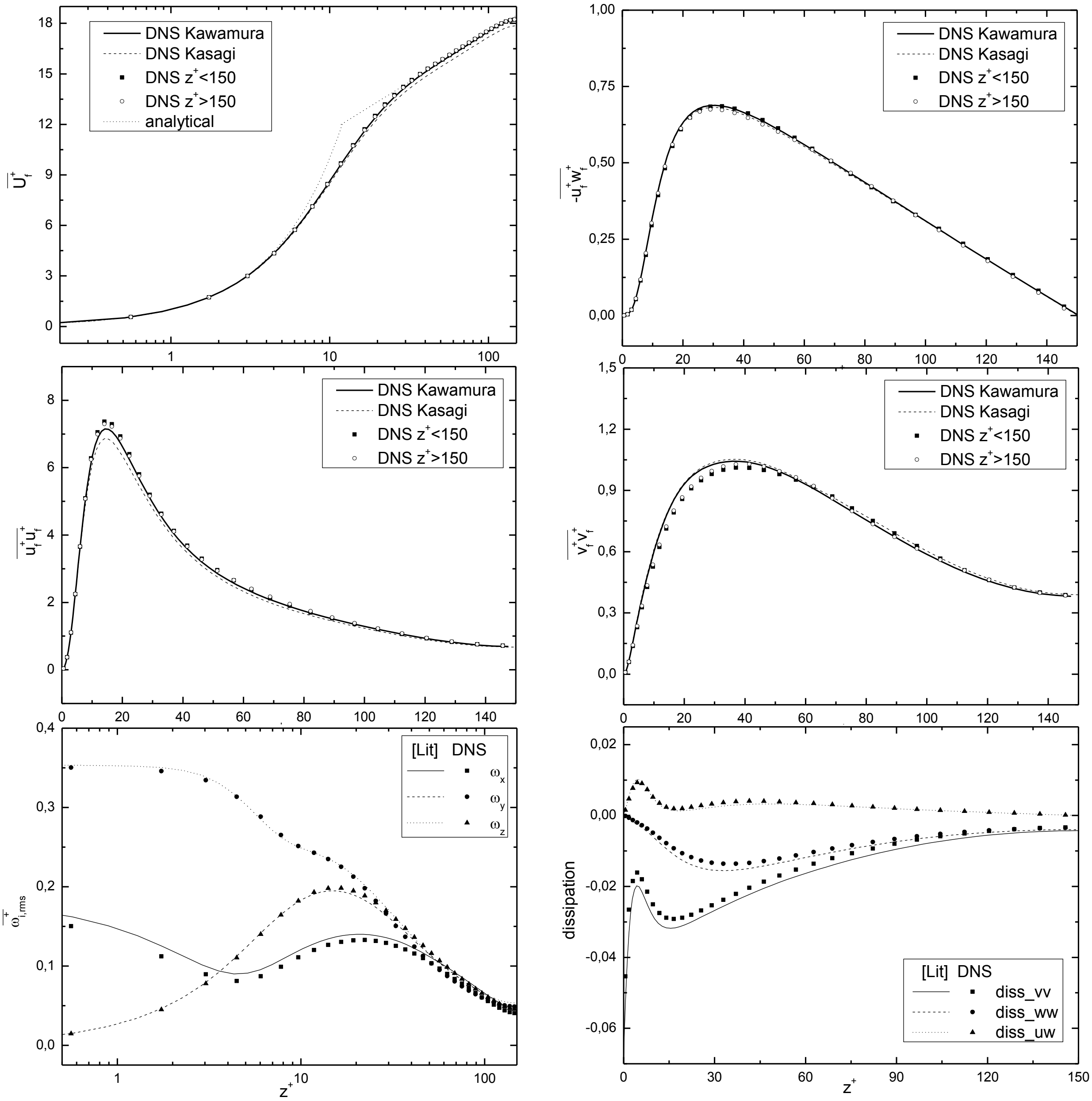

Figure 2. Fluid velocity, fluctuations, vorticity and dissipation comparing with DNS results for continous phase and with data obtained in literature [11,12] at Re_τ = *150.*

To validate quality of the DNS results and to gather necessary data for other tests, DNS simulations has been run first. Results for continuous phase are presented in Figure 2 and compare with data obtained by other researchers Kasagi[11], and Kawamura[12]. Results in generally agree very well, unless same difference can be notice cause by different approach, grid, difference in condition, and in the way of obtain statistics. The results obtained for DNS have been compared with various LES models (LES with a value of CS implies the use of Smagorinsky's model at, that C_S with Van Driest damping of the Smagorinsky eddy-viscosity and dynamic (dyn) if the dynamic eddy-viscosity model is adopted. In Figures 3 the streamwise fluid velocity component and its fluctuations are presented as a function of the wall normal coordinate for various sub-filter. Results obtained with LES are compared with DNS as well as with data available in literature Pozorski[15]. It can be seen how results depends on the SGS model, grid resolution and of the size of the computational domain. Small domain mean domain size presented in Figure 1. (6.4x3.2x2.0) and large one (12.8x6.4x2.0). For the resolutions 64^3 depends on model more or less accurate results can be obtained. For this resolution and for large domain results are better in comparison to lower resolution and small domain (in that two cases cell size is identical). Only for case without sub-filter model (C_S=0) results for different domain are similar.

The streamwise velocity and streamwise velocity fluctuations are slightly under-predicted in case when no sub-filter model is used (C_S = 0). Use of small domain (smaller grid cells) and grid 64^3 improve results only a bit. Large improvement is done by introducing SGS

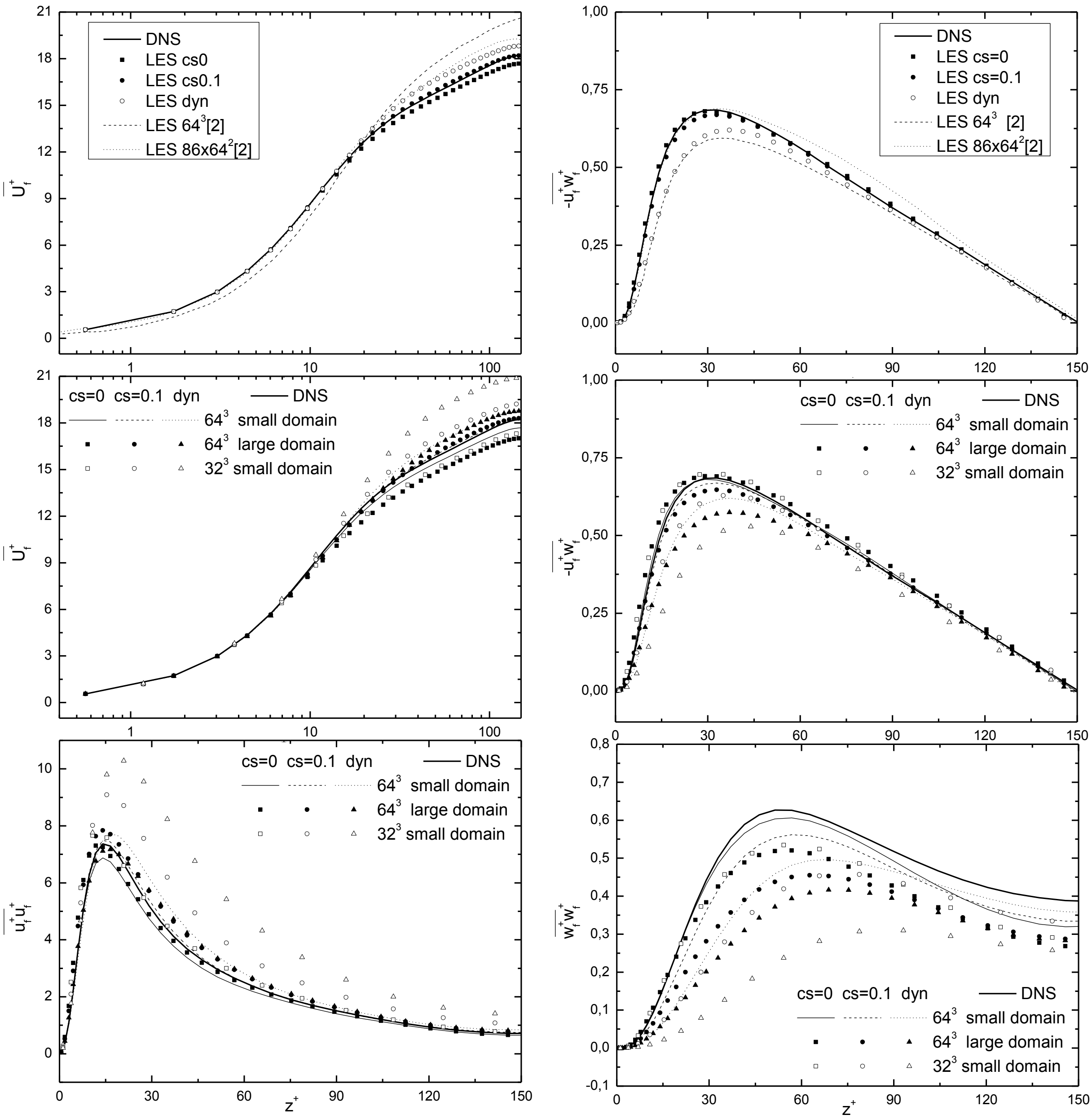

Figure 3. Fluid velocity and its fluctuations comparing various sub-filter models with DNS results at $Re_\tau = 150$. For the labeling of the LES models see main text.

model. But for much coarse grid 32^3 more advance dynamic model give worse results than simple one or even no model. The wall normal velocity fluctuations are under-predicted by all models. The use of Smagorinsky's model is seen to affect mainly the location at which the turbulent fluctuation levels are highest.

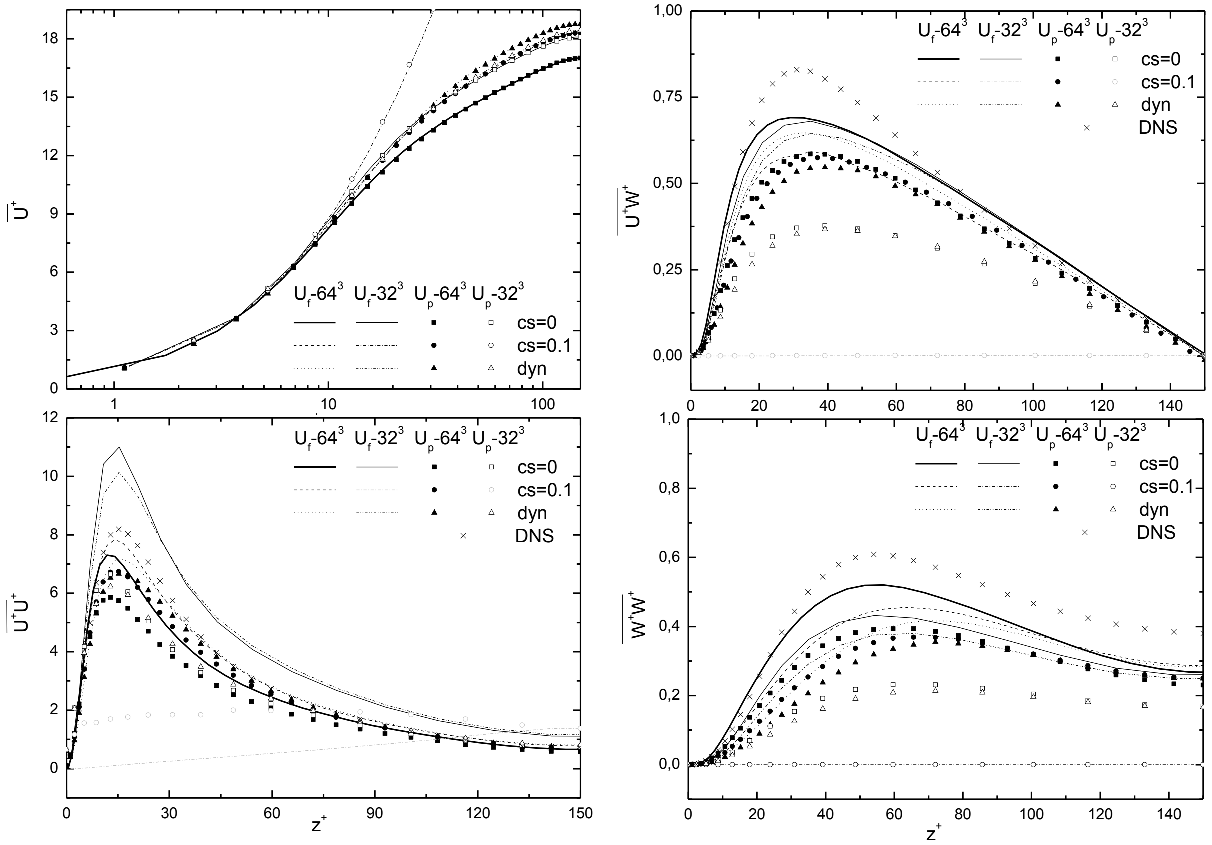

Figure 4. Particle and fluid streamwise velocity and velocity fluctuations for streamwise and wall normal components – comparison of various sub-filter LES models with DNS. Particle Stokes number St=1, Re_τ = 150.

In figure 4 the streamwise velocity and streamwise and wall-normal velocity fluctuations for fluid and for particle are presented for Stokes number St = 1. Results of LES are presented for identical large domain only. The streamwise velocity for particle agree very well with the fluid velocity for all models. Flow prediction with Smagorinsky model on coarse grid and for large domain is wrong and flow due to implementation of too dissipative model become laminar. Streamwise mean velocity component shows that all models (also Smagorinsky) gives mean particles streamwise velocity similar to the fluid velocity which is the case at St=1. This mean that this properties for particle is represented for all models correctly. That is true only in reference to the fluid velocity which is itself not always resolved properly (see fig. 3). The velocity fluctuations for particle $\overline{u_p u_p}$ are for all cases and all presented components under-predicted. This may have large consequences on particle transport and concentration. For the streamwise velocity fluctuation $\overline{u_f u_f}$ some models estimate fluid fluctuation correctly, other under or overestimate (lines on diagram). But even for cases when the fluid fluctuations are over predicted 50% or more particle fluctuations has increases its fluctuations just a few percent. The prediction $\overline{u_p u_p}$ with most advanced dynamic subgrid model are the best among the others. The results obtained with dynamic model are better than with Smagorinsky and for case with no model and still remain better on grid 32^3. For the wall-normal particle velocity fluctuations $\overline{w_p w_p}$ studied sub-filter models under-predict the fluctuation levels. In fact, the results without sub-filter model are best in resolved that component among the models studied. The particle wall-normal velocity is closely related to the particle concentration profile near the channel walls. As can be seen from figure 5 all models under-predict the particle accumulation in wall near region. The highest concentration was observed for the case when no sub-filter model was used; apparently the small-scale turbulent fluctuations near the wall are very important for proper prediction of turbophoresis. Concentration profiles for heavier particles at St = 5 and St = 25 were also studied and are presented in figure 5.

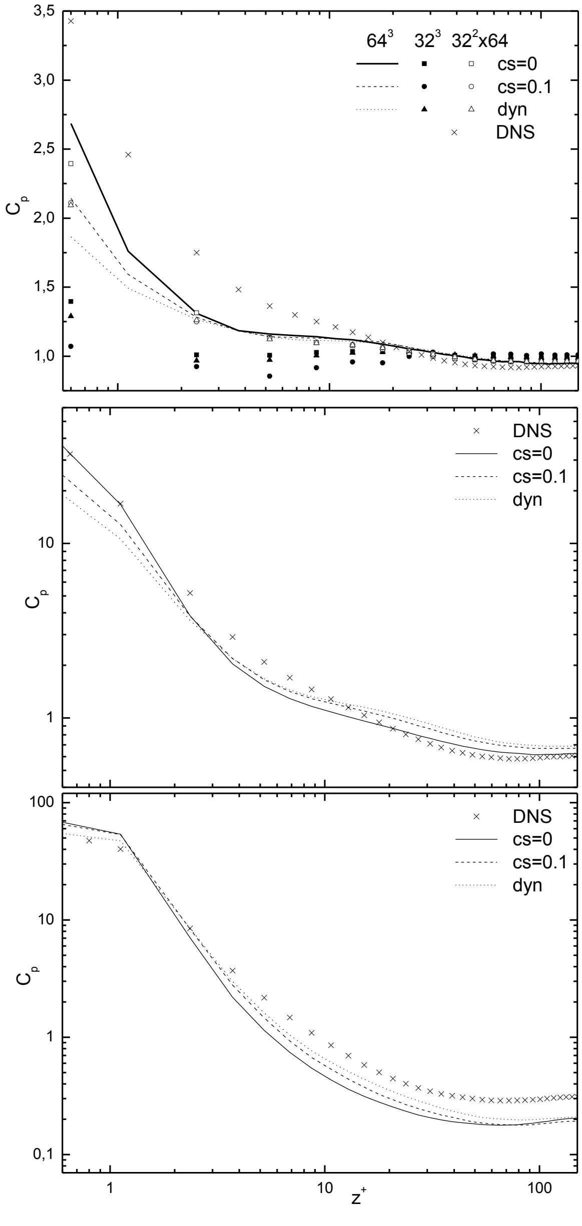

Figure 5: Concentration profiles for DNS and LES for Re_τ = 150 and particle Stokes number St=1, 5, 25 (top, middle, bottom).

At St = 5 the difference between LES and DNS results are much smaller. Still the results with the dynamic model are not as good as the no model simulation. At St = 25 the particles are so heavy that small turbulent scales are quite unimportant for their dynamics and all results was then found to be close each other in near wall region. Figure 6. shows instantaneous flow field at x-y plane and $z^+=2$ at $Re_\tau=150$, and grid resolution 64^3(top), 32x32x64 (middle) and 32^3 (bottom). It can be seen that with decreasing resolutions number of low speed streaks where particles are preferentially located is also decreasing results in lower concentration.

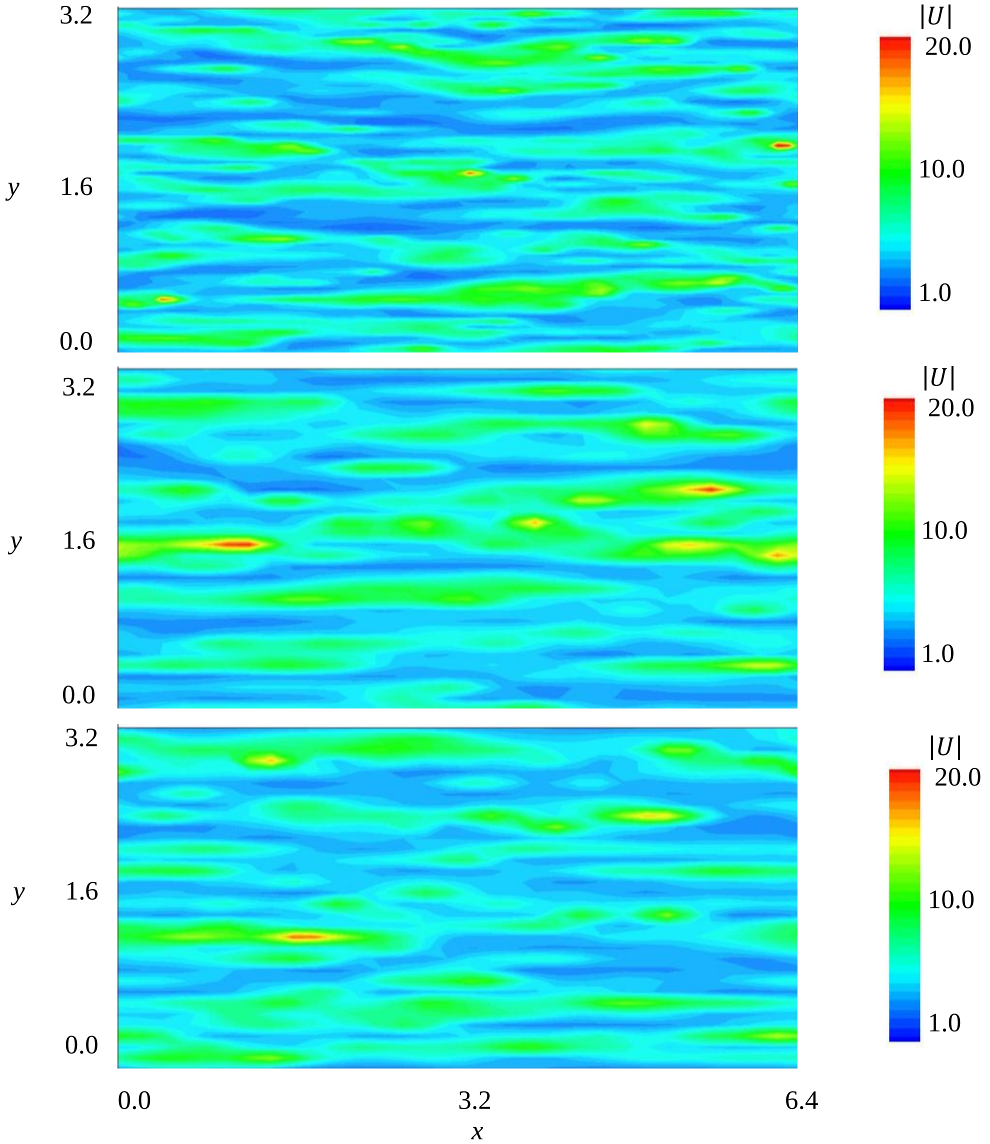

Figure 6. Instantaneous flow field at x-y plane and $z^+=2$ at $Re_\tau=150$, and grid resolution 64^3(top), 32x32x64 (middle) and 32^3 (bottom).

CONCLUSIONS

In this paper the Eulerian-Lagrangian point-particle approach has been extended in order to study particle dynamics in turbulent flow using LES and DNS. The relevance of the near-wall velocity fluctuations in relation to the particle clustering has been developed. Several statistical quantities for particle velocity, fluctuations and concentrations were obtained from the calculations. All results for the fluid phase (mean fluid velocity and correlations) show a good agreement with DNS results of other researchers. LES results has been also compare with data available in literature. The qualitative analysis of the turbulence and particle structures shows streaky patterns for the hydrodynamics. Particles are tends to be highly concentrated in the region close to the wall.

At low Stokes numbers the use of sub-filter model was found to be important for the particle statistics as well us for fluid. The predicted particle dynamics using SGS models were found to agree only for some properties better with DNS data compared to cases without models. For heavier particles the relevance of the smaller turbulent scales is less pronounced and LES results for turbophoresis were found to correspond closely to DNS data, quite independent of the sub-filter model that was used, as long as the near wall dissipation was not overestimated too much. This implies that Van Driest damping and the dynamic procedure proved to be quite reliable.

It was found that, even though the models reproduces accurately results for the continuous phase the properties of the dispersed phase computed using LES do not match the DNS results. It has to be notice that for presented results tri-linear interpolation of the fluid velocity to the particle position was used. That method acts as a additional filter and its influence on the results is important. When grid size is decreasing or domain is increasing interpolation error increases linearly and additionally smooth solutions. This can be one of the reason why particle fluctuation are always underestimated.

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