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Simulation of fully resolved finite-size particles in a turbulent flow

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1 Introduction

The particle laden flows are presented in both natural and industrial frameworks. The point-wise approach to simulate particulate flows has been used during the last 30 years. Thanks to this approach many phenomena have been understood. Nevertheless, this approach can not be used for particles which size is larger than the smaller length scale of the fluid flow. That is the reason that it is necessary to analize those phenomena for finte-size particles.

In this study we are interested on the statistics of finite sized particles. A sustained homogeneous isotropic turbulence with particles is numerically simulated in order to obtain those statistics.

2 Numerical approach

In order to meet the physical needs a one-fluid approach for particulate flows is proposed. This approach is based in a tensorial penalty method. The solid region is treated with a high viscosity (from 100 to 1000 times the fluid one). Then velocity field obtained by the Navier-Stokes solution fulfill the solid constraint. After each Navier-Stokes Resolution the velocity of each particle is computed and the particle is tracked. With the new positions the density and viscosity field is computed in the same way that done on Volume of Fluid Methods [1].

A collision algorithm is implemented in order to ensure the particle-particle rebound. This algorithm includes a model that ensures the physical lubricated rebound [2].

3 Description of the two-phase flow

As explained above our goal is to simulate statistical converged simulations. The way we maintain the turbulent energy on the fluid is near the linear forcing proposed by [3]. In our implementation at each time step the velocity field is rescale in order to maintain the kinetic energy on the domain: $\mathbf{u}^+ = \sqrt{\frac{\int_\Omega \mathbf{u}_0^2}{\int_\Omega \mathbf{u}^2}}\mathbf{u}$.

At the beginning of each simulation 512 particles are spread randomly in a sustained turbulence whose spectrum is converged. The Taylor micro-scale Reynolds number of the initial turbulent flow computed from this spectrum is 73. The moderate Reynolds number gives a small spatial scale separation: the ratio of Taylor micro-scale over Kolgomorov scale is $\lambda/\eta = 17$. The particles diameter size is near the Taylor micro-scale: $D_p/\eta = 20$. The solid fraction is 3%.

Three simulations are run with different density ratio: $\rho_p/\rho_f = \{1, 2, 4\}$. This ensures that particles respond to fluid fluctuations. Indeed, the Stokes number is small enough for particle to respond to fluctuations: based on the Kolmogorov time scale the simulations Stokes numbers are $St_k = \{26, 52, 104\}$ and based on eddy turnover time $St_E = \{1.5, 3, 6\}$.

The simulations are realized on a cube of 256^3 grid points that ensures the solution of small fluid scales ($\eta/\Delta x = 0.56$). For the simulation of one eddy turn-over time 10 real time hours are used over 512 processors. In order to obtain converged particles statistics around 12 eddy turn-over simulation time are necessary.

An study of the spatial spectrum and lagrangian temporal spectrum have shown that the inclussion of particles have no major influence on the turbulence parameters.

3.1 Particles statistics

The particle distribution has been studied and converged statistics has been obtained. The table 1 gives the agitation, q_p^2, the velocity autocorrelation time, T_L and the diffusion coefficient obtained with the approximation $D = 2q_p^2 T_L$. As comparison, those values are given divided by the same measure obtained for fluid particles distributed on the single phase case.

ρ	q_p^2	$\frac{q_p^2}{q_f^2}$	$\left(\frac{q_p^2}{q_f^2}\right)_{\text{T.-H.}}$	T_L	$\frac{T_L}{T_L^f}$	D	$\frac{D}{D_f}$	a_{rms}^2	$\frac{\tau_c^{\text{th}}}{\tau_k}$	$\frac{\tau_c^{\text{m}}}{\tau_k}$
-	$(m^2\ s^{-2})$	-	-	(s)	-	$(m^2\ s^{-1})$	-	$(m^2\ s^{-4})$	-	-
1	1.27	0.85	1	1.22	1.31	3.10	1.13	4.00	49.3	103.6
2	1.17	0.79	0.5	1.35	1.45	3.16	1.15	2.12	51.4	89.1
4	1.10	0.74	0.2	1.53	1.65	3.37	1.23	1.05	52.9	79.0

Table 1: Particle and collision statistics.

As observed for point-wise simulations the agitation decreases with the density ratio where the velocity autocorrelation time increases. Although the behaviour is the same, the values obtained can not be compared to those obtained for point-wise simulations. That is because the particles are not influenced by all fluctuations as for the point-wise simulations. The agitation expected by the Tchen-Hinze theory [4, 5] are also given on table 1.

In order to analyze the phenomena of preferential concentration he particle radial distribution function has been stablished. After 12 eddy turnover time the distribution stays normal, there, no preferential concentration are highlighted. This result can be a physical result or could be explained by different reasons: The simulation domain is not large enough to enable concentration areas, the simulation time is not long enough to allow particles to migrate to the concentration zones.

As show by figure 1 the probability density function can be approximated by an exponential distribution. In our case this p.d.f. is obtained without the accelerations of particles during collisions. This distribution is common for inertial particles. In our case as for the experiments presented by [6] the particles' acceleration r.m.s. (a_{rms}^2 on table 1) can be related to the density ratio ρ. The correlation that takes into account the turbulent parameters : $\frac{a_{rms}^2}{\epsilon^{-2/3}\nu^{1/2}} = \alpha\rho^{-\beta}$.

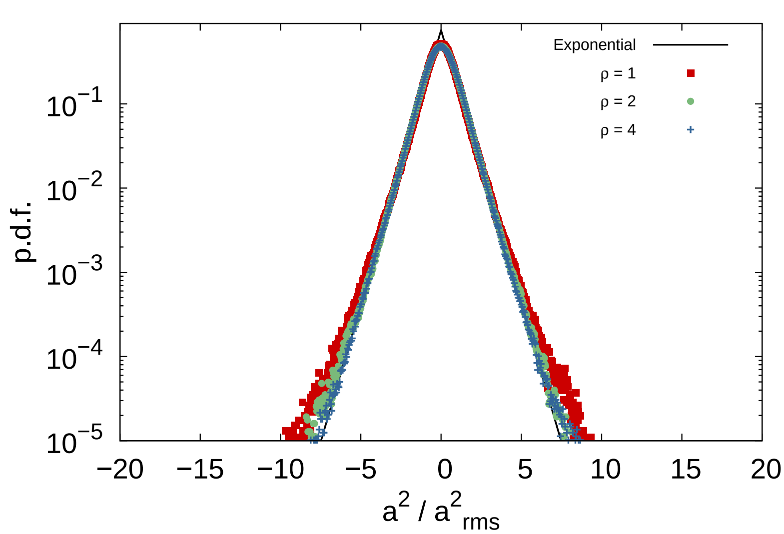

Figure 1: Probability density function of the acceleration of particles.

3.2 Collision regime

In the first simulations we considered the results of collisions without lubrication model. The the collision regime is compared to the kinetic theory. On the case of the kinetic theory the intercollision time (i.e. the mean time between two collisions) can be explaide dependig on the particles density n_p, their diameter and the agitation by the formula: $\frac{1}{\tau_c^{\mathrm{th}}} = n_p \pi D_p^2 \sqrt{\frac{16}{\pi}\frac{2}{3}q_p^2}$. On the table 1 this approximation is given and compared to the measured values. We can see that when density ratio increase the behaviour reach the kinetic theory. That is because the particles are more inertial and then the regime are more similar.

For the kinetic theory the p.d.f. of the intercollision time can be approximated by an exponential form: $P(\Delta t_{coll}) = \frac{1}{\tau_c} exp\left(-\frac{\Delta t_{coll}}{\tau_c}\right)$. On figure 2 we compare the obtained values for each simulation to the theory. The same conclusion is given: more the particles are heavy more the regime is similar to the kinetic theory.

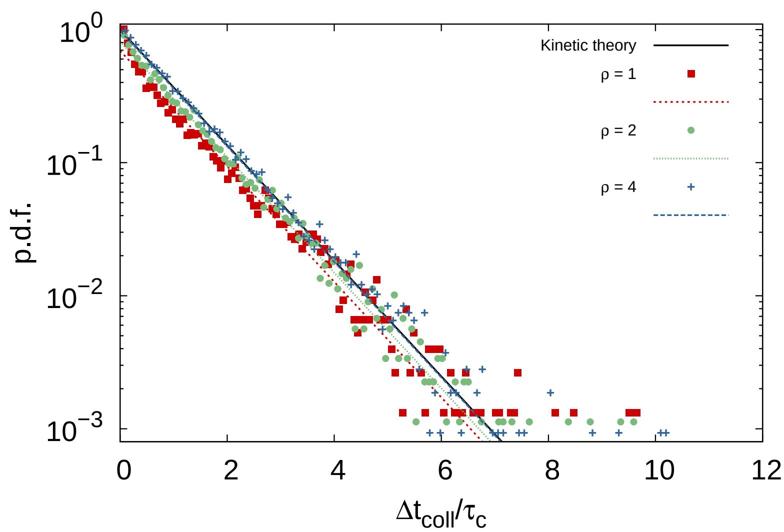

Figure 2: Probability density function of collision times.

The results given below are not satisfactory because they doesn't explain why the regime are different. To understand the different the p.d.f. of the angle at the collision is analyzed and compared to the kinetic theory on figure 3. It can be observed that there are less frontal collisions that for the kinetic theory. That is because the particle velocity is correlated to the surrounding fluid and then the velocity of pairs that are in collision are correlated too. Again, this effect is less important when the density increases.

One effect of this correlation at collision is that the energy on the collision is less important. Then the lubrication effect can not be neglected. An additional simulations have been done with the lubrication model activated for the neutrally buoyant particles case. The statistics of the particles stay similar. The major difference concern the intercollision time that increase drastically (from 103.6 τ_k to 11.6 τ_k). This can be understand by analyzing the p.d.f. of the intercollision time, figure 4. As we can see the probability of short times between two collisions increases. This increase has been explained by [7]: secondary collisions appears. For the case with lubrication model the p.d.f. of the time between two encounters is given too. For this purpose, we consider an encounter a pair that activate the lubrication model. We can see that it is similar to the solid collisions on the cases without lubrication model. The typical sequence is that two particles that are near each other activate the lubrication model, and then, before the definitive separation many solid collisions occurs. The same study has been realized for the case $\rho_p/\rho_f = 4$ and similar behaviour has been observed. Nevertheless, this effect is more important for buoyant particles because the energy on

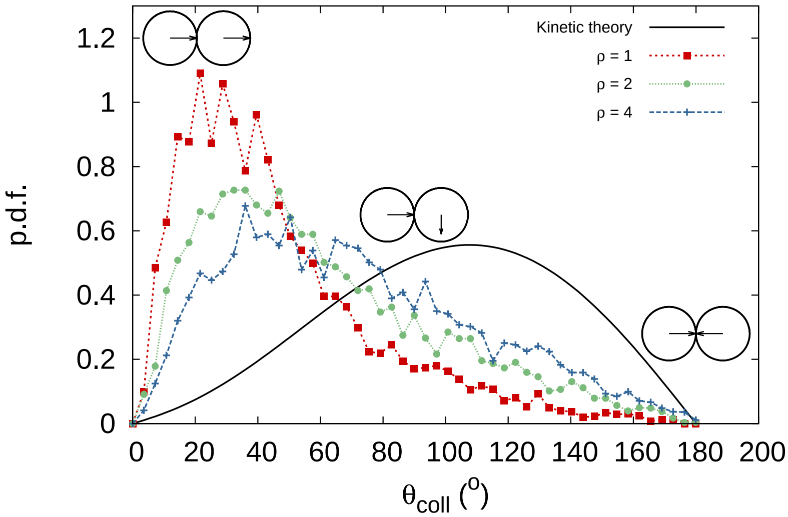

Figure 3: Probability density function of angles at contact.

the encounters are less important.

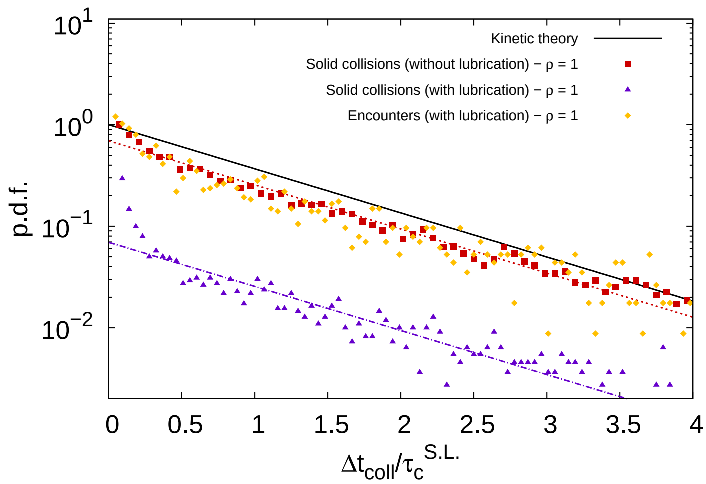

Figure 4: Probability density function of collision times with and without lubrication.

3.3 Fluid surrounding particles

As it is said before the particles are correlated to the surrounding fluid. In order to verify this point the average fluid around particles has been done taking into account the velocity of each particle. The figure 5 shows the dimensionless velocity and the streamlines around particles. The flow is similar to a Stokes flow but the velocity decreases slowly and is not symmetric.

As shown by [8] the dissipation increases around the particle. Nevertheless, in their study the structure of the dissipation is not given. In our case, the average local dissipation allows to conclude that there are an average dissipation film around particles, figure 6. This dissipation is

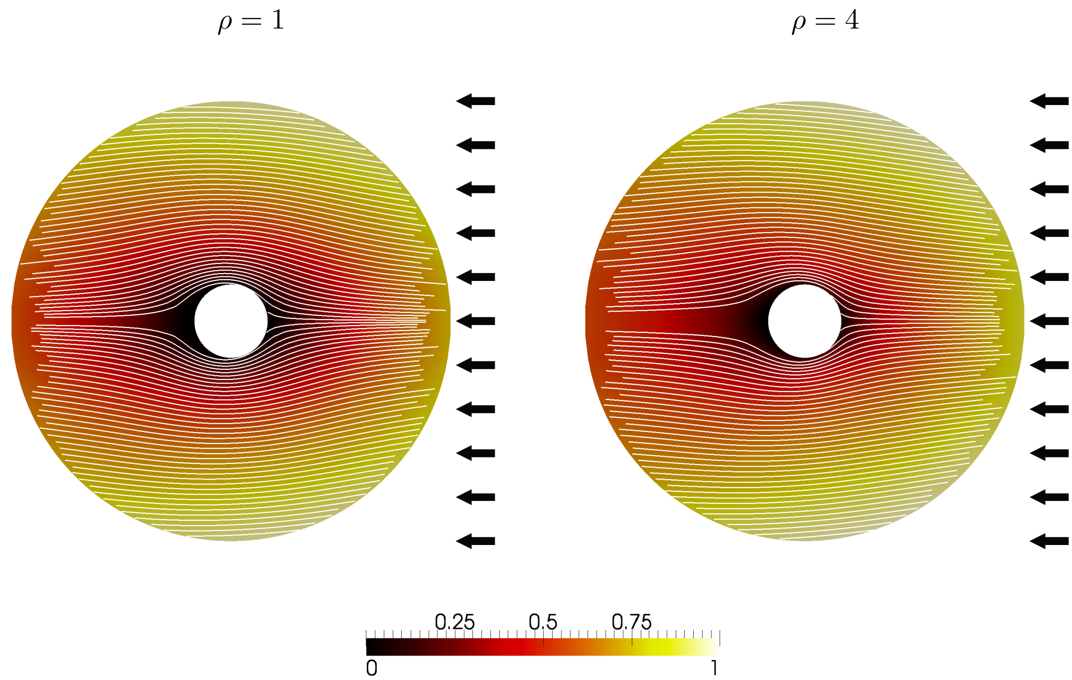

Figure 5: Streamlines obtained from the averaged velocity field. Color field by velocity divided by $< |\mathbf{V}_p| >$. (for space constraint $\rho = 2$ is not presented)

less important on the back of the particle. That can be explained by the weak created by particles.

4 Conclusion

The presented simulations had permit to better understand the behaviour of finite-size particles on a turbulent flow. Many results can be retained. The particle statistics have the same trend that the statistics obtained for point-wise simulations. The particle velocity is correlated to the surrounding fluid velocity. This have an effect on the velocity angle at collision that is smaller that for the kinetic theory. The lubrication film between particles can not be neglected for this simulations. The introduction of a lubrication model bring secondary collisions out. As a final result, the structure of the dissipation around particles is analyzed.

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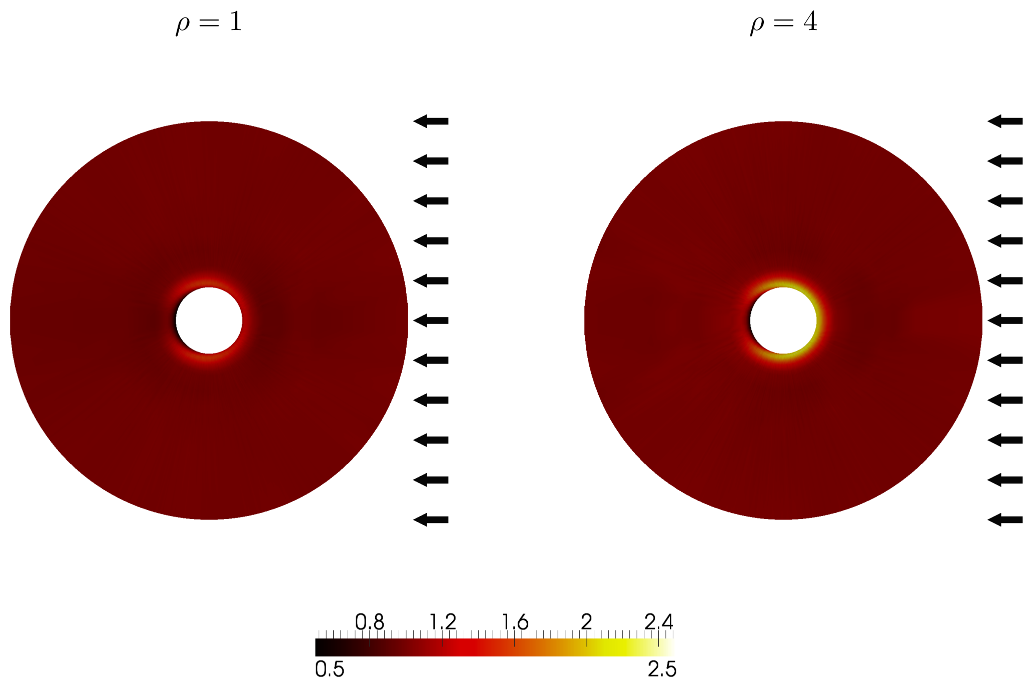

Figure 6: Averaged dissipation around particles divided by the dissipation without particles.

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