

NUMERICAL SIMULATION OF COLLISION DYNAMICS FOR FINITE SIZE PARTICLES IN TURBULENT SUSPENSION

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Outline

The particle laden flows

Numerical approach

Collision model

Simulations

Particles dynamics

Collisions

Average flow around particles

Conclusion

Goals and outline

The main goal of this presentation is to:

- ▶ **Understand collisions for finite-size particles** in a HIT.

The presentation follow those points:

- ▶ Context and motivations
- ▶ VoFLag method for finite size particles
- ▶ Lubrication phenomena and its model
- ▶ HIT characteristics
- ▶ Collisions in a HIT

The particle laden flows

Particle laden flows are common:

In natural flows:

- ▶ Rivers
- ▶ Volcanos
- ▶ Clouds
- ▶ Microorganism

In industrial applications:

- ▶ Fluidized bed
- ▶ Combustion Chamber

The particle laden flows

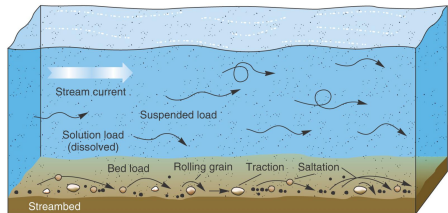
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Source:

<http://geography.unt.edu>

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Source: Wikipedia

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Source: Wikipedia

 Falkovich et al. - Nature - Vol. 4194 (2002).

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Source: Godfrey, NIWA

▣ Durham et al. - Nature - 2148 (2013)

▣ Denny et al. - Biological Bulletin - 203 (2002)

The particle laden flows

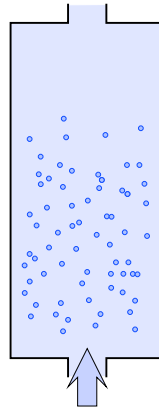
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The particle laden flows

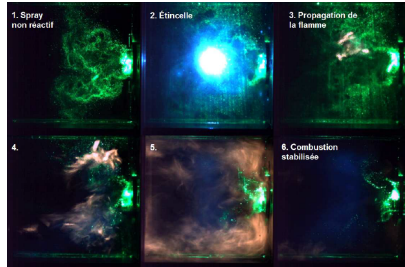
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Source: Linassier - Thèse Université de Toulouse (2012)

The particle laden flows

Particle laden flows are common:

In natural flows:

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- ▶ Volcanos
- ▶ Clouds
- ▶ Microorganism

In industrial applications:

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- ▶ Combustion Chamber

The particle laden flows

Many parameters drive those flows:

- ▶ Density Ratio
- ▶ Particle size
- ▶ Shape
- ▶ Flow
- ▶ Solid fraction
- ▶ ...

Different numerical approaches exist:

- ▶ Microscopic
- ▶ Mesoscopic
- ▶ Macroscopic

Numerical approaches

Many parameters drive those flows:

- ▶ Microscopic (Fully Resolved Particles)
- ▶ Mesoscopic (Point-wise Particles)
- ▶ Macroscopic (Continuum phase)

Numerical approaches

Many parameters drive those flows:

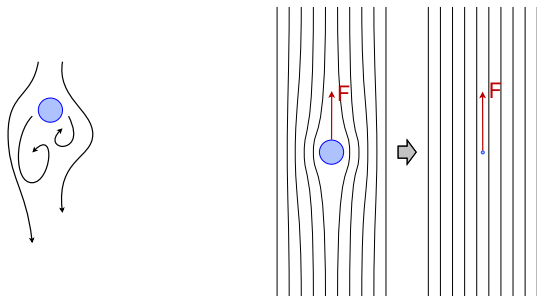
- ▶ Microscopic (Fully Resolved Particles)
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Numerical approaches

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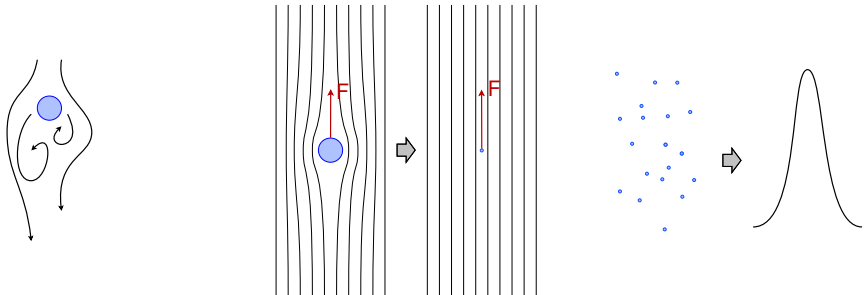
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Numerical approaches

Many parameters drive those flows:

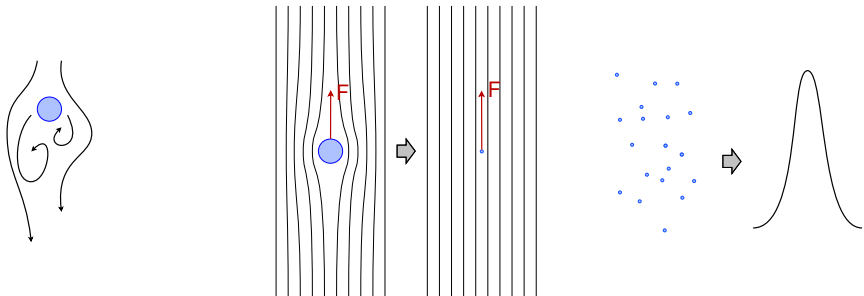
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Numerical approaches

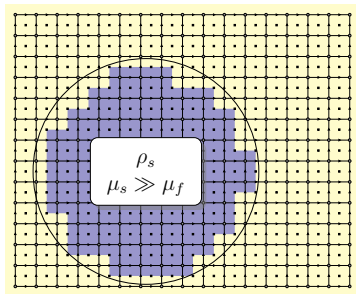
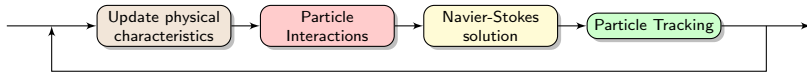
Many parameters drive those flows:

- ▶ Microscopic (Fully Resolved Particles)
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Microscopic method permits to understand surrounding fluid behaviour

Method



Thetis code

- MAC staggered unstructured grid
- Finite volumes
- Fictitious Domain Approach

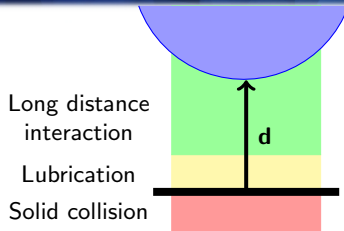
The solid behaviour is enforced by high viscosity.

■ Randrianarivelo et al. Int. J. Num. Meth. in Fluids (2005)

■ Vincent et al. - Comp. & Fluids (2007)

■ Vincent et al. - J. Comp. Phy. (2013)

Collisions

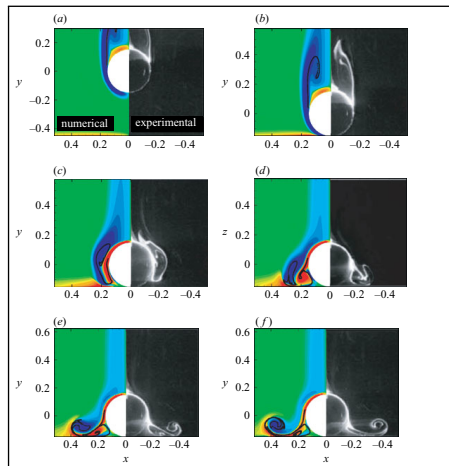
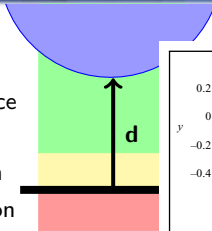


Collisions

Long distance
interaction

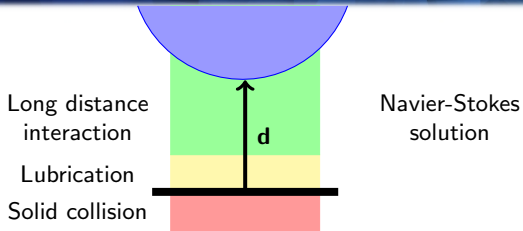
Lubrication

Solid collision

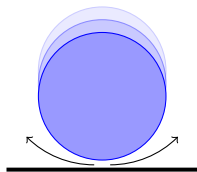
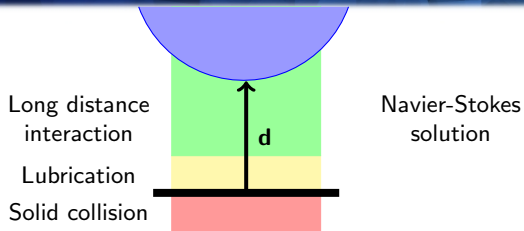


Ardekani et Rangel - J. Fluid. Mech. - Vol. 596 (2008)

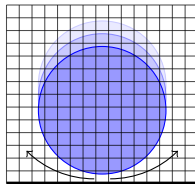
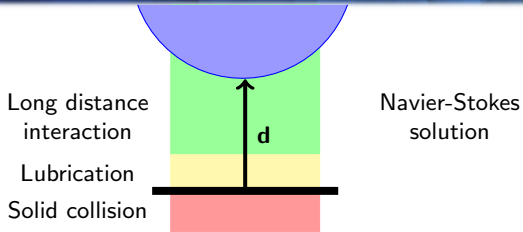
Collisions



Collisions

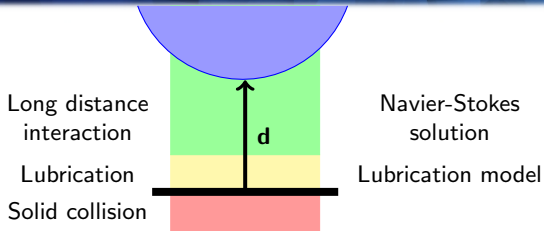


Collisions



A model is required.

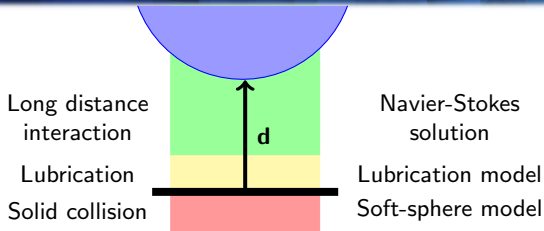
Collisions



$$\mathbf{F}_I(\epsilon, \mathbf{u}_n) = -6\pi\mu_f R\mathbf{u}_n [\lambda(\epsilon) - \lambda(\epsilon_{al})]$$

☰ Brenner - Chem. Eng. Sci. - Vol. 16 (1961)

Collisions

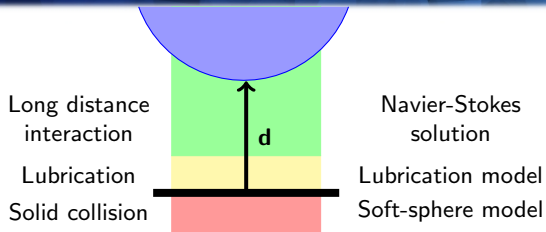


$$\mathbf{F}_I(\epsilon, \mathbf{u}_n) = -6\pi\mu_f R \mathbf{u}_n [\lambda(\epsilon) - \lambda(\epsilon_{al})]$$

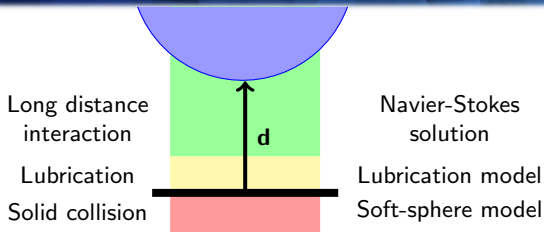
- ▶ μ_f dynamic viscosity
- ▶ R particle radius
- ▶ \mathbf{u}_n normal velocity
- ▶ $\epsilon = \frac{d}{R}$ dimensionless distance
- ▶ λ Taylor series

☰ Brenner - Chem. Eng. Sci. - Vol. 16 (1961)

Collisions



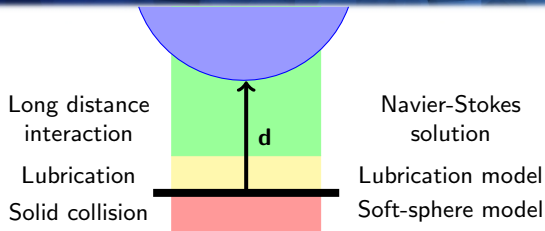
Collisions



$$F_s = \underbrace{\frac{m_e (\pi^2 + [lne_d]^2)}{[N_c \Delta t]^2}}_{\text{spring}} d - \underbrace{\frac{2m_e [lne_d]}{[N_c \Delta t]}}_{\text{dashpot}} \dot{d}$$

☰ Schäfer et al. - Jo. de Phys. - Vol 6 (1996)

Collisions

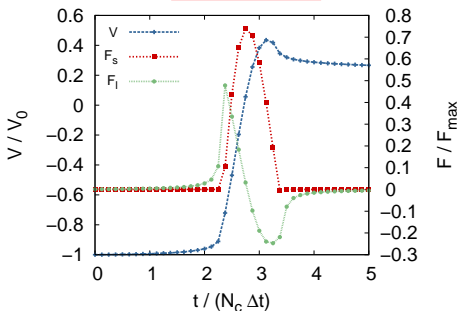
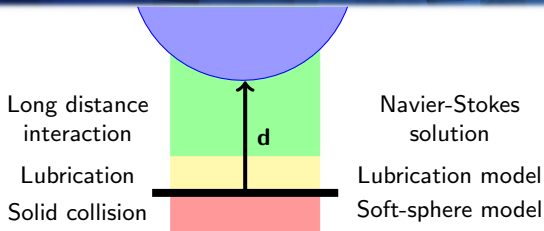


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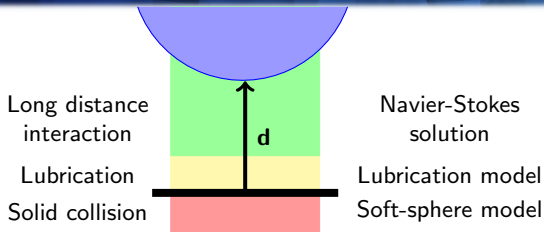
- ▶ m_e reduced mass
- ▶ e_d coefficient of restitution *in vaccum*
- ▶ N_c number of time step during collision
- ▶ Δt time step (fluid)

☰ Schäfer et al. - Jo. de Phys. - Vol 6 (1996)

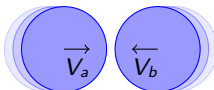
Collisions



Collisions

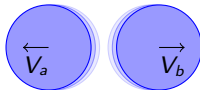


Before Collision



$$V = V_a - V_b$$

After collision



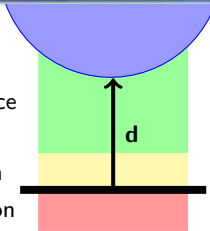
$$e = \frac{v_{\text{after}}}{v_{\text{before}}}$$

Collisions

Long distance
interaction

Lubrication

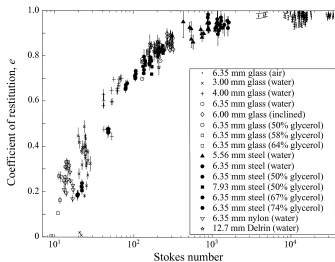
Solid collision



Navier-Stokes
solution

Lubrication model

Soft-sphere model



$$St = \frac{2}{9} \frac{RV\rho_p}{\mu_f}$$

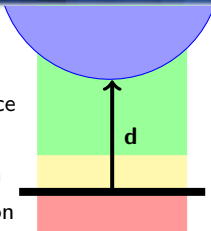
Joseph et al. - J. Fluid. Mech. - Vol. 433 (2001)

Collisions

Long distance
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Lubrication

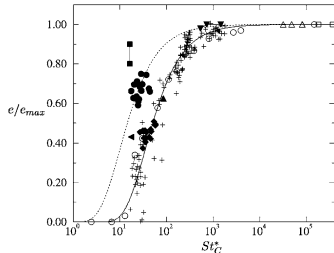
Solid collision



Navier-Stokes
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Lubrication model

Soft-sphere model



$$\frac{e_l}{e_d} = \exp\left(-\frac{35}{St}\right)$$

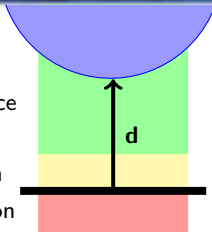
Legendre et al. - Phys. Fluids - Vol. 17 (2005)

Collisions

Long distance
interaction

Lubrication

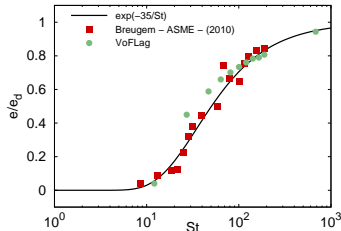
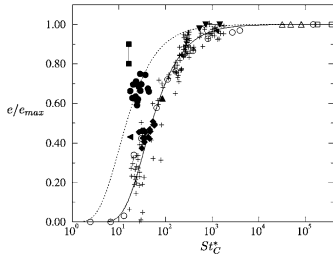
Solid collision



Navier-Stokes
solution

Lubrication model

Soft-sphere model



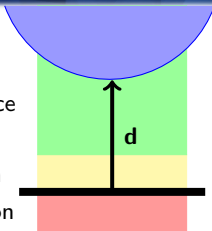
Legendre et al. - Phys. Fluids - Vol. 17 (2005)

Collisions

Long distance
interaction

Lubrication

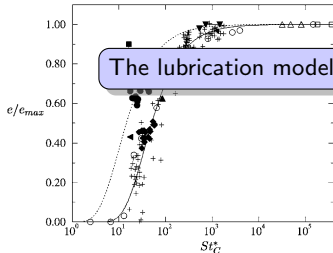
Solid collision



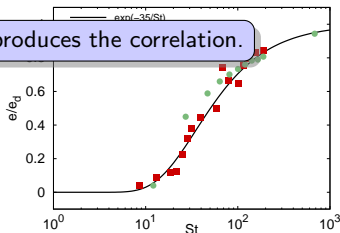
Navier-Stokes
solution

Lubrication model

Soft-sphere model

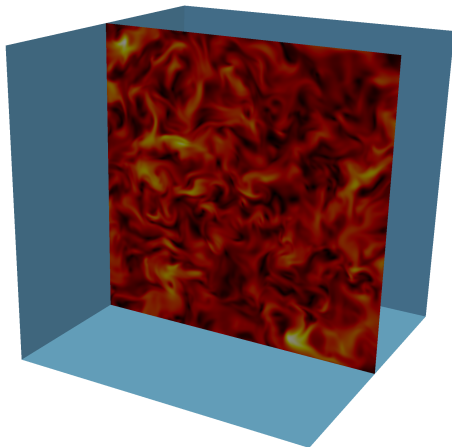


The lubrication model reproduces the correlation.



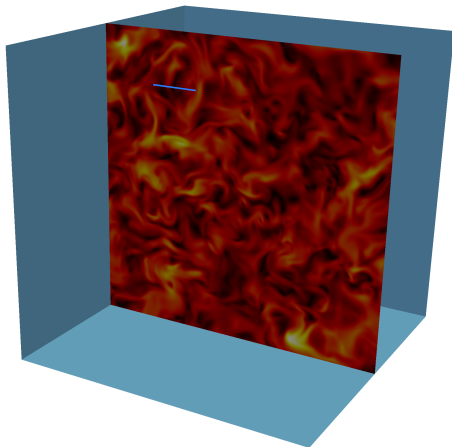
Legendre et al. - Phys. Fluids - Vol. 17 (2005)

HIT: Initial condition



$$L_b = 2\pi$$

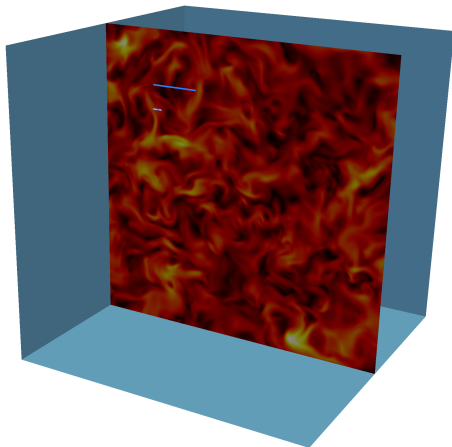
HIT: Initial condition



$$L_b = 2\pi$$

$$\frac{L_b}{\Lambda} = 2\pi$$

HIT: Initial condition

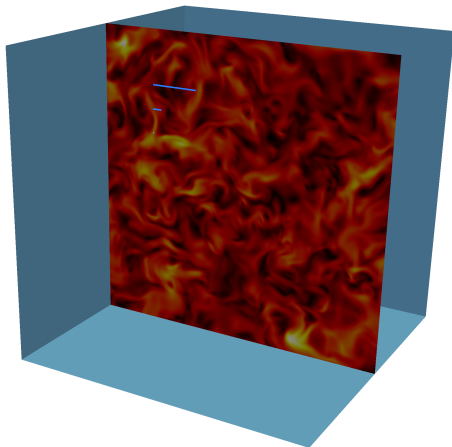


$$L_b = 2\pi$$

$$\frac{L_b}{\Lambda} = 2\pi$$

$$\frac{\Lambda}{\lambda} = 4.3$$

HIT: Initial condition



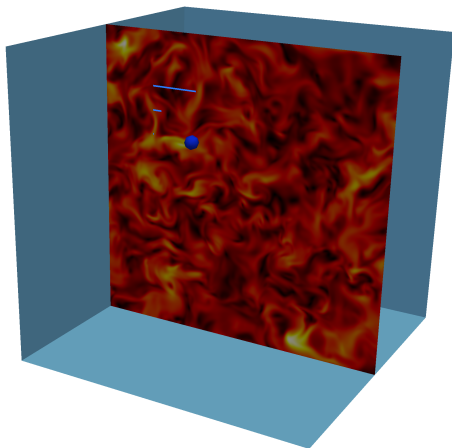
$$L_b = 2\pi$$

$$\frac{L_b}{\Lambda} = 2\pi$$

$$\frac{\Lambda}{\lambda} = 4.3$$

$$\frac{\eta}{\lambda} = 17$$

HIT: Initial condition



$$L_b = 2\pi$$

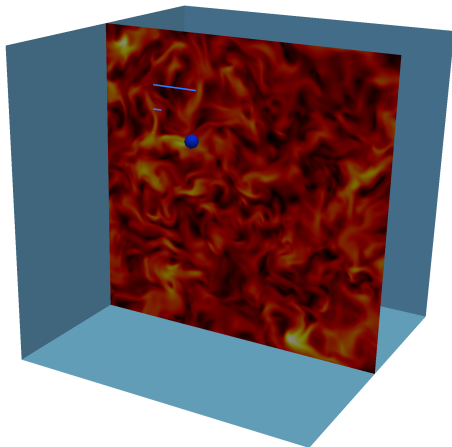
$$\frac{L_b}{\Lambda} = 2\pi$$

$$\frac{\Lambda}{\lambda} = 4.3$$

$$\frac{\eta}{\lambda} = 17$$

$$\frac{R_p}{\eta} = 11$$

HIT: Initial condition



$$Re_\lambda = 73$$

$$Re_\Lambda = 315$$

$$L_b = 2\pi$$

$$\frac{\rho_p}{\rho_f} = \{1, 2, 4\}$$

$$\frac{L_b}{\Lambda} = 2\pi$$

$$\frac{\Lambda}{\lambda} = 4.3$$

$$St_k = 26 \frac{\rho_p}{\rho_f}$$

$$St_E = 1.5 \frac{\rho_p}{\rho_f}$$

$$\frac{\eta}{\lambda} = 17$$

$$N_p = 512$$

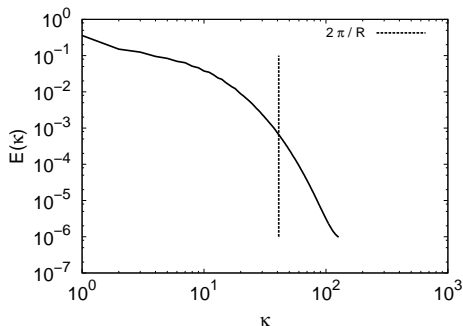
$$\frac{R_p}{\eta} = 11$$

$$\phi_v = 3\%$$

$$\frac{\eta_k}{\Delta x} = 0.56$$

$$\text{Nodes} = 256^3$$

HIT: Initial condition



The particles are on the inertial range.

$$Re_\lambda = 73$$

$$Re_\Lambda = 315$$

$$L_b = 2\pi$$

$$\frac{L_b}{\Lambda} = 2\pi$$

$$\frac{\Lambda}{\lambda} = 4.3$$

$$\frac{\eta}{\lambda} = 17$$

$$\frac{R_p}{\eta} = 11$$

$$\frac{\rho_p}{\rho_f} = \{1, 2, 4\}$$

$$St_k = 26 \frac{\rho_p}{\rho_f}$$

$$St_E = 1.5 \frac{\rho_p}{\rho_f}$$

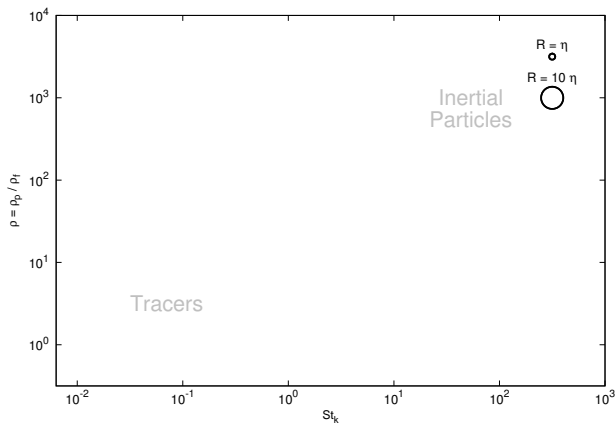
$$N_p = 512$$

$$\phi_v = 3\%$$

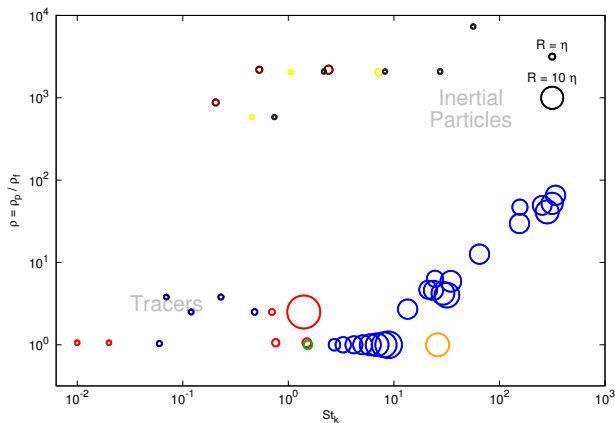
$$\frac{\eta_k}{\Delta x} = 0.56$$

$$\text{Nodes} = 256^3$$

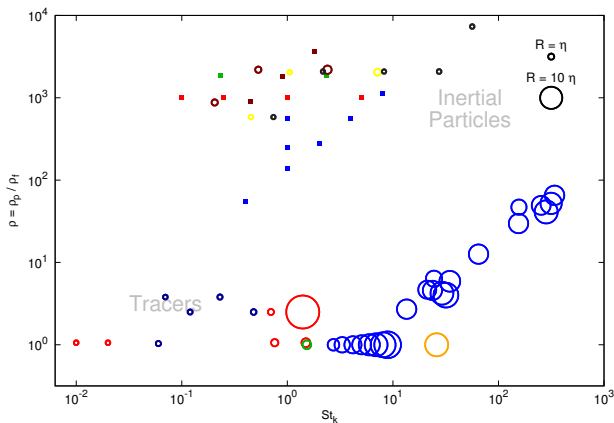
HIT: Initial condition



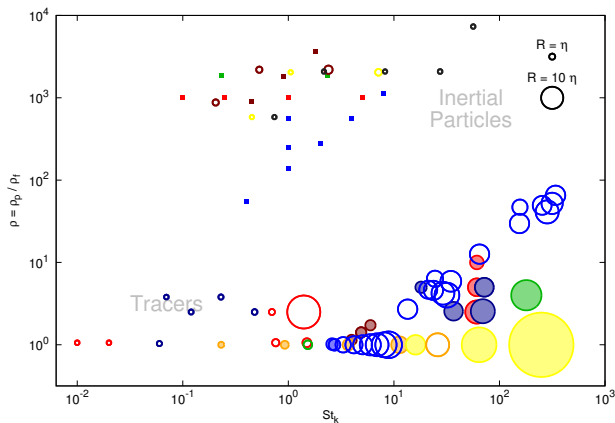
HIT: Initial condition



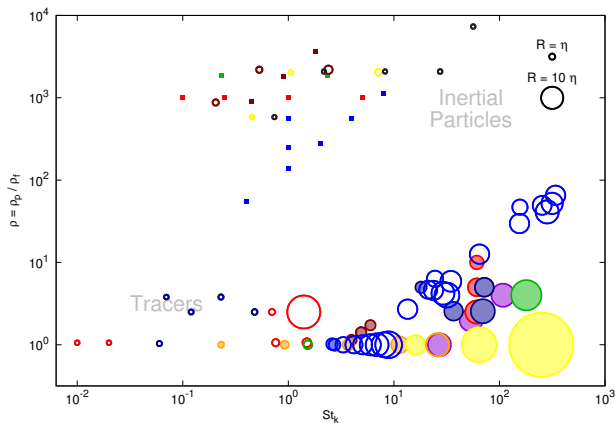
HIT: Initial condition



HIT: Initial condition



HIT: Initial condition



Visualization of one simulation

512 particles

256³ grid nodes

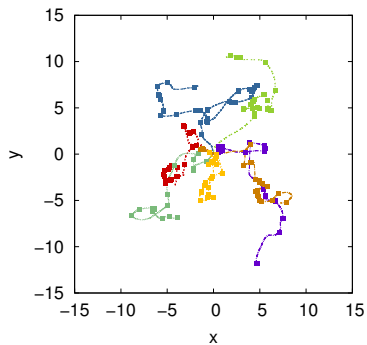
512 processors

~ 10h / T_E

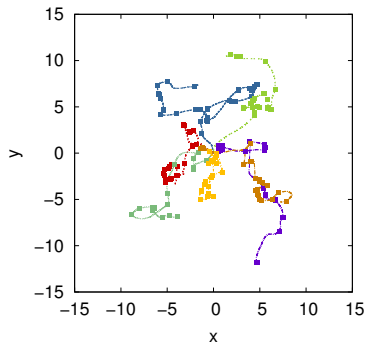
(Movie)

In this section only solid collision model is activated (no lubrication).

Collision time

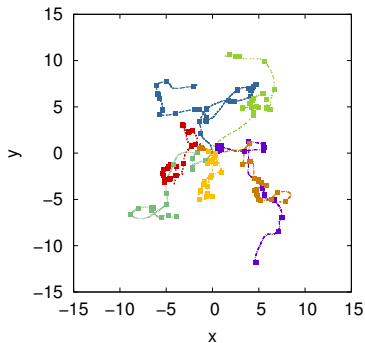


Collision time



$$\frac{1}{\tau_c} = n_p \pi d_p^2 \langle |\mathbf{w}| \rangle$$

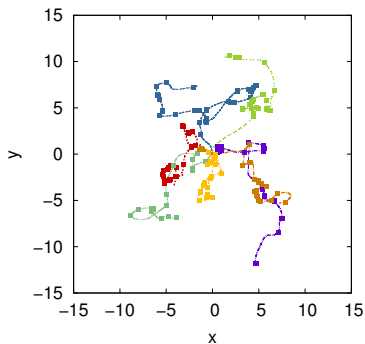
Collision time



$$\frac{1}{\tau_c} = n_p \pi d_p^2 \langle |\mathbf{w}| \rangle$$

$$\langle |\mathbf{w}| \rangle = \langle |\mathbf{V}_p^a - \mathbf{V}_p^b| \rangle$$

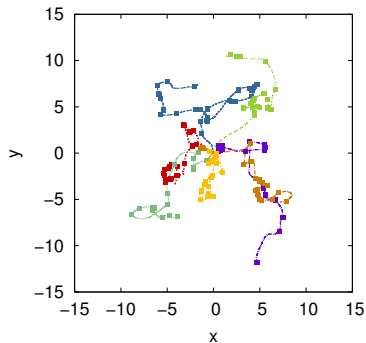
Collision time



$$\frac{1}{\tau_c} = n_p \pi d_p^2 \langle |\mathbf{w}| \rangle$$

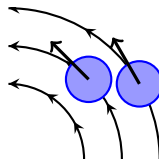
$$\frac{1}{\tau_c^{\text{th}}} = n_p \pi d_p^2 \sqrt{\frac{16}{\pi} \frac{2}{3} q_p^2}$$

Collision time

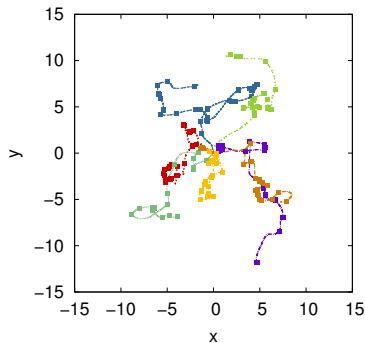


$$\frac{1}{\tau_c} = n_p \pi d_p^2 \langle |\mathbf{w}| \rangle$$

$$\frac{1}{\tau_c^{\text{th}}} = n_p \pi d_p^2 \sqrt{\frac{16}{\pi} \frac{2}{3} q_p^2}$$



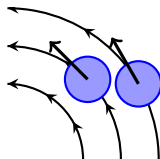
Collision time



$$\frac{1}{\tau_c} = n_p \pi d_p^2 \langle |\mathbf{w}| \rangle$$

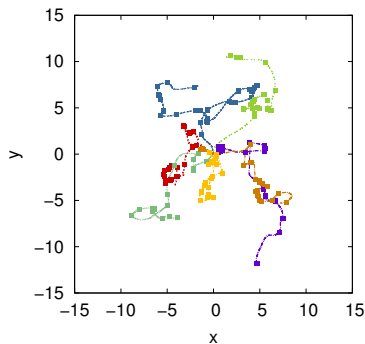
$$\frac{1}{\tau_c^{\text{th}}} = n_p \pi d_p^2 \sqrt{\frac{16}{\pi} \frac{2}{3} q_p^2}$$

$$\frac{1}{\tau_c^{\text{S.-T.}}} = n_p d_p^3 \sqrt{\frac{8\pi}{15} \frac{\epsilon}{\nu}}$$



Saffman and Turner - J. Fluid. Mech. - Vol. 1 (1956)

Collision time



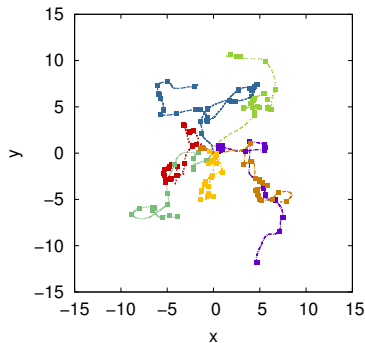
$$\frac{1}{\tau_c} = n_p \pi d_p^2 \langle |\mathbf{w}| \rangle$$

$$\frac{1}{\tau_c^{\text{th}}} = n_p \pi d_p^2 \sqrt{\frac{16}{\pi} \frac{2}{3} q_p^2}$$

$$\frac{1}{\tau_c^{\text{S.-T.}}} = n_p d_p^3 \sqrt{\frac{8\pi}{15} \frac{\epsilon}{\nu}}$$

ρ	$\tau_c^{\text{th}}/\tau_k$	$\tau_c^{\text{S.-T.}}/\tau_k$	τ_c^{m}/τ_k	
1	21.5	13.9	24.5	
2	22.48	-	20.8	
4	23.1	-	17.1	

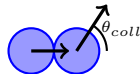
Collision time



$$\frac{1}{\tau_c} = n_p \pi d_p^2 \langle |\mathbf{w}| \rangle$$

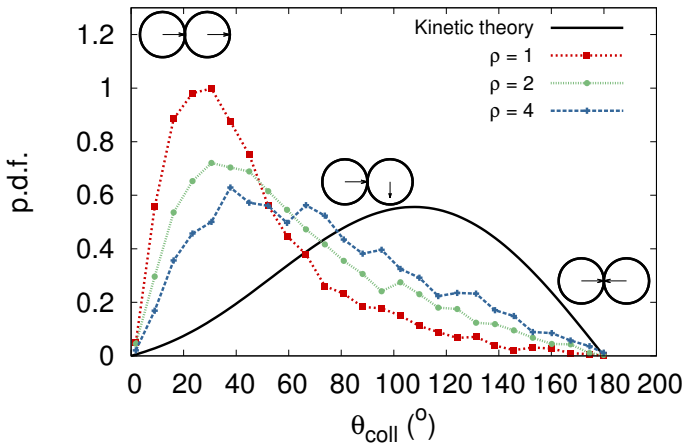
$$\frac{1}{\tau_c^{\text{th}}} = n_p \pi d_p^2 \sqrt{\frac{16}{\pi} \frac{2}{3} q_p^2}$$

$$\frac{1}{\tau_c^{\text{S.-T.}}} = n_p d_p^3 \sqrt{\frac{8\pi}{15} \frac{\epsilon}{\nu}}$$



ρ	$\tau_c^{\text{th}}/\tau_k$	$\tau_c^{\text{S.-T.}}/\tau_k$	τ_c^{m}/τ_k	$\langle \theta_{\text{coll}} \rangle$
1	21.5	13.9	24.5	44 °
2	22.48	-	20.8	59 °
4	23.1	-	17.1	69 °

Contact angle



The velocity between particles at collision are correlated.

Collision velocity



Effect of the lubrication on intercollision time

Visualization of secondary collisions

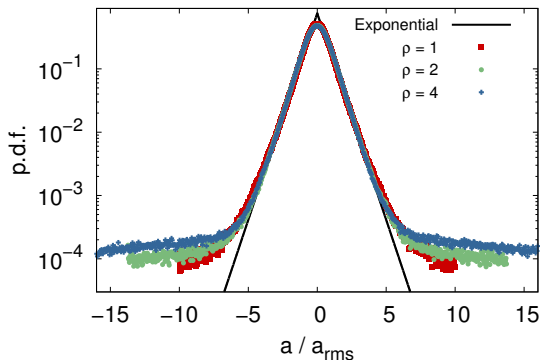
$\rho = 1$ with lubrication model

- = Encounter
- = Solid collision
(Movie)

Effect of lubrication in acceleration p.d.f

Collisions increase the p.d.f. for large accelerations.

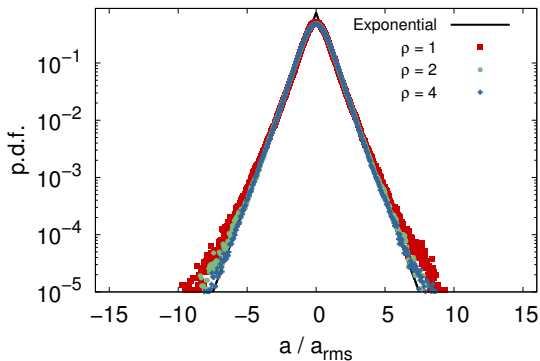
Comparison for different density ratio



Effect of lubrication in acceleration p.d.f

Collisions increase the p.d.f. for large accelerations.

Suppress accelerations during collision



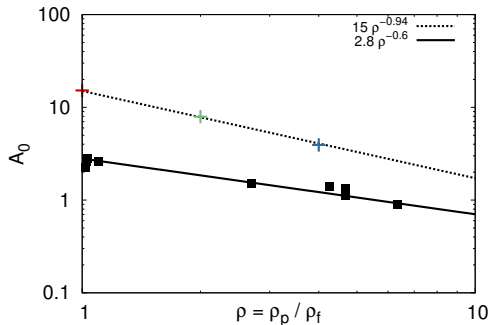
Effect of lubrication in acceleration p.d.f

Collisions increase the p.d.f. for large accelerations.

Acceleration r.m.s. is related to density.

$$A_0 = a_{r.m.s.}^2 / \epsilon^{3/2} \nu^{1/2}$$

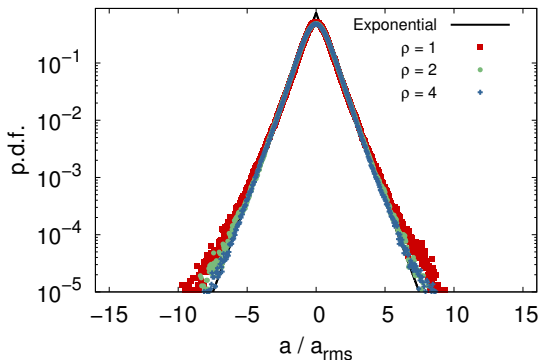
■ Qureshi et al. - European Phy. Jo. B - 2008



Effect of lubrication in acceleration p.d.f

Collisions increase the p.d.f. for large accelerations.

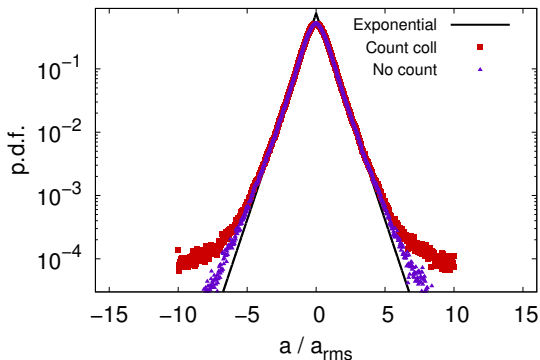
Suppress accelerations during collision



Effect of lubrication in acceleration p.d.f

Collisions increase the p.d.f. for large accelerations.

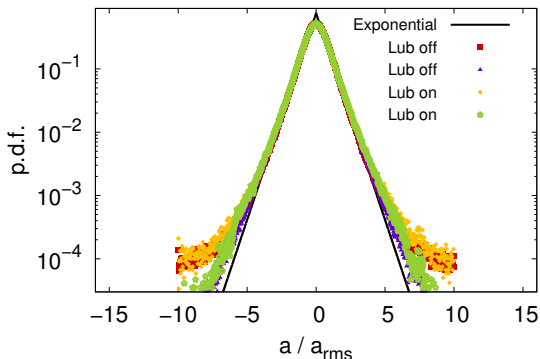
Comparison for $\rho = 1$



Effect of lubrication in acceleration p.d.f

Collisions increase the p.d.f. for large accelerations.

Same but for lubricated case



The lubrication do not modify the p.d.f. for larger accelerations

Conclusions and future work

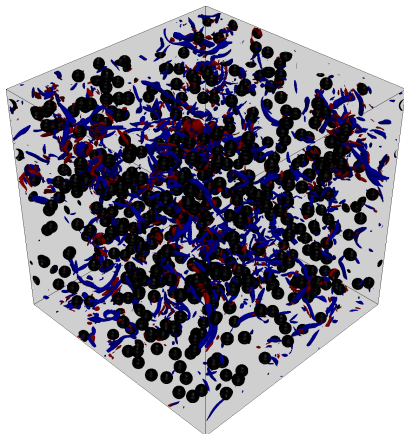
This work highlight some important effects:

- ▶ The lubrication model is representative for collisions in viscous fluids
- ▶ The lubrication creates the secondary collisions
- ▶ This secondary collisions have an effect on collision time
- ▶ The collisions modify the acceleration p.d.f.

These effects have to be considered when the collision frequency is treated. New models have to be put in place.

Thanks

Thanks for your attention.
Some questions ?



Acknowledgements:

P. Fedem, W.-P. Breugem, P. Costa, J. Derksen, ...
Supercomputer support: CALMIP, CINES

Appendix

Appendix:

Method

VoFLag method

Simulation

Collision

Particle Stats

Average flow calculation

Validations

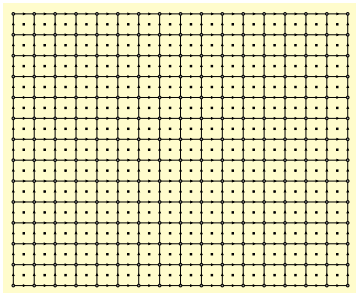
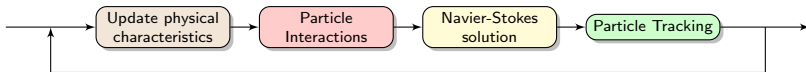
Poiseuille

Rotation

Sedimentation

Job time

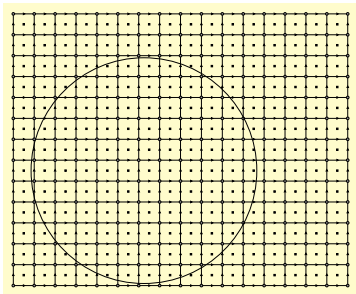
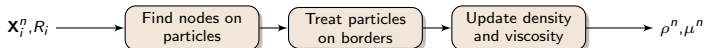
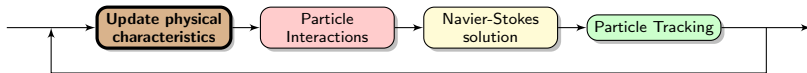
Method



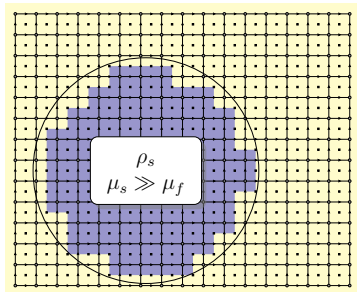
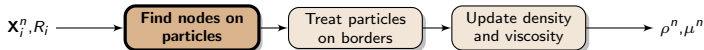
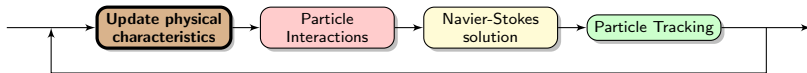
Thetis code

- MAC staggered grid
- Finite volumes
- Fictitious Domain Approach

Method



Method



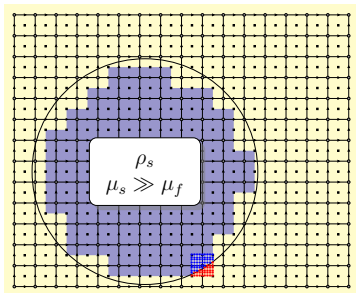
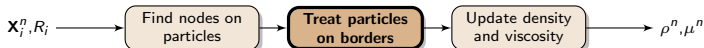
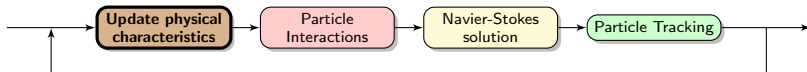
The solid behaviour is enforced by high viscosity.

■ Randrianarivelo et al. Int. J. Num. Meth. in Fluids - Vol. 47

(2005)

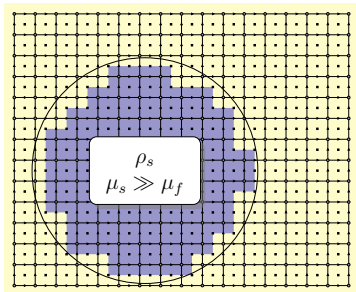
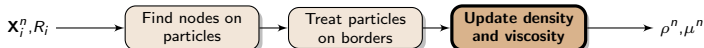
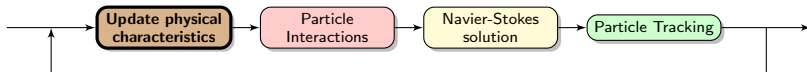
■ Vincent et al. - Comp. & Fluids - Vol. 36 (2007)

Method



$$C = \frac{\sum_1^{25^N} \delta_{P \in R}}{25^N}$$

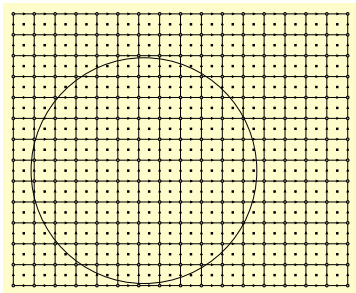
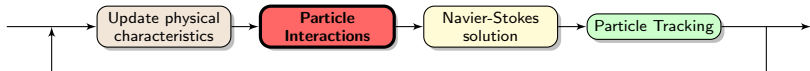
Method



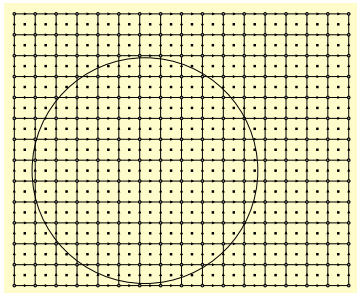
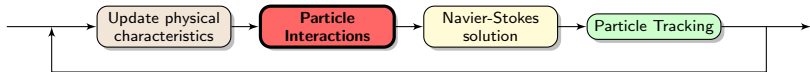
$$\rho = C\rho_s + (1 - C)\rho_l$$

$$\mu = \frac{\mu_f \mu_s}{C\mu_f + (1 - C)\mu_s}$$

Method



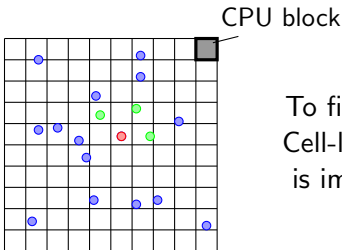
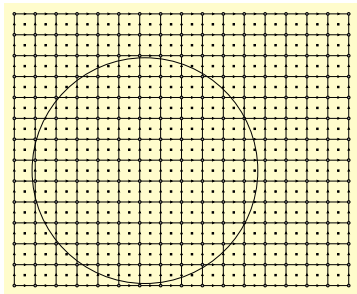
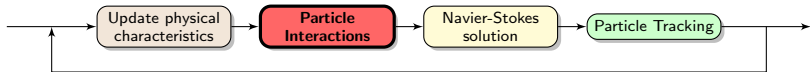
Method



$$\tilde{\mathbf{x}}_i^{n+\frac{1}{2}} = \mathbf{x}_i^n + \frac{\Delta t}{2} \mathbf{v}_i^n t$$

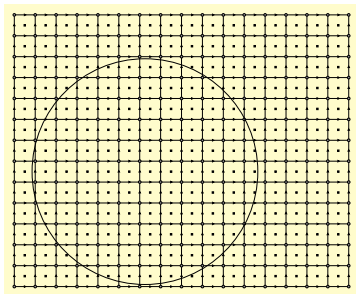
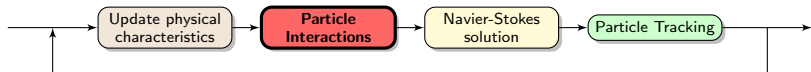
$$\tilde{\mathbf{v}}_i^{n+\frac{1}{2}} = \frac{3}{2} \mathbf{v}_i^n - \mathbf{v}_i^{n-1}$$

Method



To find collisions
Cell-list approach
is implemented.

Method

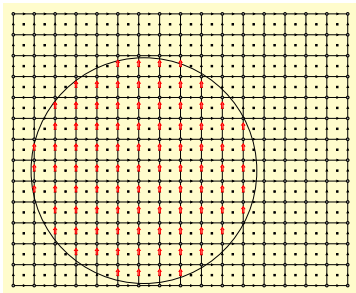
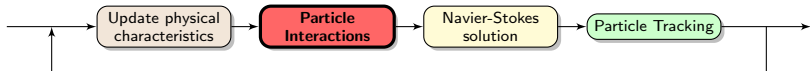


A collision model gives the force applied on each particle.
The model developed is explained in later.

Brändle et al. - Phys. Fluids - (2013)

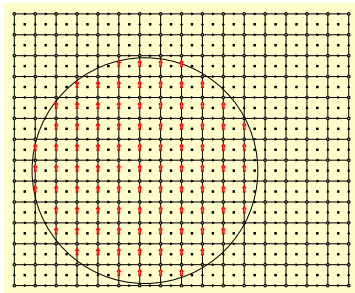
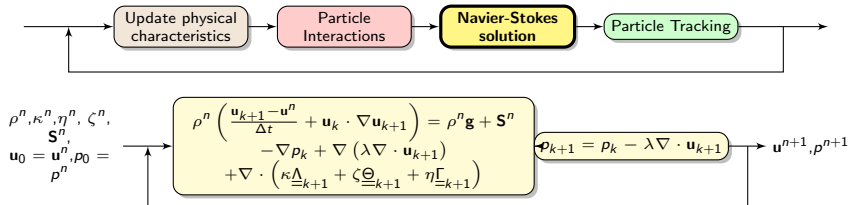
Bruegem - ASME Summer Meeting - Montreal (2010)

Method



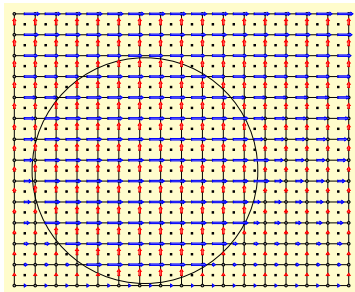
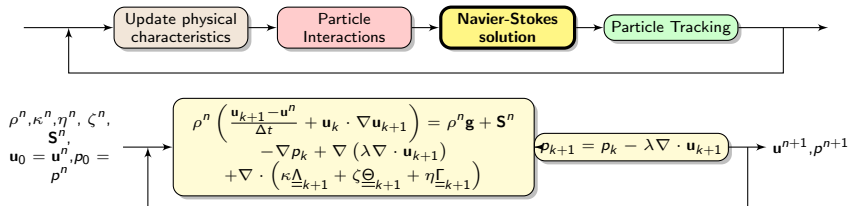
The force is distributed on the solid volume and becomes a source term for N.-S. solution.

Method



An augmented Lagrangian method is implemented.
With BiCG Stab solver.

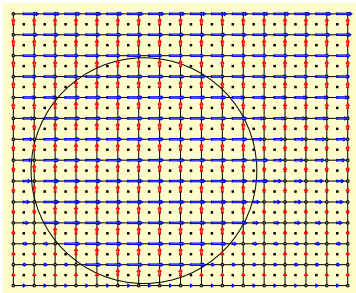
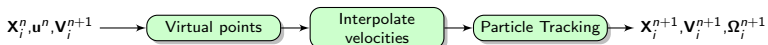
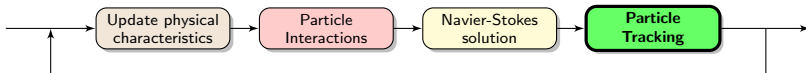
Method



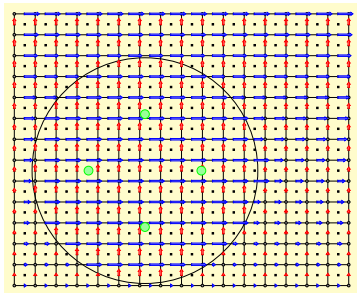
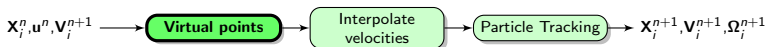
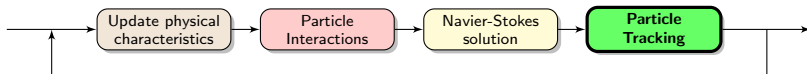
The new velocity field is calculated.
The solid behaviour is respected by this field.

Vincent et al. - Comp. & Fluids - Vol. 36. (2007)

Method

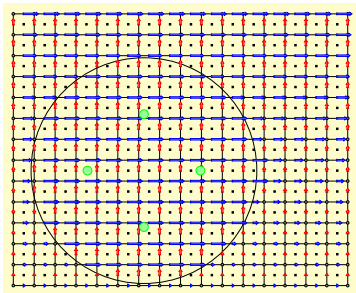
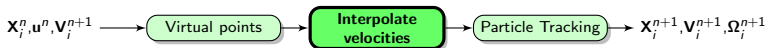
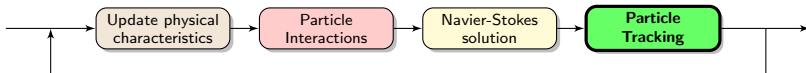


Method

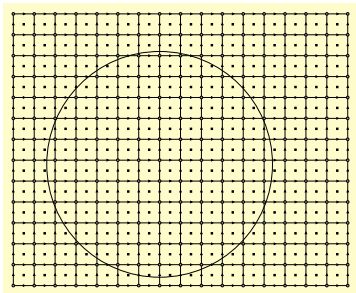
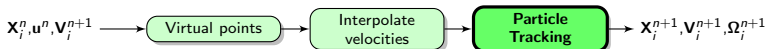
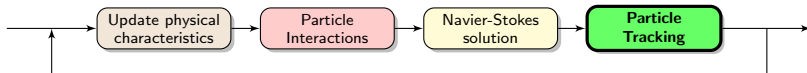


The particle velocity is calculated by interpolating the velocity

Method



Method

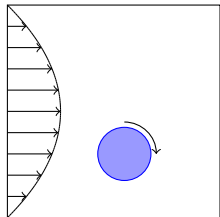


$$\mathbf{x}_i^{n+1} = \mathbf{x}_i^n + \Delta t \left(\frac{\mathbf{v}_i^{n+1} + \mathbf{v}_i^n}{2} \right)$$

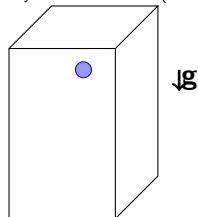
Validations

Inamuro et al. -

IJMF - Vol 26 (2000)

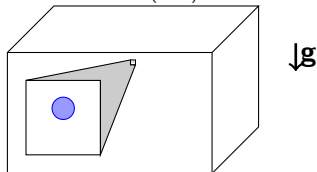


ten Cate et al. - Phys. Fluids - Vol 14 (2002)

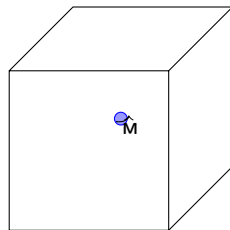


Mordant et al. - Europ. Physical

Journal B - Vol. 18 (2000)

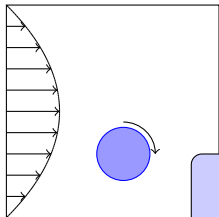


Dennis et al. - JFM - Vol 101 (1980)

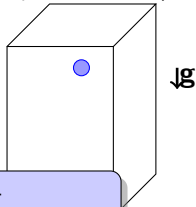


Validations

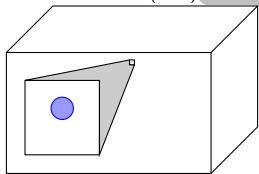
Inamuro et al. - IJMF - Vol 26 (2000)



ten Cate et al. - Phys. Fluids - Vol 14 (2002)

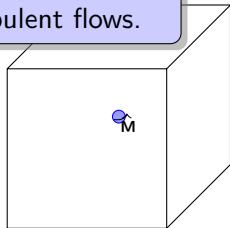


Mordant et al. - Euro Journal B - Vol. 18 (2000)



With only 8 nodes per diameter results agree.
We use 20 for the simulations for more reliability in fully turbulent flows.

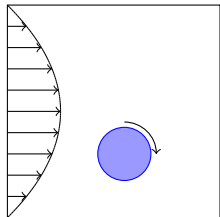
101 (1980)



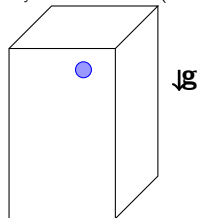
Validations

Inamuro et al. -

IJMF - Vol 26 (2000)

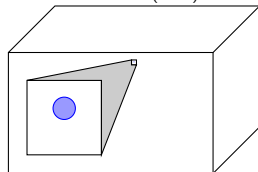


ten Cate et al. - Phys. Fluids - Vol 14 (2002)



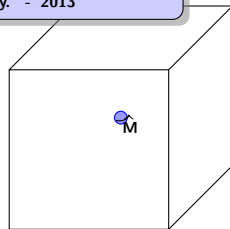
Mordant et al. - Euro

Journal B - Vol. 18 (2000)



Vincent et al. - J. Comp. Phy. - 2013

101 (1980)



Constraints

Physics:

- ▶ Scale separation
- ▶ Moderate concentrated
- ▶ Not too inertial

Numerical:

- ▶ $\frac{\eta}{\Delta x} \sim 1$
- ▶ $\frac{D}{\Delta x} \sim 20$
- ▶ $Nx \sim 256$
- ▶ As many particles as possible

Constraints

Physics:

- ▶ Scale separation
- ▶ Moderate concentrated
- ▶ Not too inertial

Numerical:

- ▶ $\frac{\eta}{\Delta x} \sim 1$
- ▶ $\frac{D}{\Delta x} \sim 20$
- ▶ $Nx \sim 256$
- ▶ As many particles as possible

Consequences:

Constraints

Physics:

- ▶ Scale separation
- ▶ Moderate concentrated
- ▶ Not too inertial

Numerical:

- ▶ $\frac{\eta}{\Delta x} \sim 1$
- ▶ $\frac{D}{\Delta x} \sim 20$
- ▶ $Nx \sim 256$
- ▶ As many particles as possible

Consequences:

- ▶ $60 < Re_\lambda < 90$

■ Pope and Pope - Cambridge Univ. Press. -
(2000)

Constraints

Physics:

- ▶ Scale separation
- ▶ Moderate concentrated
- ▶ Not too inertial

Numerical:

- ▶ $\frac{\eta}{\Delta x} \sim 1$
- ▶ $\frac{D}{\Delta x} \sim 20$
- ▶ $Nx \sim 256$
- ▶ As many particles as possible

Consequences:

- ▶ $60 < Re_\lambda < 90$
- ▶ $\frac{D}{\eta} \sim 20$

Constraints

Physics:

- ▶ Scale separation
- ▶ Moderate concentrated
- ▶ Not too inertial

Numerical:

- ▶ $\frac{\eta}{\Delta x} \sim 1$
- ▶ $\frac{D}{\Delta x} \sim 20$
- ▶ $Nx \sim 256$
- ▶ As many particles as possible

Consequences:

- ▶ $60 < Re_\lambda < 90$
- ▶ $\frac{D}{\eta} \sim 20$
- ▶ $St_k < 100$

Constraints

Physics:

- ▶ Scale separation
- ▶ Moderate concentrated
- ▶ Not too inertial

Numerical:

- ▶ $\frac{\eta}{\Delta x} \sim 1$
- ▶ $\frac{D}{\Delta x} \sim 20$
- ▶ $Nx \sim 256$
- ▶ As many particles as possible

Consequences:

- ▶ $60 < Re_\lambda < 90$
- ▶ $\frac{D}{\eta} \sim 20$
- ▶ $St_k < 100$
- ▶ $\rho < 10$

Constraints

Physics:

- ▶ Scale separation
- ▶ Moderate concentrated
- ▶ Not too inertial

Numerical:

- ▶ $\frac{\eta}{\Delta x} \sim 1$
- ▶ $\frac{D}{\Delta x} \sim 20$
- ▶ $Nx \sim 256$
- ▶ As many particles as possible

Consequences:

- ▶ $60 < Re_\lambda < 90$
- ▶ $\frac{D}{\eta} \sim 20$
- ▶ $St_k < 100$
- ▶ $\rho < 10$
- ▶ $\phi_v \sim 3\%$

HIT: Forcing

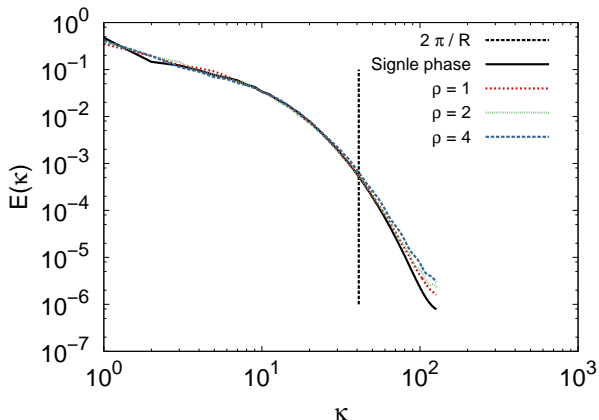
The turbulence forcing is done in physical space by maintaining the total energy

$$u_n = \sqrt{\frac{E_0}{E_n}}$$

(the density of particles is not taken into account)

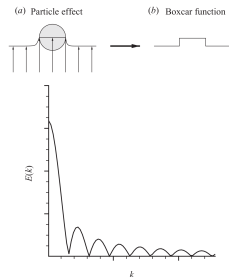
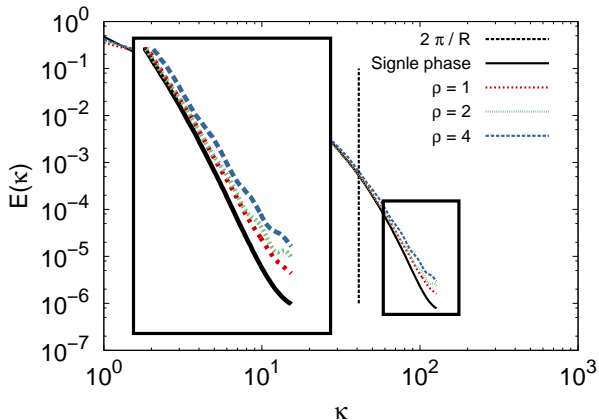
☰ Rosales et. al - Phys. Fluids - Vol. 17 (2005)


HIT: Turbulence modulation



Turbulence increases for high wave numbers

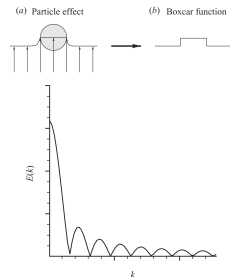
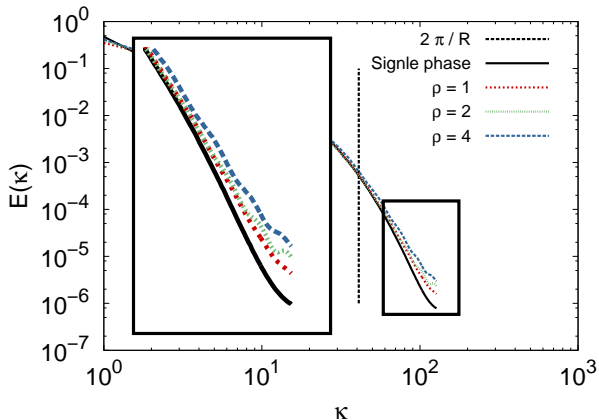
HIT: Turbulence modulation



 Lucci et al. - J. Fluid. Mech. -
 Vol. 650 (2010)

Turbulence increases for high wave numbers (Numerical effect?)

HIT: Turbulence modulation



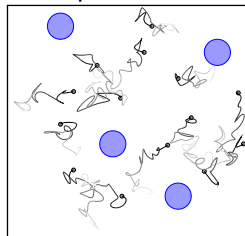
■ Lucci et al. - J. Fluid. Mech. -
 Vol. 650 (2010)

Turbulence increases for high wave numbers (Numerical effect?)

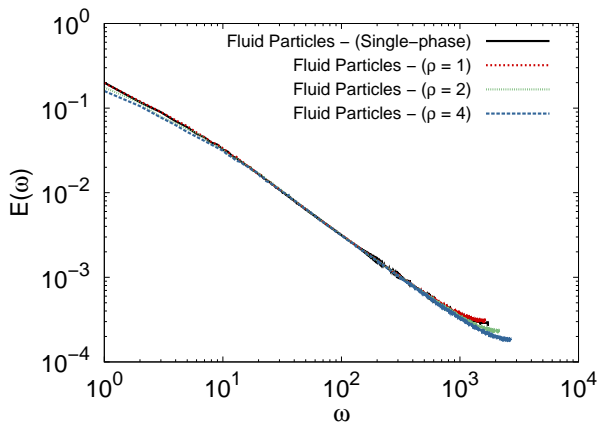
⇒ We need to analyze the Lagrangian spectrum

HIT: Lagrangian spectrum

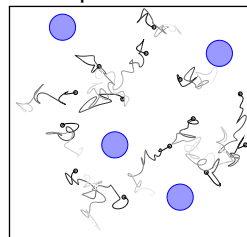
Fluid particles



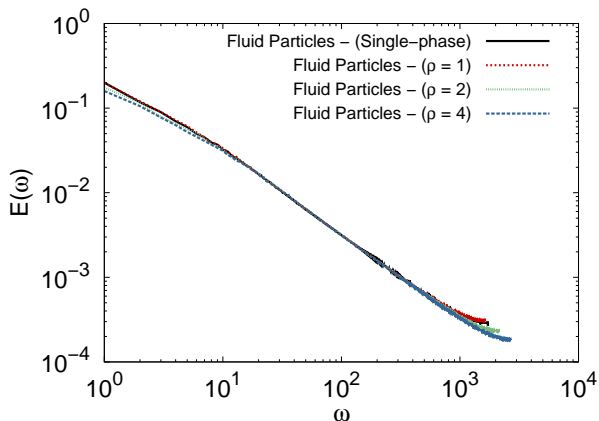
HIT: Lagrangian spectrum



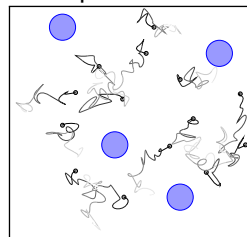
Fluid particles



HIT: Lagrangian spectrum

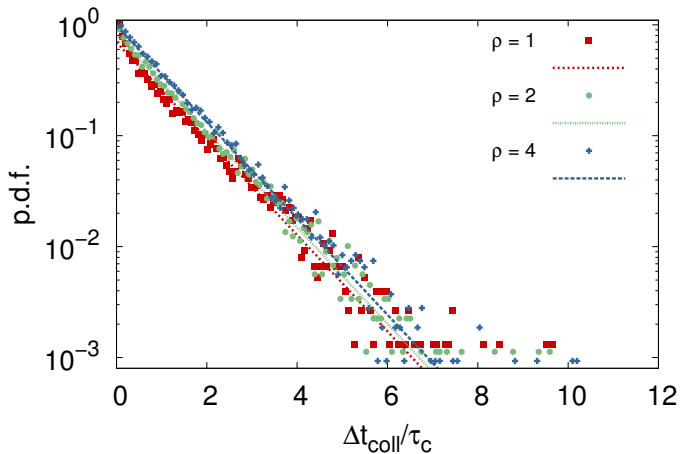


Fluid particles



The turbulence is not modified by the particles

Intercollision time



Statistics

ρ -	q_p^2 ($m^2 s^{-2}$)	$\frac{q_p^2}{q_f^2}$ -	T_L (s)	$\frac{T_L}{T_L^f}$ -	D ($m^2 s^{-1}$)	$\frac{D}{D_f}$ -
1	1.27	0.85	1.22	1.31	3.10	1.13
2	1.17	0.79	1.35	1.45	3.16	1.15
4	1.10	0.74	1.53	1.65	3.37	1.23

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4	1.10	0.74	1.53	1.65	3.37	1.23

The q_p^2 agitation decreases with ρ .

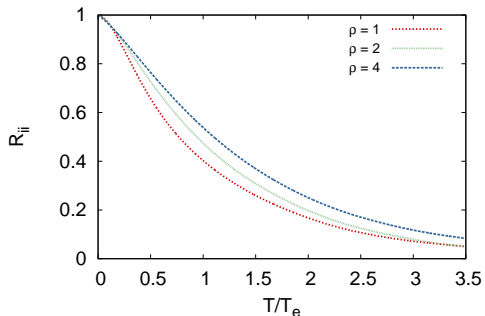
Statistics

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The velocity autocorrelation time T_L increases with ρ .

Statistics

ρ	q_p^2 ($m^2 s^{-2}$)	$\frac{q_p^2}{q_f^2}$	T_L (s)	$\frac{T_L}{T_L^f}$	D ($m^2 s^{-1}$)	$\frac{D}{D_f}$
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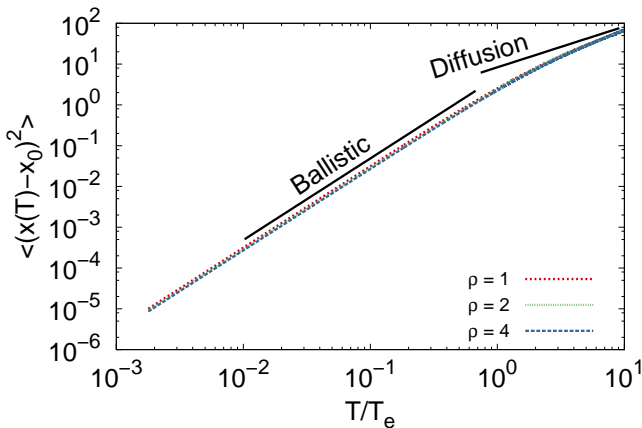


Statistics

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4	1.10	0.74	1.53	1.65	3.37	1.23

q_p^2 and T_L balance and give similar diffusion coefficient.

Particles diffusion

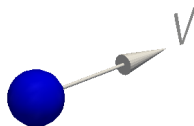


$$\frac{D}{D_f} = \frac{2q_p^2 T_L}{2q_f^2 T_L^f} = \{1.13, 1.15, 1.23\}$$

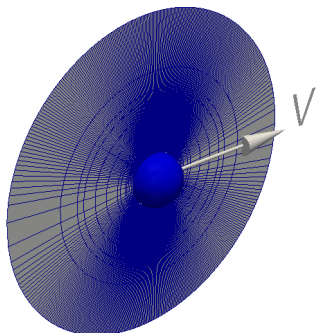
Average flow calculation



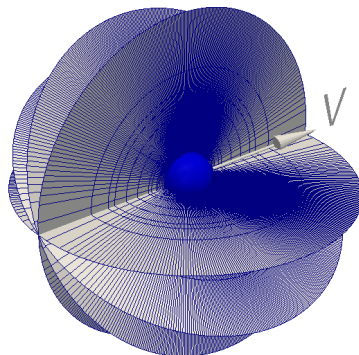
Average flow calculation



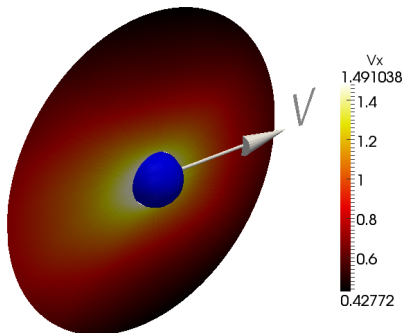
Average flow calculation



Average flow calculation



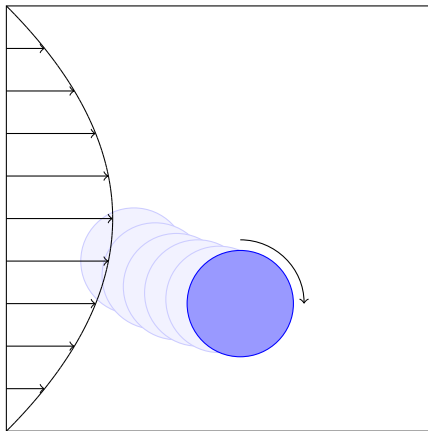
Average flow calculation



Validations

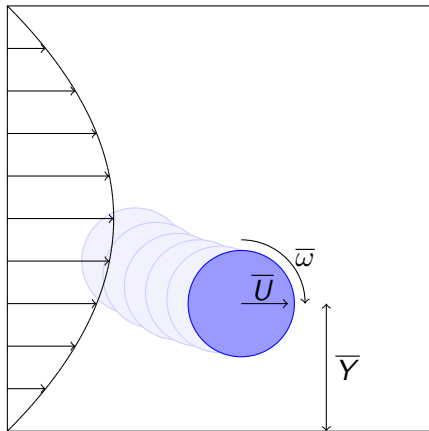
Ici je vais mettre les slides que j'avais fait sur les validations afin de répondre aux questions

Validations: Poiseuille



☰ Segré and Silberberg - Nature - Vol. 189 (1961)

Validations: Poiseuille



Equilibrium

☰ Segré and Silberberg - Nature - Vol. 189 (1961)

Validations: Poiseuille

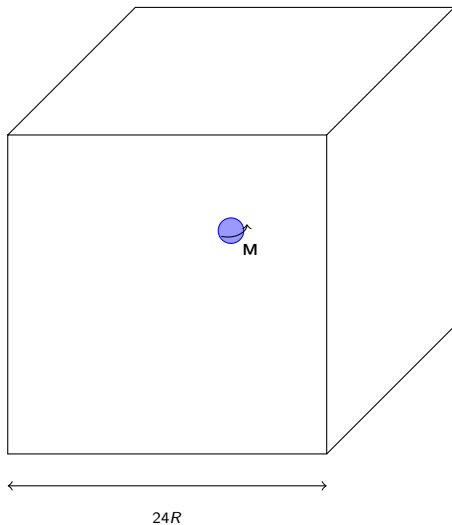
A :  Inamuro et al. - IJMF - Vol 26 - 2000

B :  Pan et al. - JCP - Vol 181 - 2002

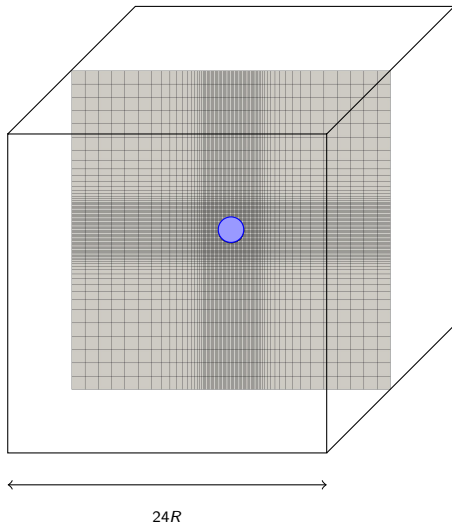
	Author	Case1	Case2	Case3	Case4	Case5	Case6
$Re = \frac{L u_f}{\mu}$		12.78	27.72	43.40	55.55	69.13	96.74
\bar{Y}	A	0.2745	0.2733	0.2728	0.2723	0.2716	0.2706
	B	0.2732	0.2725	0.2723	0.2720	0.2719	0.2722
	VofLag	0.2643	0.2636	0.2637	0.2643	0.2650	0.2752
	Error	3.8%	3.6%	3.4%	3.0%	2.5%	2.0 %
\bar{u}	A	0.04137	0.04131	0.04091	0.04118	0.04110	0.04101
	B	0.04155	0.04159	0.04122	0.04166	0.04148	0.04144
	VofLag	0.04599	0.04605	0.04570	0.04628	0.04623	0.04682
	Error	10.6%	10.9%	11.1%	11.7%	11.7%	13.2%
\bar{z}	A	-0.054675	-0.054694	-0.053772	-0.053765	-0.053101	-0.051607
	B	-0.05345	-0.05343	-0.05264	-0.05264	-0.05206	-0.05052
	VofLag	-0.05500	-0.05331	-0.05082	-0.04966	-0.04761	-0.05276
	Error	0.6%	2.6%	5.6%	7.9%	10.9%	2.2%

With 6 nodes per diameter we obtain a low relative error

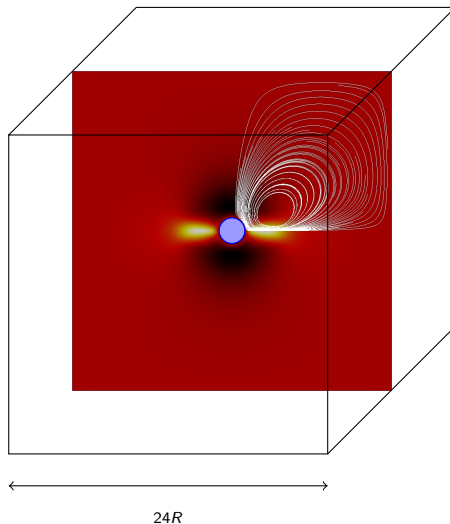
Validations : Dennis 1980



Validations : Dennis 1980

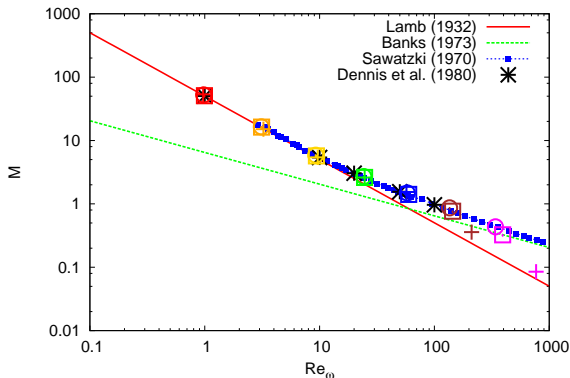


Validations : Dennis 1980



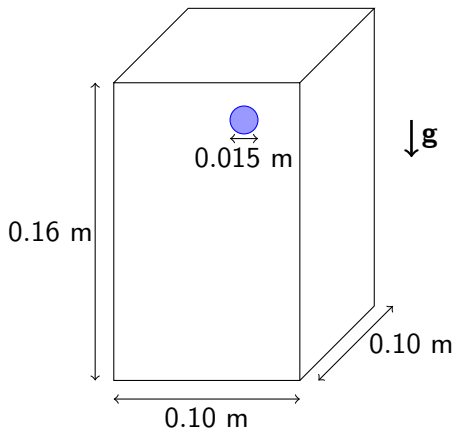
Validations : Dennis 1980

Dimensionless torque $M = \frac{2T}{\rho_f R^5 \omega^2}$ vs Reynolds number $Re_\omega = \frac{R^2 \omega \rho}{\mu_f}$

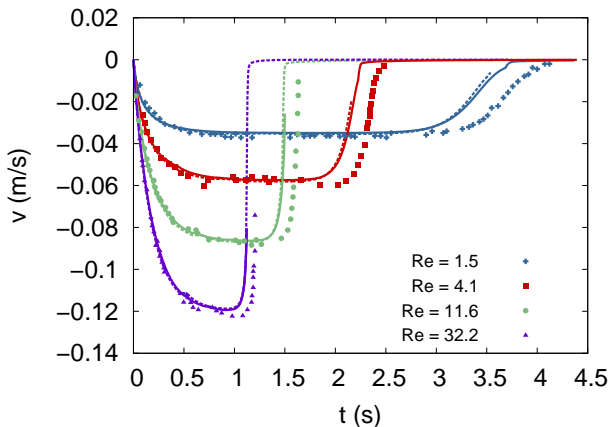


Symbols by
 $\frac{\Delta x}{D} = \{10, 20, 40\}$
 Colors by
 T

Validations: Ten Cate 2002



Validations: Ten Cate 2002



Dashed lines $\frac{D}{\Delta T} = 8$, straight line $\frac{D}{\Delta T} = 16$.

ten Cate et al. - Phys. Fluids - Vol 14 (2002)

HIT : Jobs time

With 512 procs

	T_{sim}/T_E	Percentage
Navier-Stokes Resolution	26828 s	75%
Postraitement (Out + Spectra)	3977 s	11%
Fluid Particles	2121 s	6%
Advection	2105 s	6%
Collisions	39 s	< 1%
Others	714 s	2%
Total	35784 s ~ 10 h	