Four-way coupled simulations of turbulent flows with non-spherical particles

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Training School "*Behaviour of Non-Spherical Particles in Flows*"
COST FP1005

OUTLINE

1. PARTICLES IN TURBULENCE
   - Equations of motion
   - Forces on non-spherical particles
2. CASE 1: CHANNEL FLOW WITH $Re_\tau = 150$
   - Effect of *St*
   - Effect of shape
3. CASE 2: CHANNEL FLOW WITH $Re_\tau \approx 1,000$
   - Rough wall modelling
   - Effect of gravity
   - Effect of shape and orientation
4. CONCLUSIONS

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Particles in Turbulence

- Particles affect turbulent flow and are affected by turbulent flow.
- So-far almost all computational studies in gas-solid flow assume spherical particles.
- In many flows, this is not an valid assumption.
- There is little data on non-spherical particles.
- Objective: How do non-spherical particles behave in and affect turbulent channel flow?

Equations of motion for particles

Momentum Equation

$$m_p \frac{D\boldsymbol{v}_p}{Dt} = \boldsymbol{F}_d + \boldsymbol{F}_l + m_p \boldsymbol{g} - V_p \nabla P_f + \sum^{N_p} \boldsymbol{F}_{pp} + \sum^{N_w} \boldsymbol{F}_{pw} + \dots$$

Angular Momentum Equation

$$I_{ij\,p} \frac{d\omega_P}{dt} = \boldsymbol{T}_{aero} - \boldsymbol{T}_{rot} + \sum^{N_p} \boldsymbol{T}_{pp} + \sum^{N_w} \boldsymbol{T}_{pw}$$

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Algorithm Summary

For each body in the simulation,

1. Determine the mass and mass middle point.
2. Determine the inertia tensor in “body-space”.
3. Define a unit Quaternion.

For each time-step for each body,

1. Determine the effect of collisions and fluid (force + torque).
2. Determine the effect of rotation, $\tilde{Q}$.
3. Integrate the state-vector and move the body accordingly.

Zhao & van Wachem (2013). A novel Quaternion integration approach for describing the behaviour of non-spherical particles. Acta Mechanica, 224

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Fluid Forces and Torques on a Particle

Drag Force

$$F_d = C_D\left(\ldots\right)\frac{1}{2}\rho_g\frac{\pi}{4}d_p^2\left(\tilde{\boldsymbol{v}}_f - \boldsymbol{v}_p\right)^2$$

Lift Force

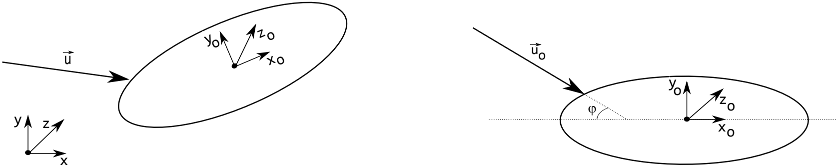
$$F_l = C_L\left(\ldots\right)\frac{1}{2}\rho_g\frac{\pi}{4}d_p^2\left(\tilde{\boldsymbol{v}}_f - \boldsymbol{v}_p\right)^2$$

Aerodynamic Torque

$$T_{aero} = C_T\left(\ldots\right)\frac{1}{2}\rho_g\frac{\pi}{8}d_p^3\left(\tilde{\boldsymbol{v}}_f - \boldsymbol{v}_p\right)^2$$

Rotational Torque

$$\boldsymbol{T}_{rot} = C_R\left(\ldots\right)\frac{\rho}{2}\left(\frac{d_p}{2}\right)^5|\boldsymbol{\omega}_p|\boldsymbol{\omega}_p$$



world space body space

$$\varphi = \left| \arctan \left(\frac{u_{o,sh}}{u_{o,ln}} \right) \right|$$

$$F_o, x = \frac{1}{2} \cdot \rho \cdot A_{eq} \cdot C_D(\varphi, Re) \cdot |\boldsymbol{u}_o| u_{o,x} + F_L \cdot \sin\varphi \cdot sign(-u_{o,x})$$

$$F_o, y = \frac{1}{2} \cdot \rho \cdot A_{eq} \cdot C_D(\varphi, Re) \cdot |\boldsymbol{u}_o| u_{o,y} + F_L \cdot \cos\varphi \cdot \frac{u_{o,y}}{\sqrt{u_{o,y}^2 + u_{o,z}^2}}$$

$$F_o, z = \frac{1}{2} \cdot \rho \cdot A_{eq} \cdot C_D(\varphi, Re) \cdot |\boldsymbol{u}_o| u_{o,z} + F_L \cdot \cos\varphi \cdot \frac{u_{o,z}}{\sqrt{u_{o,y}^2 + u_{o,z}^2}}$$

Zastawny et al. (2012) Int. J. Multiphase Flows 39, pp 227

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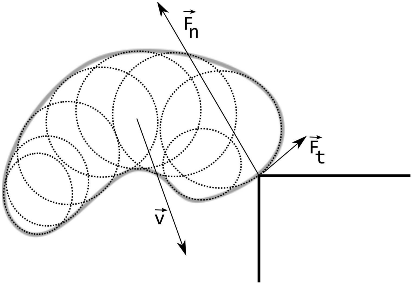
contacts can be found through "spheres":



Hertzian contact model:

$$\boldsymbol{F}_n(t) = K_n(t)\delta_n^{\frac{3}{2}}(t)\boldsymbol{n}(t)$$
$$\boldsymbol{F}_t(t) = min\left(\mu \boldsymbol{F}_n(t), K_t(t)\boldsymbol{\delta}_t(t)\right)$$

$\rightarrow$ In doing this, we assume the deformation plane is circular!

Zhao & van Wachem, B. G. M. (2013). Direct numerical simulation of ellipsoidal particles in turbulent channel flow. Acta Mechanica, 224

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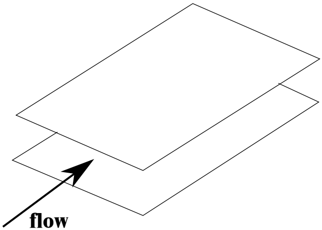
Case 1

- In Case 1, we consider the DNS of the "*Marchioli et al*" channel flow
- We look at the effect of various shapes of particles.
- This means including effect of fluid on particles, particles on fluid and including particle-particle collisions.
- In this case we perform real DNS of the fluid: resolution sub-Kolmogorov scale.

Marchioli, C., *et al.* (2008). Int J of Multiphase Flow, 34(9), 879-93.

SIMULATION SET-UP

- Dimensions: $2\pi h \times 4\pi h \times 2h$
- $Re_\tau = 150$
- Flow driven by fixed pressure drop (source term) to sustain channel flow: the wall shear stress is always the same.
- Discretisation in domain of $169 \times 171 \times 169$ cells.



Marchioli, C., *et al.* (2008). Int J of Multiphase Flow, 34(9), 879-93.

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Governing equations

Navier-Stokes

$$\frac{\partial u_i^f}{\partial x_i} = 0$$

$$\frac{\partial u_i^f}{\partial t} + u_j^f \frac{\partial u_i^f}{\partial x_j} = -\frac{1}{\rho^f}\frac{\partial p}{\partial x_i} + \nu^f \frac{\partial^2 u_i^f}{\partial x_j^2} + \delta P_i + \Pi_i$$

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Equations governing turbulent channel flow

Shear stress

$$\tau(y) = \rho^f \nu^f \frac{d\overline{u_1}}{dx_2} - \rho^f \overline{u_1^{f'} u_2^{f'}} = \tau_0 = const$$

$$Re_\tau = \frac{u_\tau h}{\nu} \qquad u_\tau = \sqrt{\frac{\tau_0}{\rho_f}}$$

Driving pressure drop

$$\delta P_1 = \frac{\rho_f {\nu_f}^2 Re_\tau^2}{h^3}$$

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Channel flow: Turbulence kinetic energy

Turbulence kinetic energy with particles

$$\frac{d}{dy}\left(\frac{1}{2} < u_y'^f u_i'^f u_i'^f > + \frac{< u_y'^f p' >}{\rho^f} - \nu^f \frac{d}{dy}(k + < u_y'^{f2} >)\right) =$$

$$\mathcal{P} - \tilde{\varepsilon} - \varepsilon_p$$

Production of TKE

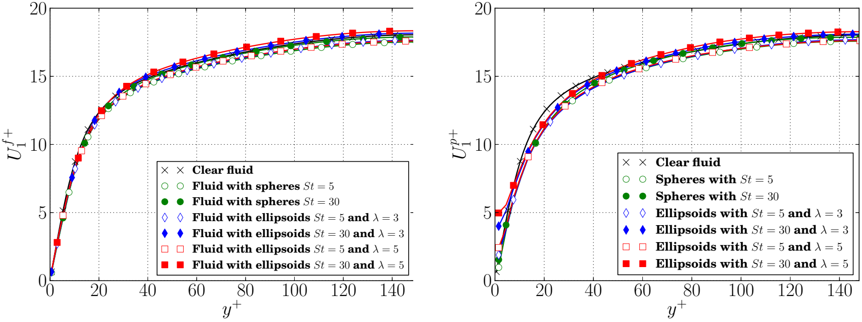
$$\mathcal{P} = - < u_x'^f u_y'^f > \frac{\partial \boldsymbol{U}_x^f}{\partial y}$$

Dissipation of TKE

$$\tilde{\varepsilon} = 2\nu^f < S_{ij} S_{ij} >$$

Particle dissipation rate

$$\varepsilon_p = < \Pi_i' u_i'^f >$$



Fluid mean velocity — Particle mean velocity

- The wall shear stress is exactly the same for all plots.
- Different centerline values imply drag reduction.
- The viscosity is exactly the same also. Collapse at low y^+ implies no change in viscosity.

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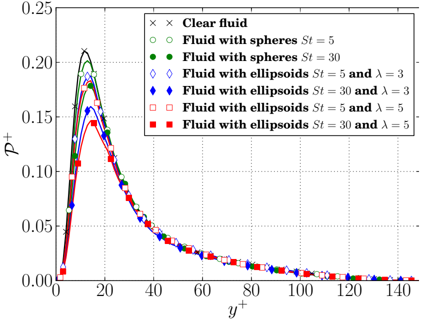
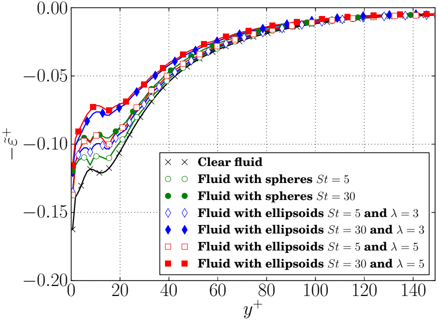
Channel flow with particles: Production and Dissipation



Fluid TKE production



Fluid TKE direct dissipation

- The particles decrease the *fluid* production and dissipation.
- The magnitude of dissipation decreases faster than production when adding ellipsoids.

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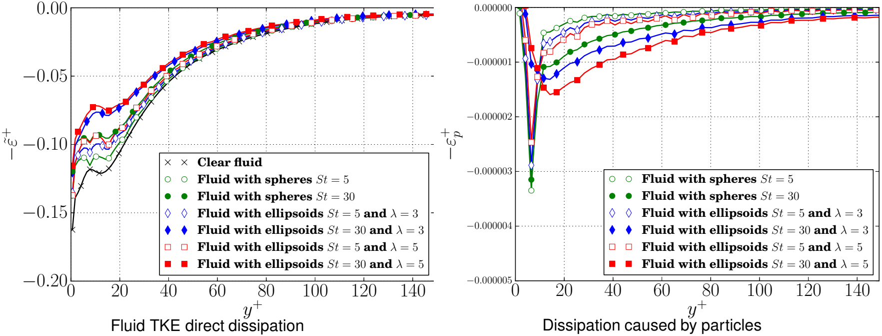
Channel flow with particles: Production and Dissipation



- The particles decrease the *fluid* dissipation.
- The magnitude of dissipation decreases faster than production when adding ellipsoids.
- The dissipation caused directly by particles is negligible.

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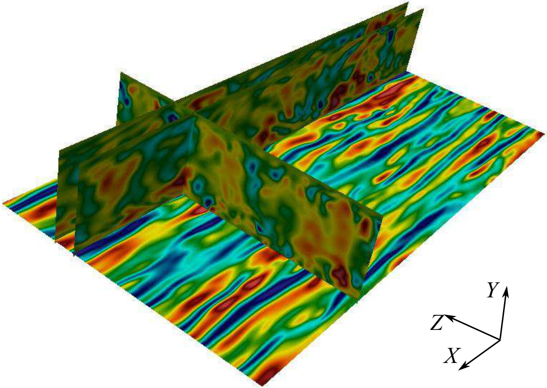
Channel flow with particles



Streamwise fluid velocity (horizontal planes) and wall-normal velocity (vertical planes) of the flow in the channel

- The flow shows “sweeps” slowly moving towards or near the wall.
- The flow shows “ejections” quickly moving away from the wall.

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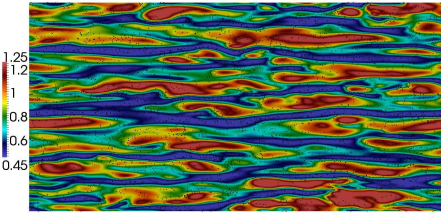

FIGURE : Fluid velocity with particles of $St = 5$ in stream-wise direction at $y^+ = 8$

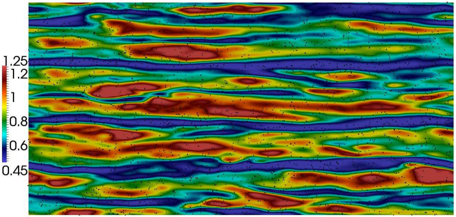

FIGURE : Fluid velocity with ellipsoids of $St = 30$ in stream-wise direction at $y^+ = 8$

- Particles affect sweeps and ejections in near-wall region.

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Slip velocity of particles with fluid

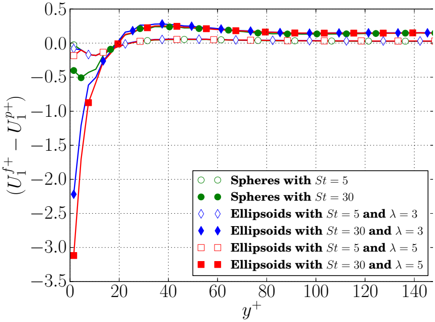

FIGURE : Fluid-particle slip velocity in streamwise direction

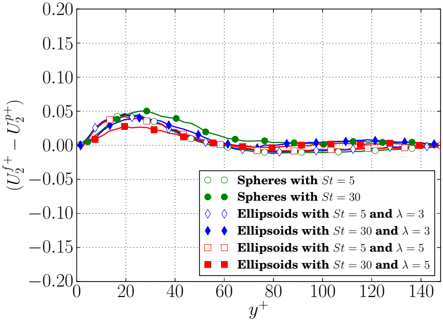

FIGURE : Fluid-particle slip velocity in wall-normal direction

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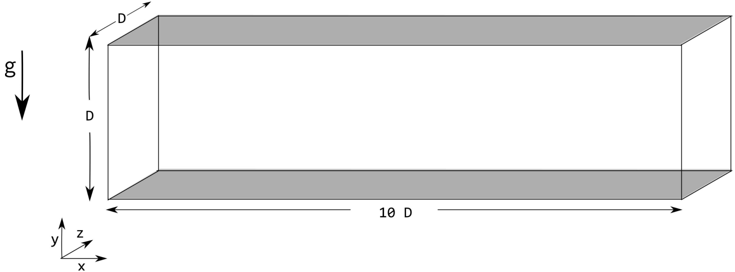
- Effect of dilute solutions not due to viscosity changes.
- Main effect is to change turbulence structures near wall by suppressing ejections.
- Continuity (of flow) implies both sweeps and ejections affected.
- But no continuity for particles - so clustering until collisions and bouncing from wall dominate other effects.
- High inertia ellipsoids pretty much ignore flow, but do affect the flow.

Case 2: Simulation Domain



D	d_p	m	Re_D	$< U >$	St
$35\,mm$	$200\,\mu m$	1.0	$42,000$	$19.7\,m/s$	≈ 52

Exp. data: Kussin and Sommerfeld (2002), Int J Heat and Fluid Flow, 23, pp 647

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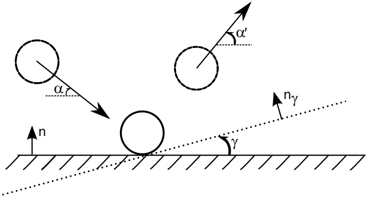
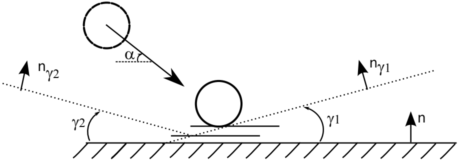
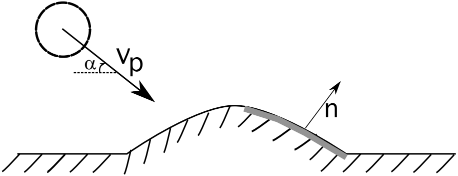


hard-sphere model



soft-sphere model

Including the "shadow-effect": particles do not see walls with $\boldsymbol{v}_p \cdot \boldsymbol{n}_\gamma \geq 0$.



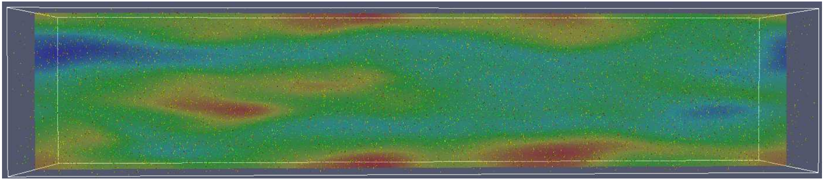
Spherical particles

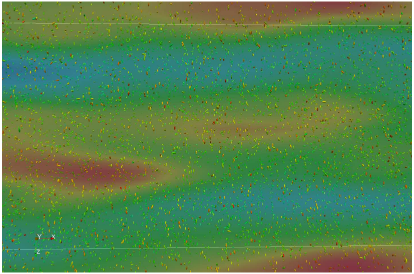
Spheres colliding with a rough wall

Ellipsoids

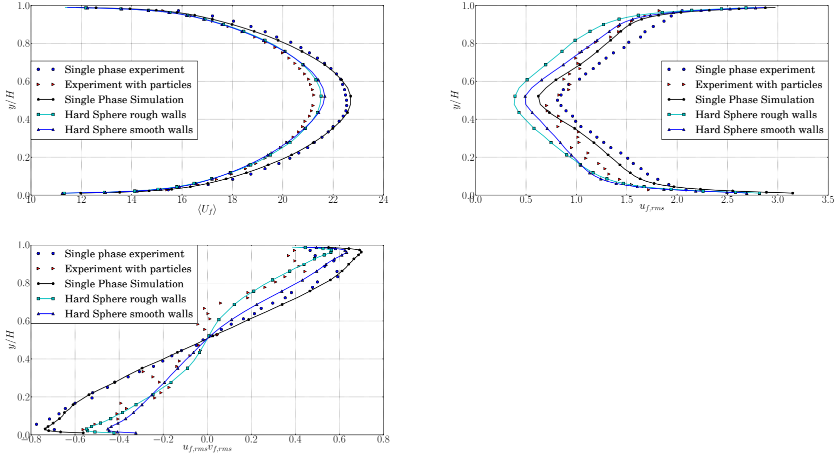
Ellipoids colliding with a rough wall
$\longrightarrow$ the effect of rough walls is different for non-spherical particles.

Snapshots of results





Effect of wall roughness



Exp. data: Kussin and Sommerfeld (2002), Int J Heat and Fluid Flow, 23, pp 647

Results: Mallouppas and van Wachem (2013), Int J. Multiphase Flow, 54, pp 65

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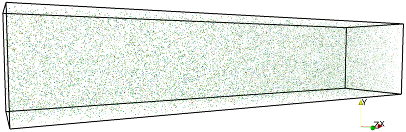
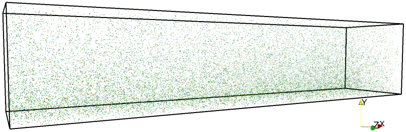
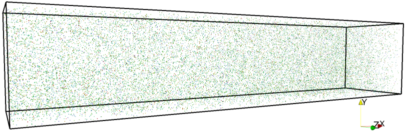
SPHERICAL PARTICLES

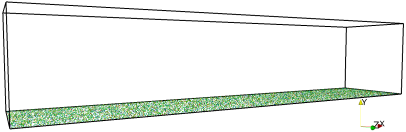
with part-part collisions and wall rough.

with part-part coll but NO wall rough.









NO

no part-part collisions but with wall rough.

part-part collisions and NO wall rough.

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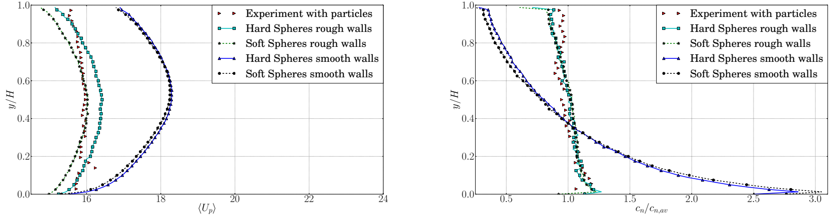
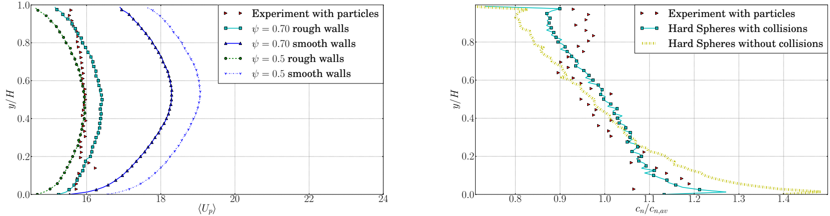
Spherical particles

Comparison of hard and soft-sphere models





Effect of collision parameters

Exp. data: Kussin and Sommerfeld (2002), Int J Heat and Fluid Flow, 23, pp 647; Results: Mallouppas and van Wachem (2013), Int J. Multiphase Flow, 54, pp 65

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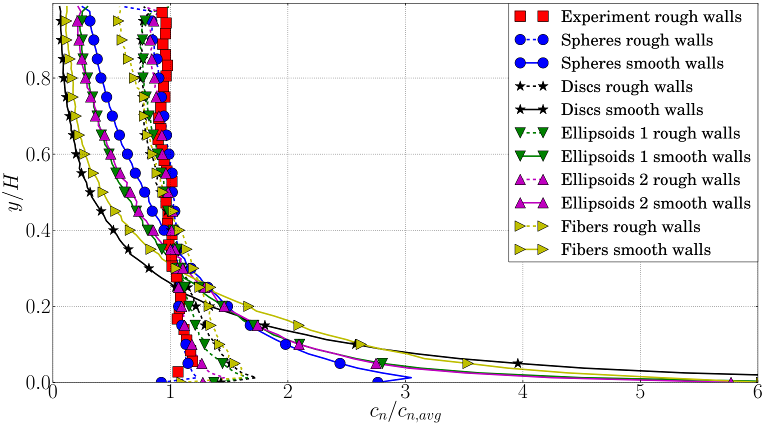

Concentration of particles vs channel height

Van Wachem, Zastawny, Zhao, Mallouppas, G. (2015). Modelling of gas-solid turbulent channel flow with non-spherical particles with large Stokes numbers. International Journal of Multiphase Flow, 68, 80-92.

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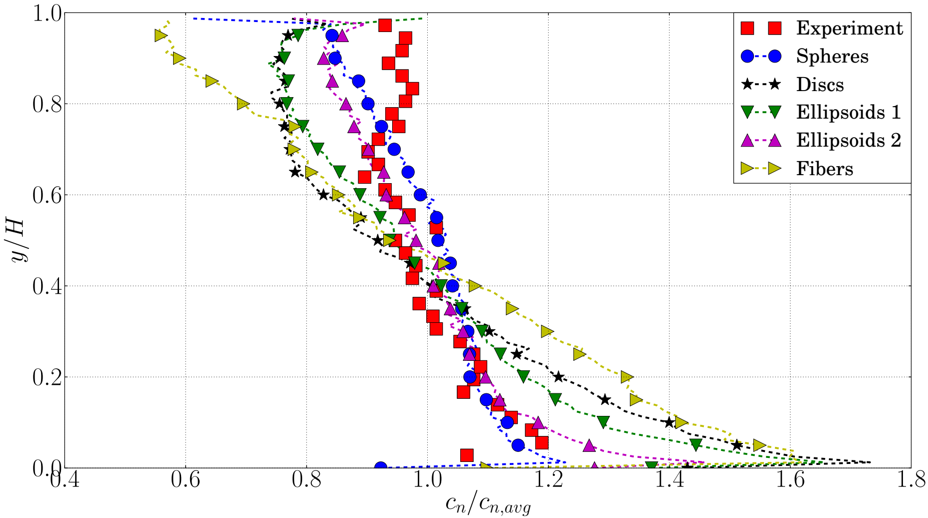
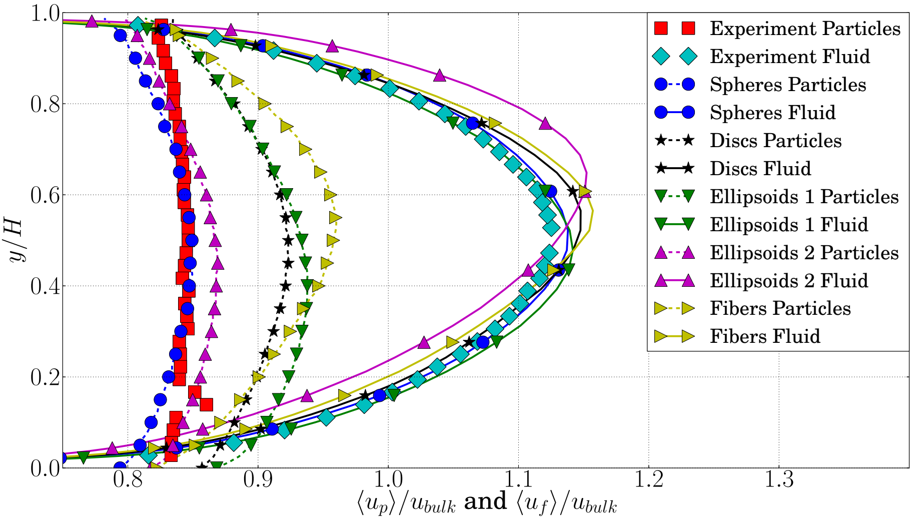


concentration of particles vs channel height, rough walls only.



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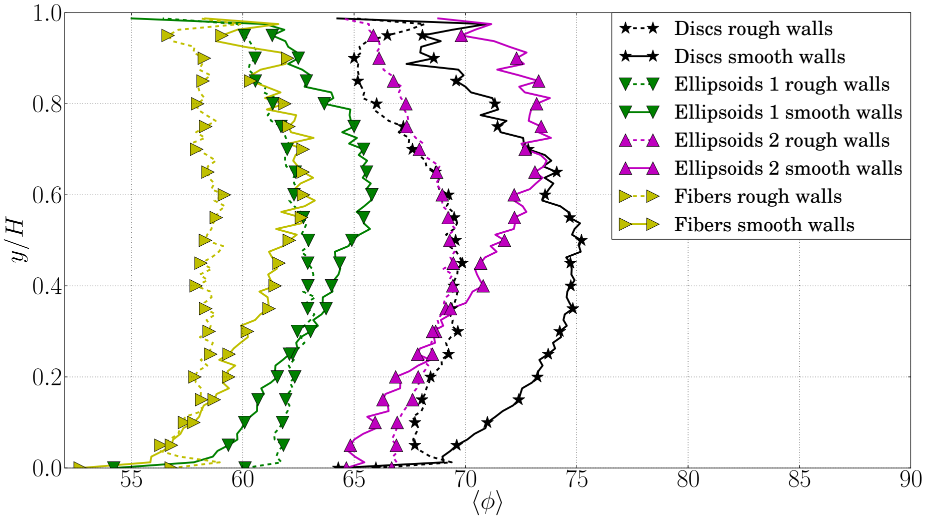
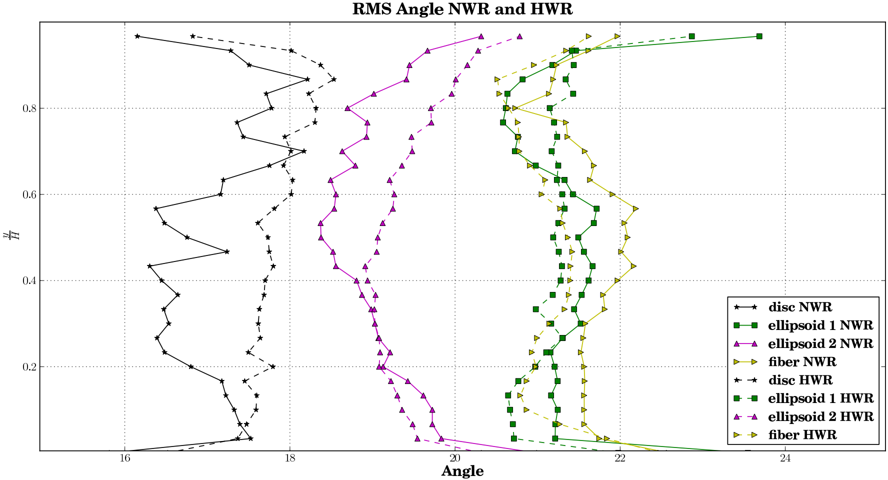
average particle and fluid velocities.



Angle of particles vs channel height



RMS of angle of particles vs channel height

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- Results for single-phase and spheres in line with experimental data.
- Comparison of soft-sphere and hard-sphere model.
- Strong effect of wall roughness predicted, in line with exp observations
- Wall roughness has different effect for spheres as for non-spherical particles.
- Non-spherical particles try to locally maximize their drag. Reason?