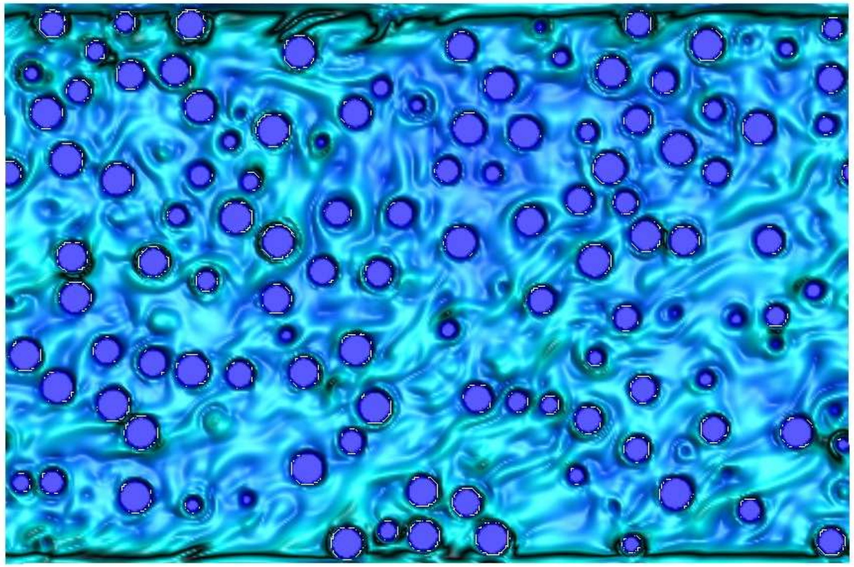
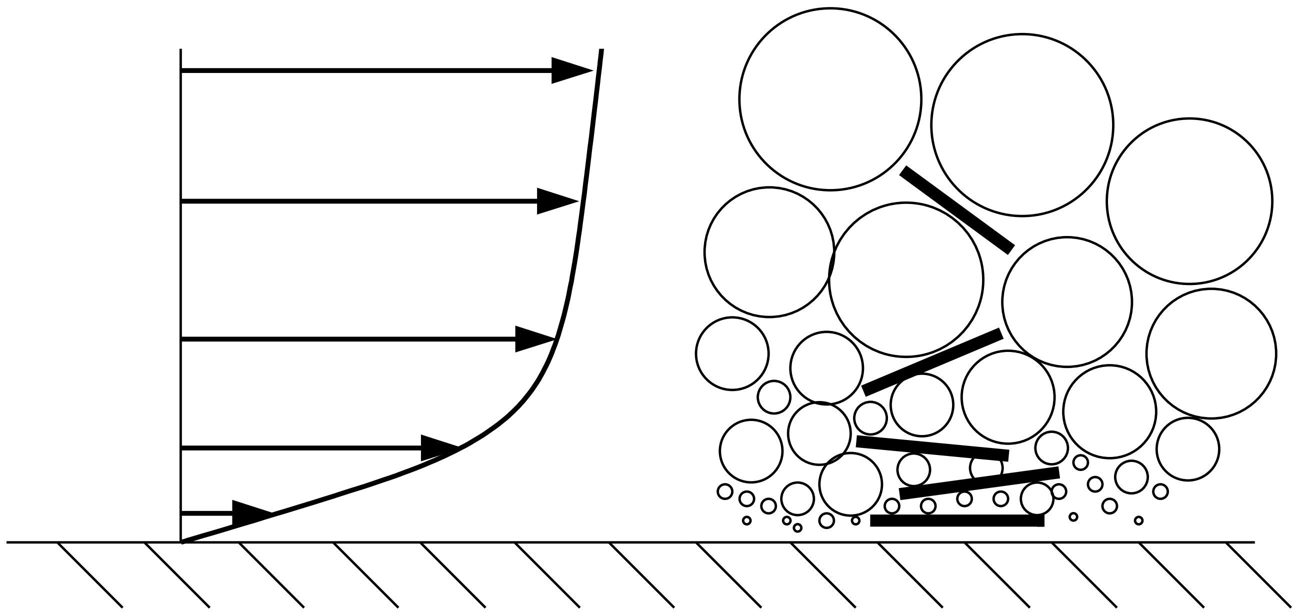
Turbulent drag reduction using spherical additives

Jurriaan Gillissen



Department of Multi-Scale Physics, TUDelft, 11.11.2011

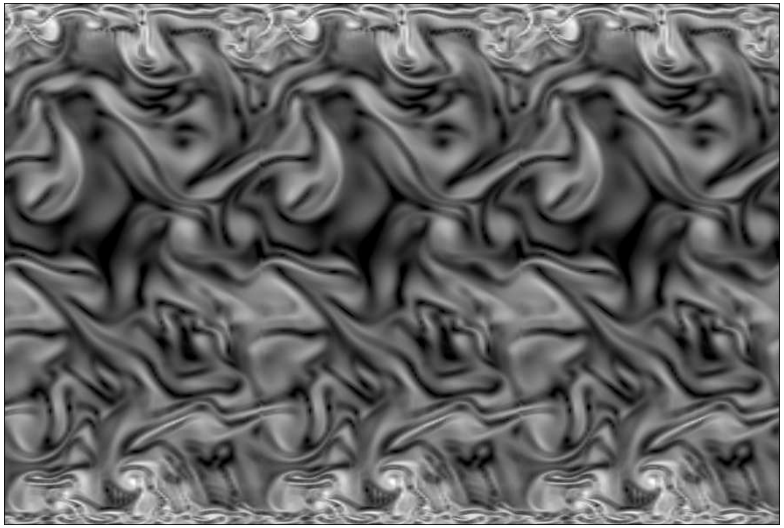
Mechanism



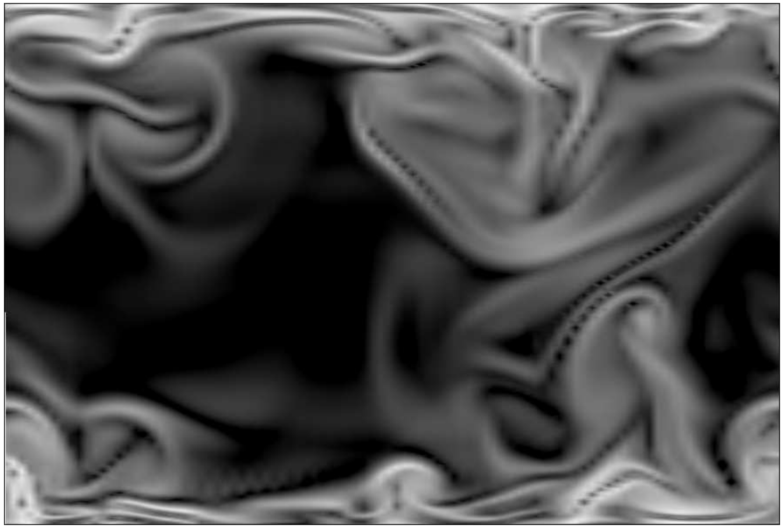
- Orientation of Elongated Particles depends on wall-distance.
- Effective viscosity that grows with wall-distance

Flow Structures

Newtonian:



Drag Reduced:

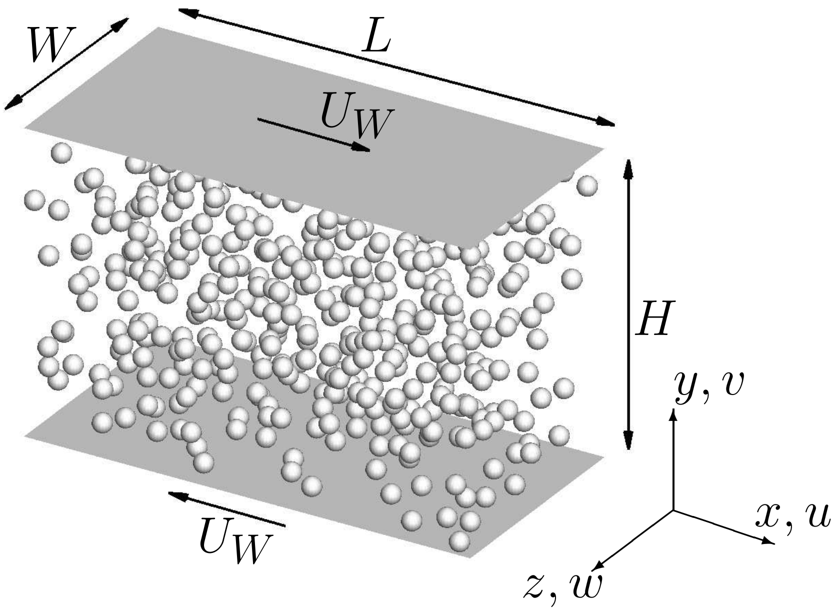


Additives

- Polymers $\surd$
- Fibres $\surd$
- Surfactants $\surd$
- Spherical particles ?

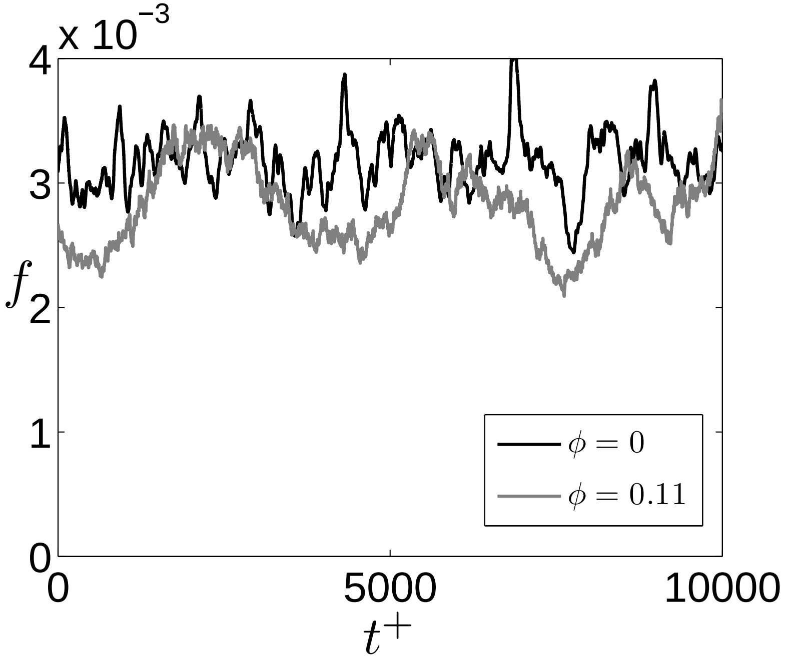
Numerical Setup

- DNS, boundary layer resolved
- Turbulent Couette
- Lattice Boltzmann
- Immersed Boundary
- $L = 1.5H$, $W = 0.75H$
- $N_x \times N_y \times N_z = 192 \times 128 \times 96$
- $H/R = 32$, $R^+ = 11$, $R/\Delta = 4$
- $2U_{wall}H/\nu = 1.3 \times 10^4$
- $\rho_P/\rho = 1$
- $\phi =$0 and 0.1
- $N_P =$0 and 880



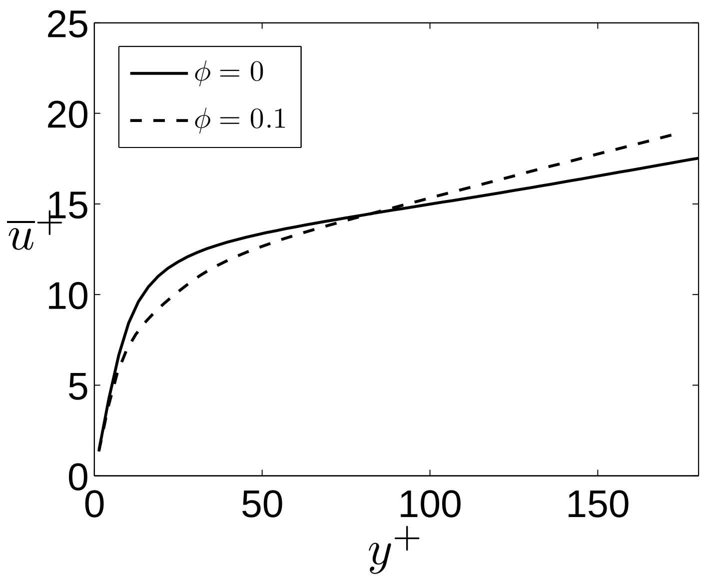
Friction Factor

10% reduction in friction factor: $f = \tau_w/\rho U_{wall}^2$

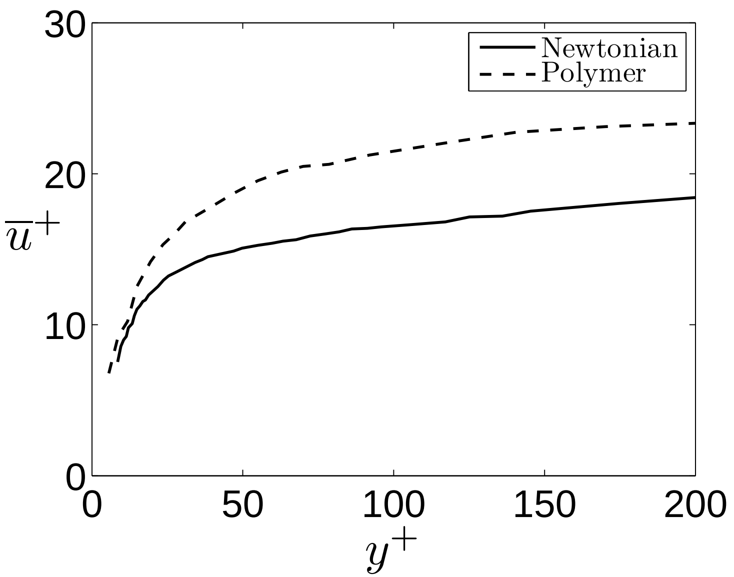


Mean Flow

Spheres:



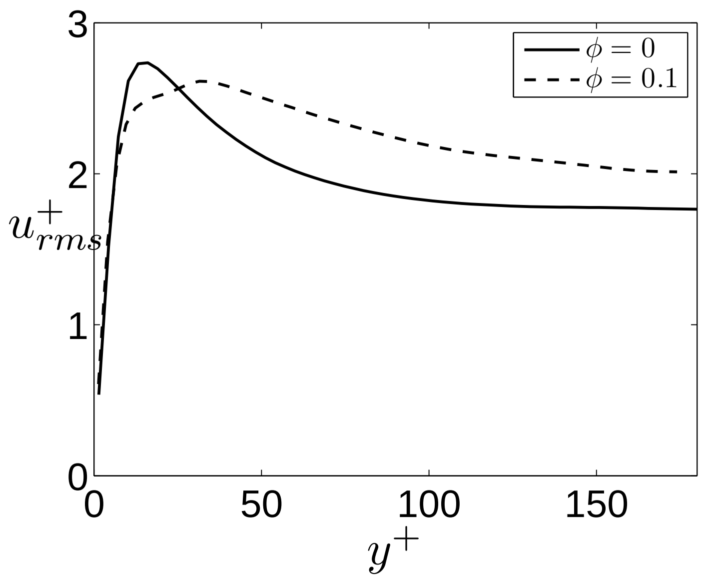
Polymers:



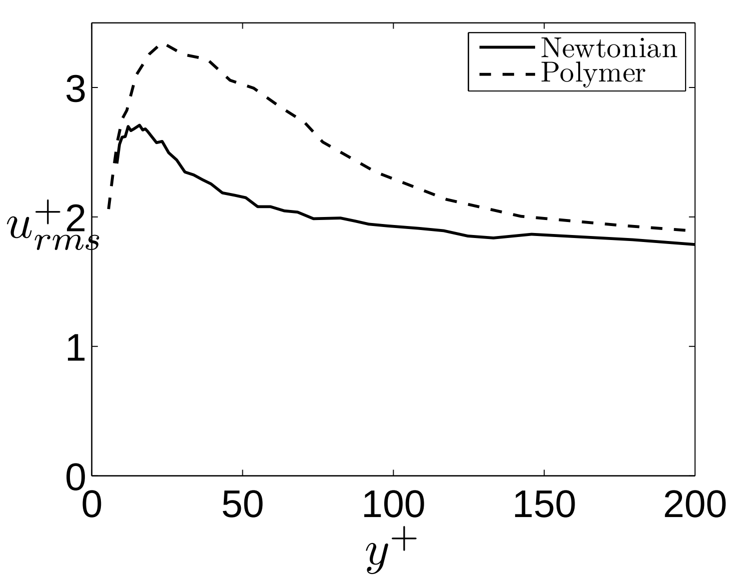
Warholic *et al.* 1999

Fluctuating Flow in x

Spheres:



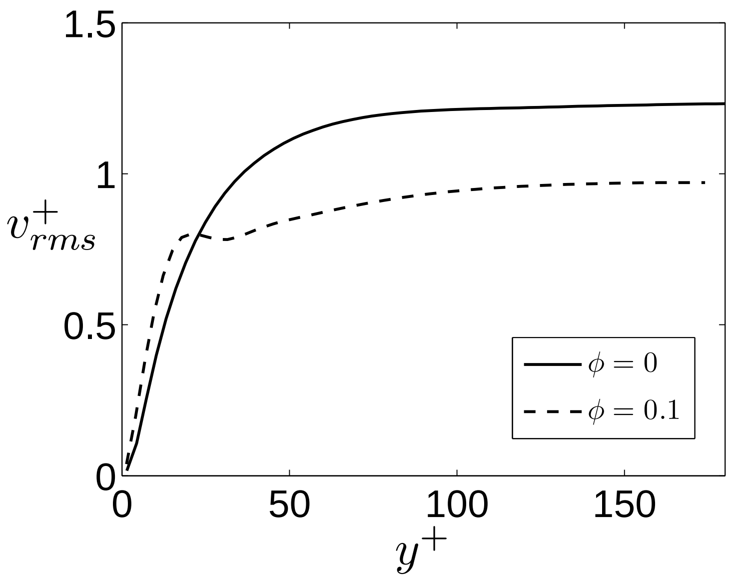
Polymers:



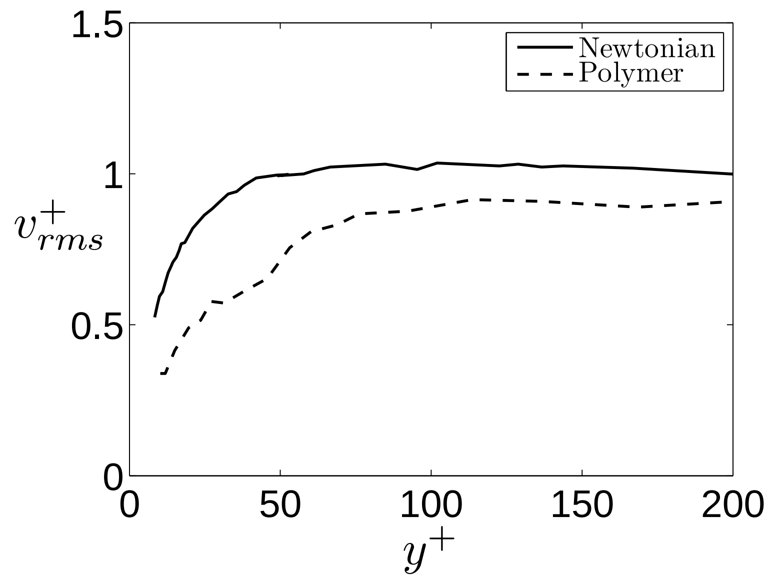
Warholic *et al.* 1999

Fluctuating Flow in y

Spheres:



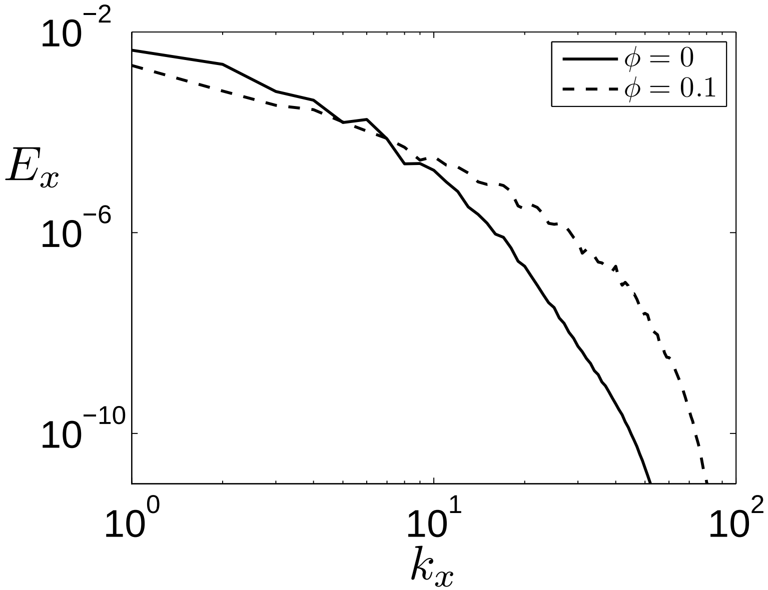
Polymers:



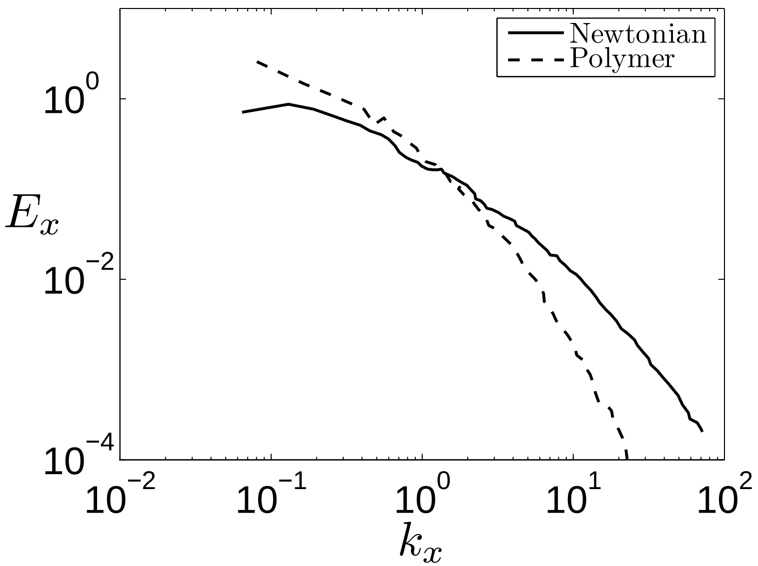
Warholic *et al.* 1999

Streamwise Energy Spectrum at $y^+ = 20$

Spheres:



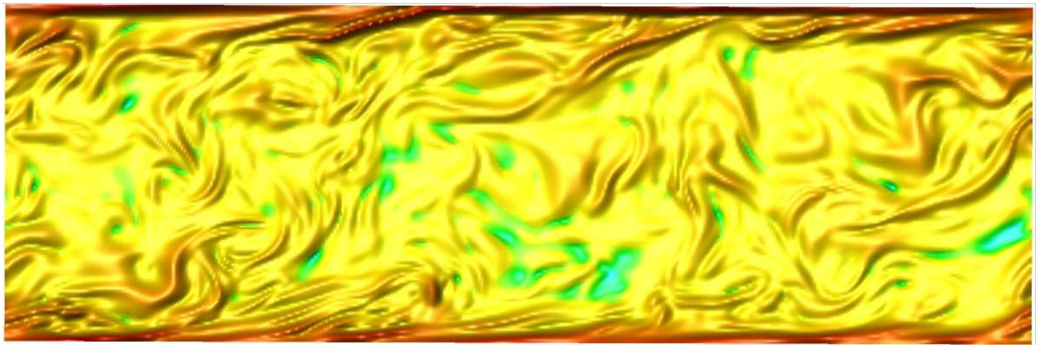
Polymers:



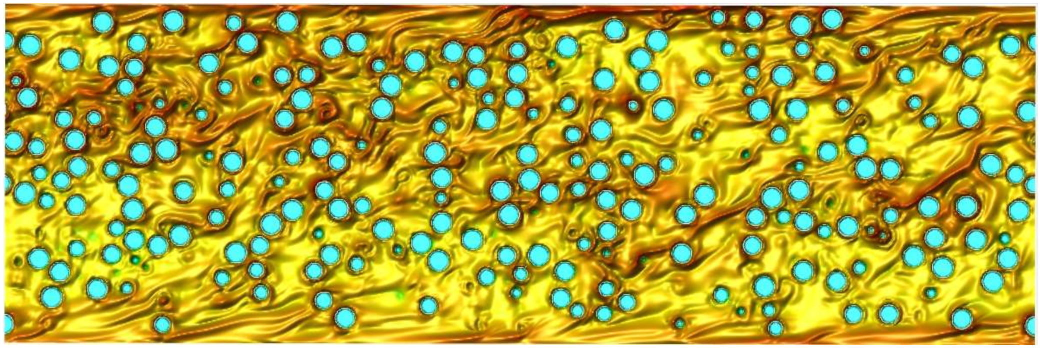
Warholic *et al.* 1999

Flow Structures

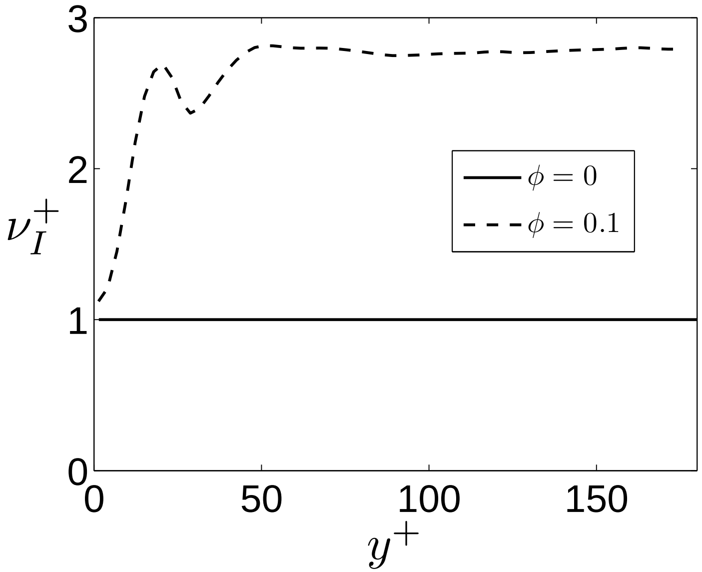
Newtonian:

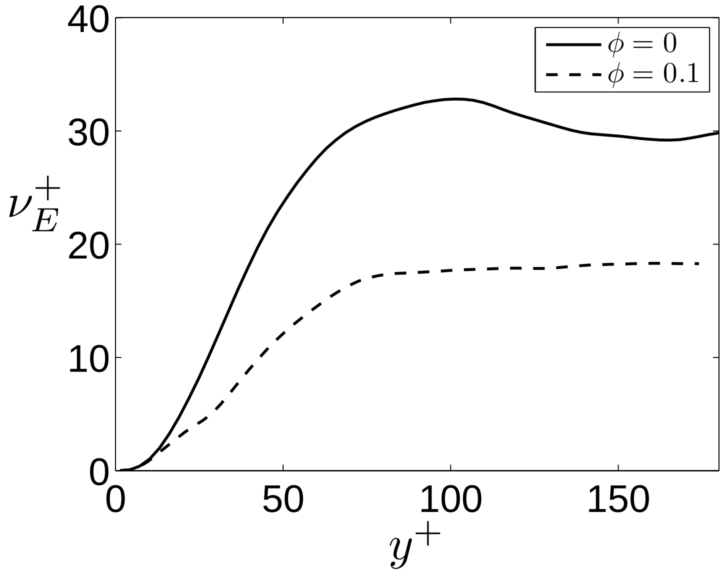


Suspension:



Effective Viscosities

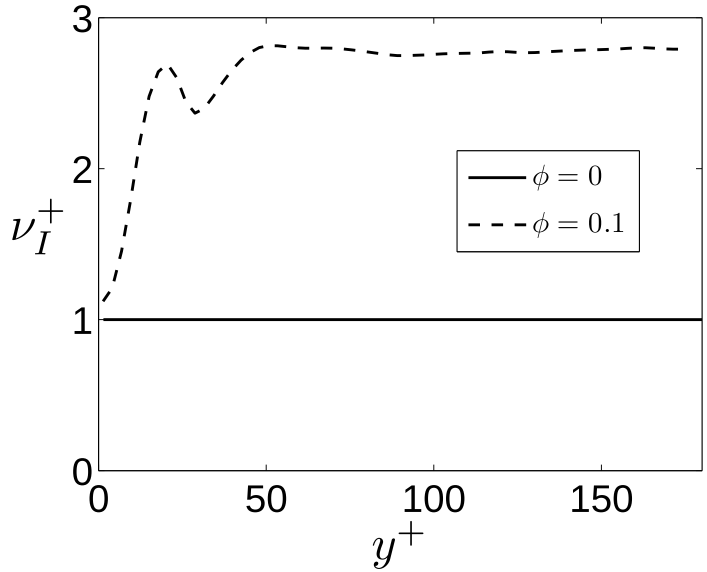


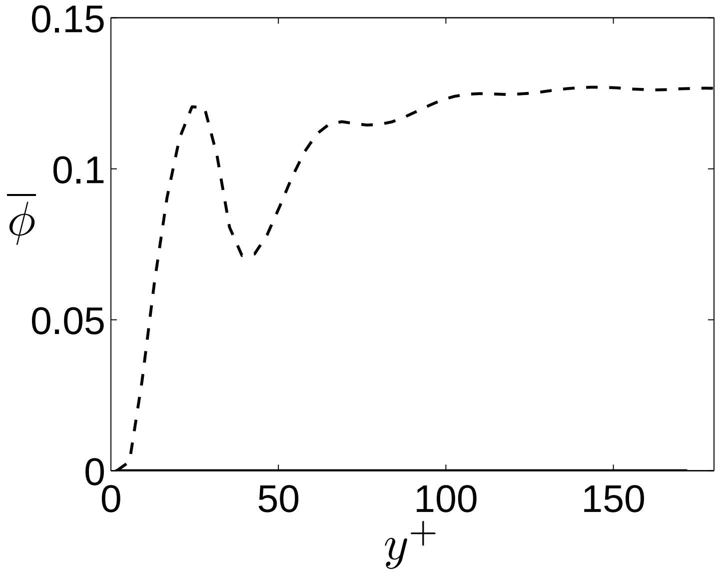


$$\nu_I = \frac{\tau_V + \tau_P}{\rho \frac{d\overline{u}}{dy}}, \qquad \nu_E = \frac{\tau_R + \tau_M}{\rho \frac{d\overline{u}}{dy}}.$$

ν_I-profile can be understood by considering the concentration profile.

Particle Concentration





Conclusions

- Drag reduction mechanism:
  negligible particle effect in the viscous region while substantial effect in the turbulent region.
- Rationalised by a "particle viscosity"
- Related to the particle density profile
- Anomalous drag reduction characteristics

Particle Equations of Motion

The particle equation of motion:

$$\rho V_P \boldsymbol{a}_P = -\int_S (p - 2\mu \boldsymbol{S}) \cdot \boldsymbol{n} \, dS.$$

The Navier Stokes equation:

$$\rho \left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \boldsymbol{\nabla} \boldsymbol{u} \right) = \boldsymbol{\nabla} \cdot (-p\boldsymbol{\delta} + 2\mu \boldsymbol{S}) + \boldsymbol{F},$$

where:

$$\boldsymbol{F}(\boldsymbol{x}) = \sum_{\alpha=1}^{N} \boldsymbol{F}_{\boldsymbol{\alpha}} \, \delta \left(\boldsymbol{x} - \boldsymbol{y}_\alpha \right),$$

and:

$$\boldsymbol{F}_{\boldsymbol{\alpha}} = \frac{\rho \Delta S}{\Delta t \Delta x^2} \left(\boldsymbol{u}_P + \boldsymbol{\omega}_P \times \boldsymbol{R}_\alpha - \boldsymbol{u}_\alpha \right).$$

Integrate NS over particle volume:

$$\rho V_P \boldsymbol{a}_P = -\int_S (p\boldsymbol{\delta} - 2\mu \boldsymbol{S}) \cdot \boldsymbol{n} \, dS + \sum_{\alpha=1}^{N} \boldsymbol{F}_\alpha.$$

Thus:

$$\sum_{\alpha=1}^{N} \boldsymbol{F}_\alpha = \boldsymbol{0} \Rightarrow$$

$$\boldsymbol{u}_P = \frac{1}{N} \sum_{\alpha=1}^{N} \boldsymbol{u}_\alpha.$$

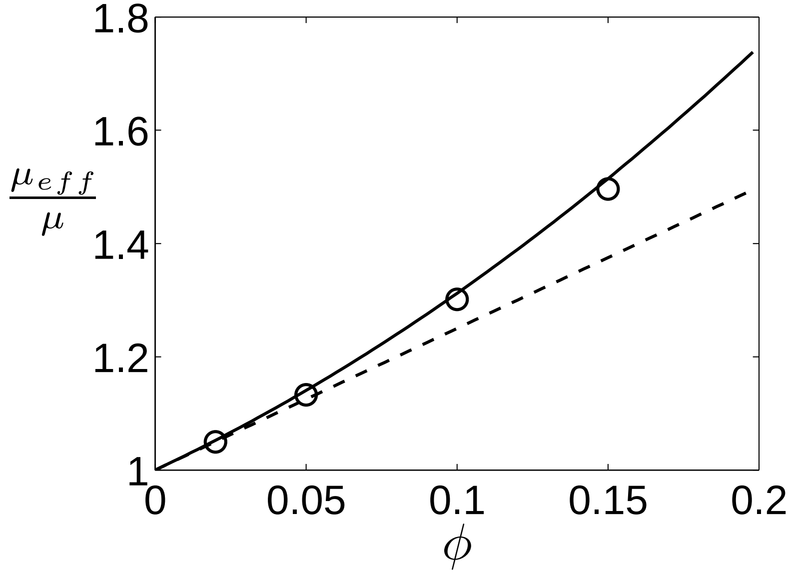
Similarly:

$$\sum_{\alpha=1}^{N} \boldsymbol{R}_\alpha \times \boldsymbol{F}_\alpha = \boldsymbol{0} \Rightarrow$$

$$\boldsymbol{\omega}_P = \frac{2}{3NR^2} \sum_{\alpha=1}^{N} \boldsymbol{R}_\alpha \times \boldsymbol{u}_\alpha$$

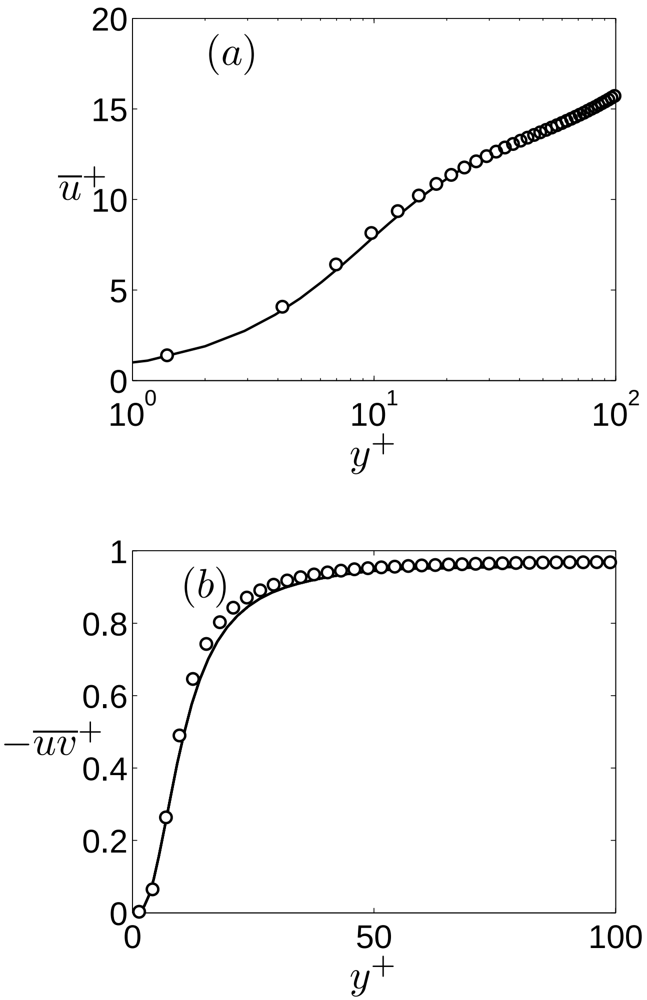
Validation

Low Re-suspension:

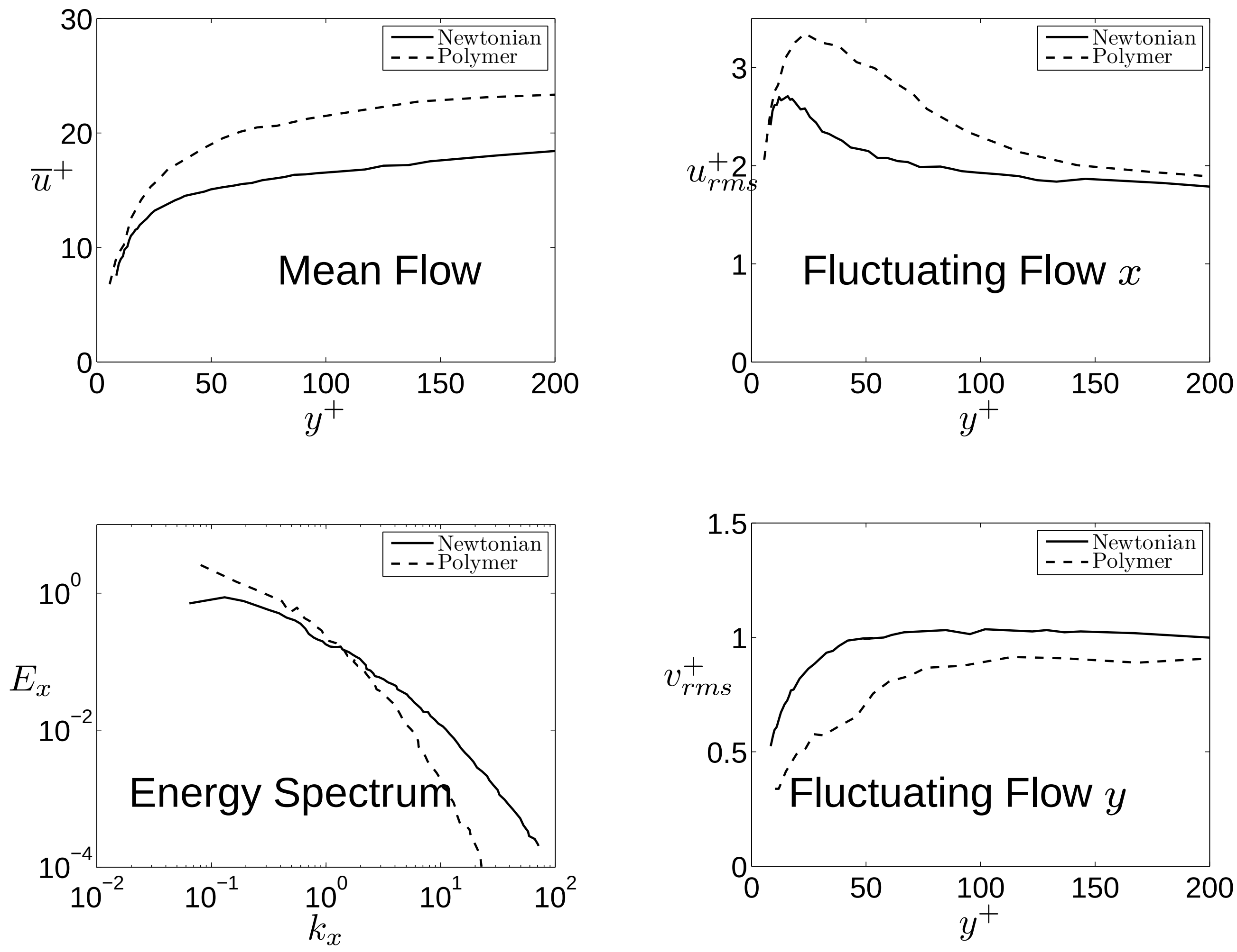


$$\mu_{eff} = \frac{\tau_{wall} H}{2U_{wall}}$$

Single Phase Couette:



Statistics, Warholic et al. 1999



Shear Stress Balance

The Reynolds average of the x-component of the Navier Stokes equation:

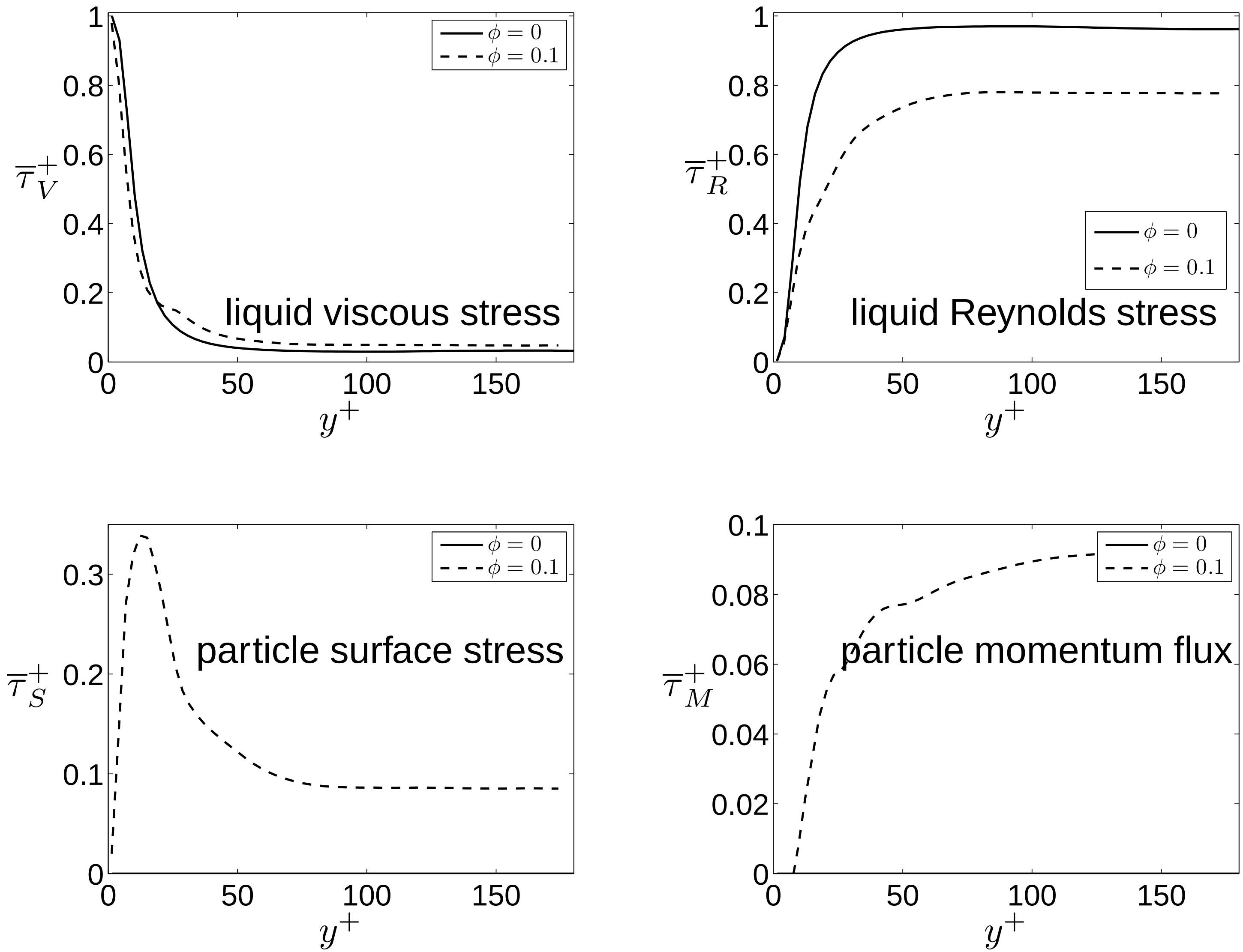
$$\frac{d}{dy}\left[-\rho\overline{u_x u_y} + 2\mu\overline{S_{xy}}\right] + \overline{F_x} = 0.$$

$$\frac{d}{dy}\left[-\rho\overline{u_x u_y \Psi} + 2\mu\overline{S_{xy}\Psi} - \overline{\rho u_x u_y (1-\Psi)} + 2\mu\overline{S_{xy}(1-\Psi)}\right] + \overline{F_x} = 0.$$

integrated over y yields the shear stress balance:

$$\underbrace{-\rho\overline{u_x u_y \Psi}}_{\tau_R} + \underbrace{2\mu\overline{S_{xy}\Psi}}_{\tau_V} \underbrace{-\rho\overline{u_x u_y (1-\Psi)}}_{\tau_M} + \underbrace{2\mu\overline{S_{xy}(1-\Psi)} + \int_0^y \overline{F_x}(y')dy'}_{\tau_S} = \tau_W,$$

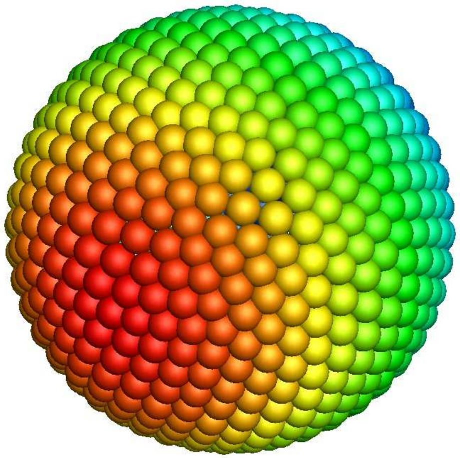
Shear Stress Balance



Numerical Method

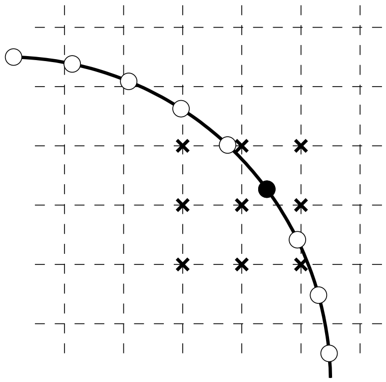
Lattice Boltzmann:

$$\frac{\partial f}{\partial t} + \boldsymbol{v} \cdot \boldsymbol{\nabla} f + \boldsymbol{F} \cdot \boldsymbol{\nabla}_{\boldsymbol{v}} f = \frac{f^{(0)} - f}{\tau}.$$



Immersed Boundary:

$$\boldsymbol{F} = \sum_{\alpha} \boldsymbol{F}_{\boldsymbol{\alpha}}.$$



$$\boldsymbol{F}_{\boldsymbol{\alpha}} \sim \left(\boldsymbol{u}_P + \boldsymbol{\omega}_P \times \boldsymbol{R}_\alpha - \boldsymbol{u}_\alpha \right).$$