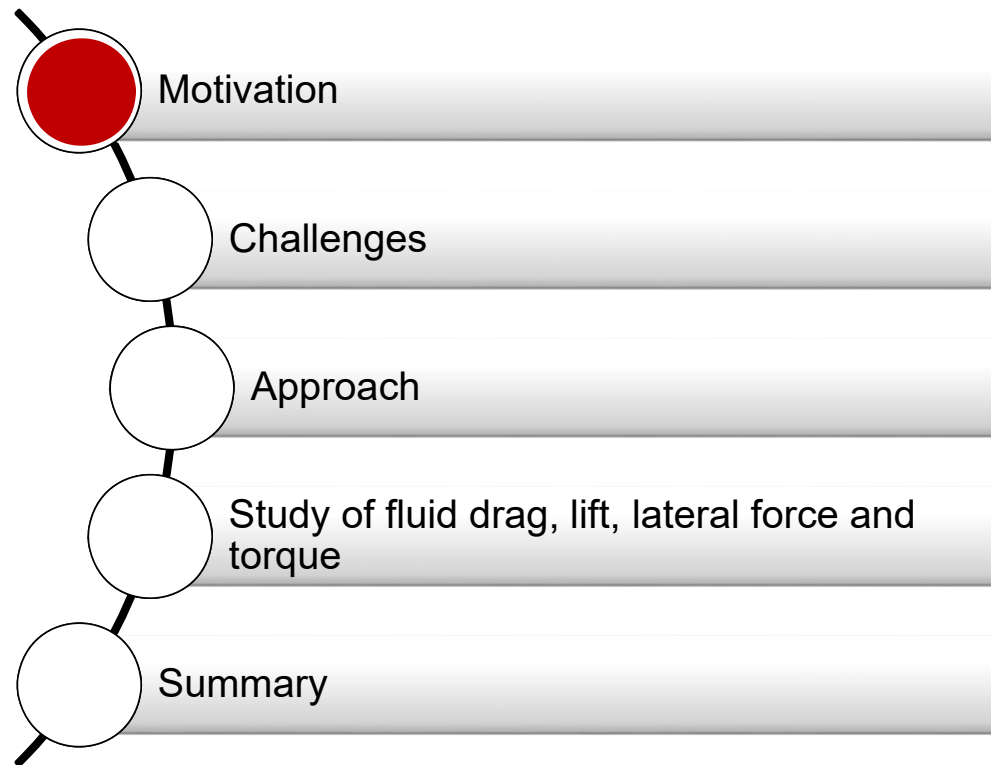


Variation of Drag, Lift, and Torque in a Suspension of Ellipsoidal Particles

Long He, Danesh Tafti
Dept. Of Mechanical Engineering
Blacksburg, VA 24061
Virginia Tech

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Outline

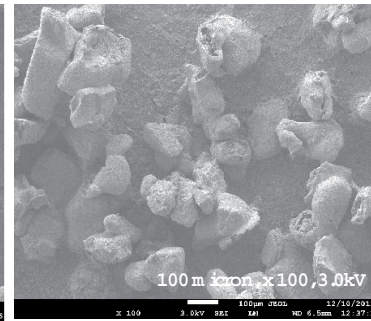
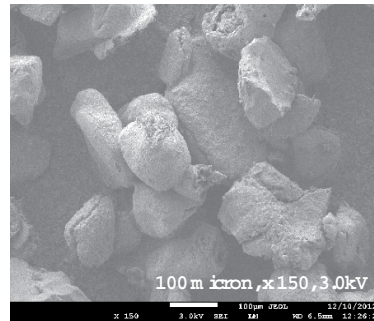


Motivation

Fluid flow with non-spherical particles is fundamental to many industrial processes

- Catalyst in chemical reactor
- Biomass/waste combustion and gasification
- Tablet coating

Predicting **Momentum**, **heat** and **mass** transfer between fluid and particle is critical



Particles in chemical reactor
Courtesy: Mehrdad Shahnam, NETL

Biomass
Courtesy: Shandong Union Biomass Energy



Catalyst in chemical reactors

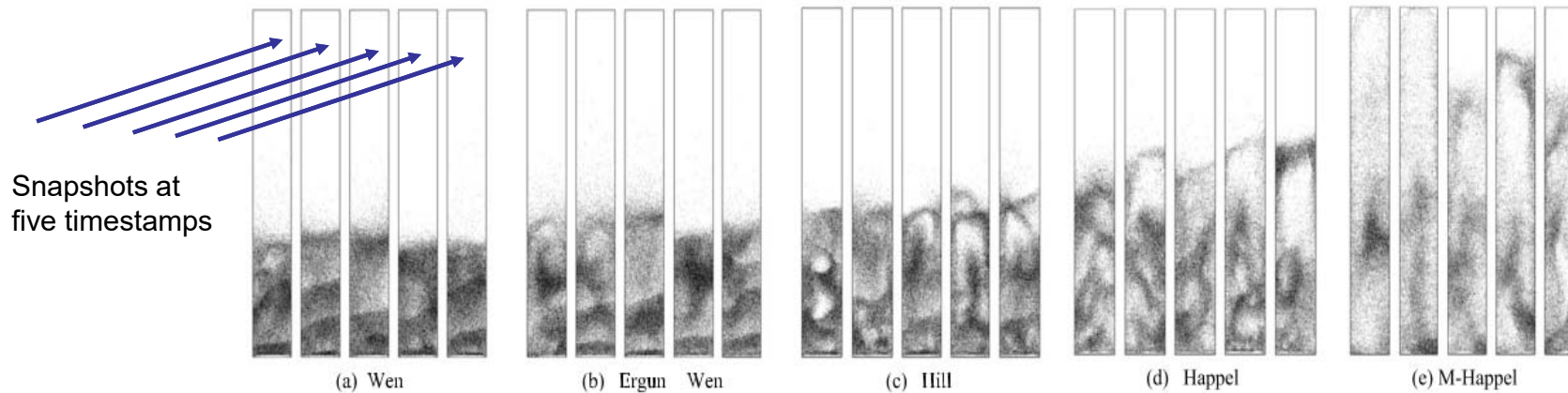
Courtesy: GLP inc

Tablet coating

Reference: :DEM/CFD-DEMModelling of Non-spherical Particulate Systems
Theoretical Developments and Applications

Drag correlation is critical in modeling

Fluidized bed simulation: the same problem set up, different drag correlation



(a),(b) and (c) show significant difference comparing to (d) and (e).

Plot from: Li et al. Gas-particle interactions in dense gas-fluidized beds, Chemical Engineering Science

Correlations mostly developed for **suspension of spherical particles**

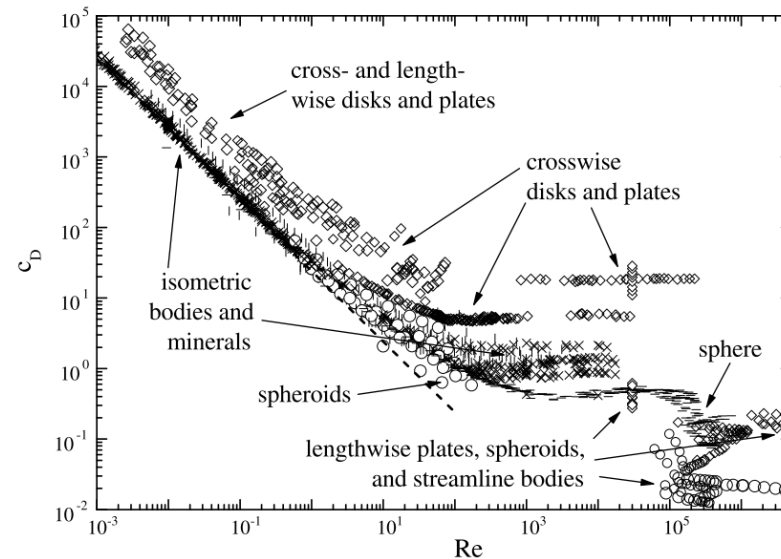
Drag correlations for Suspensions of Spherical Particles:

Ergun[1952], Happel [1958], Wen and Yu [1966], Syamlal and O'Brien[1987], Felice [1994], Koch and Sangani [1999], Koch and Hill [2001], Tenneti et al.[2011].

Heat transfer correlations :

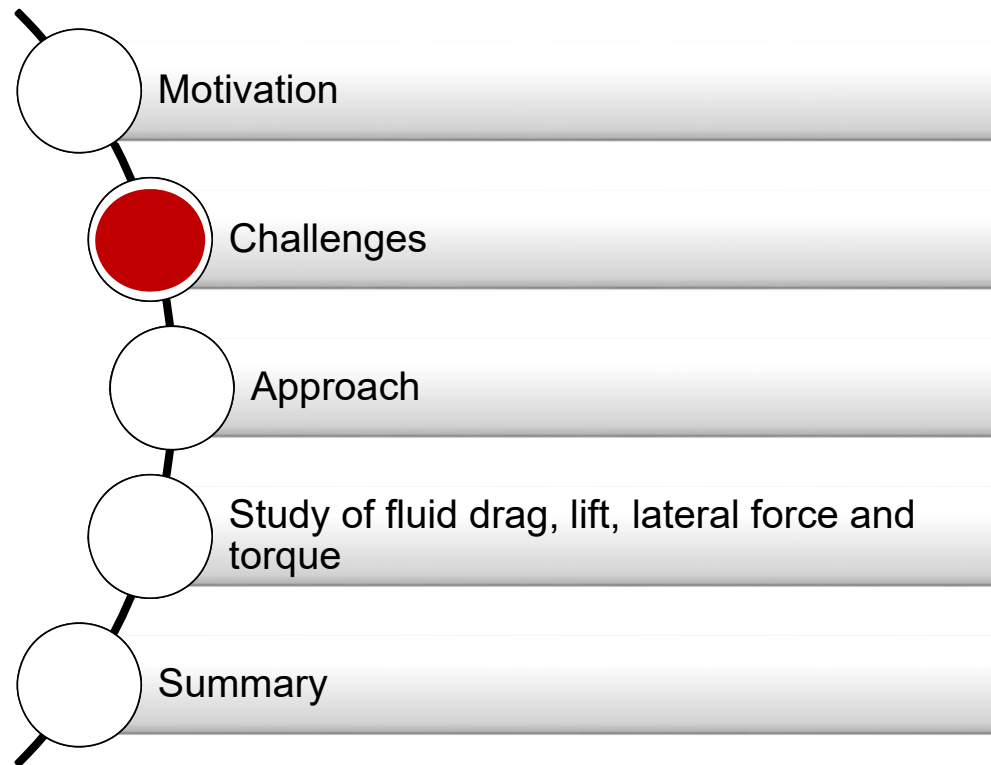
Gunn [1978], Wakao [1982], Tenneti et al [2013], Tavassoli [2014]

Single non-spherical particle drag coefficient



Very few studies have been carried out for non-spherical particles in suspension.

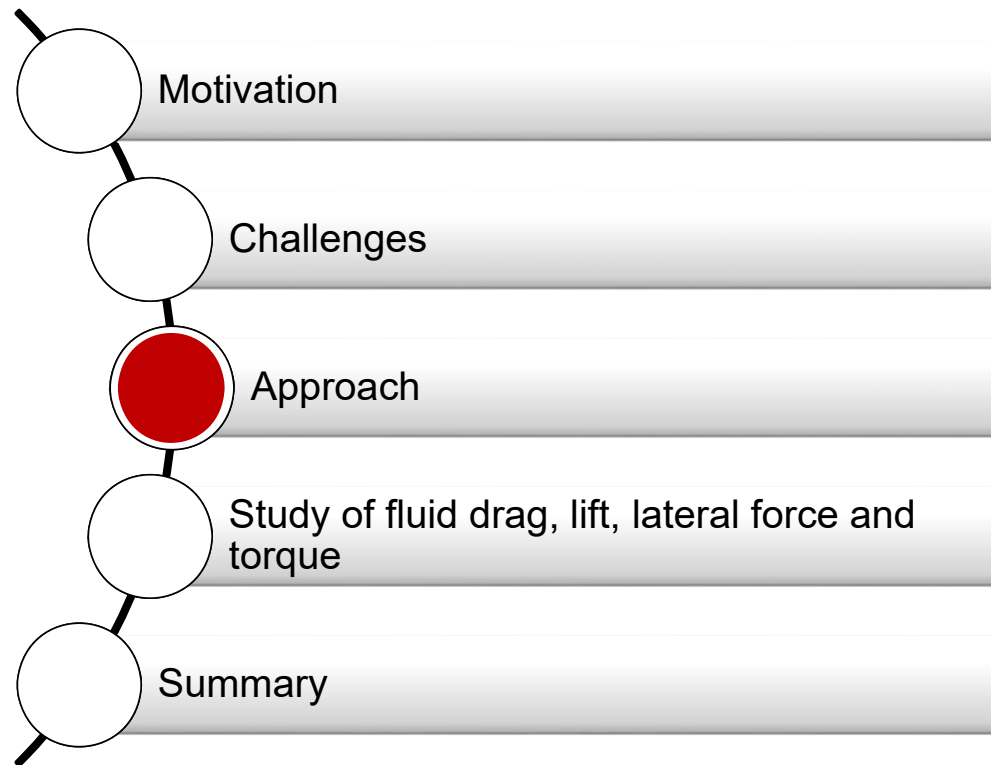
Outline



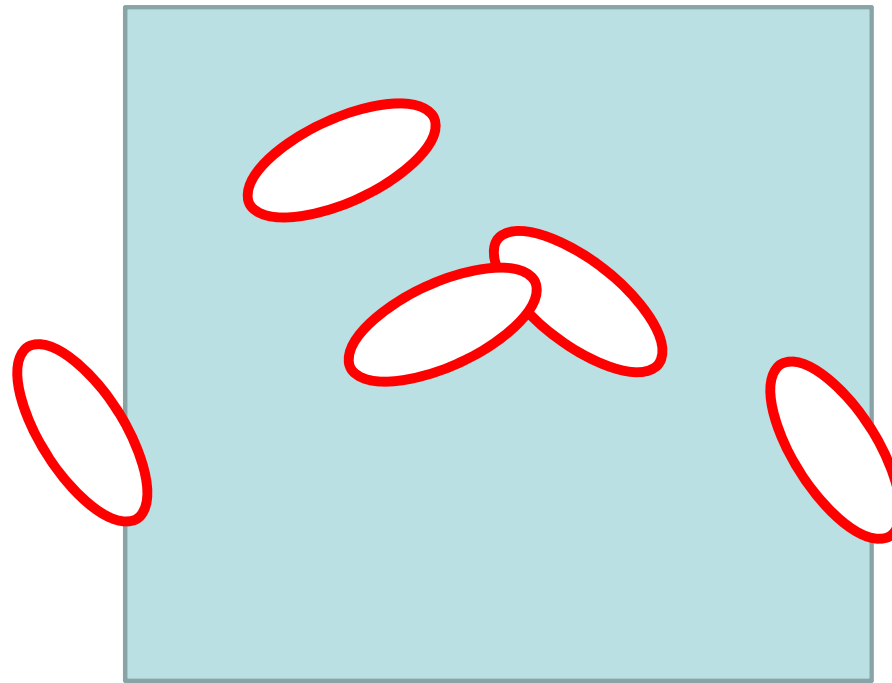
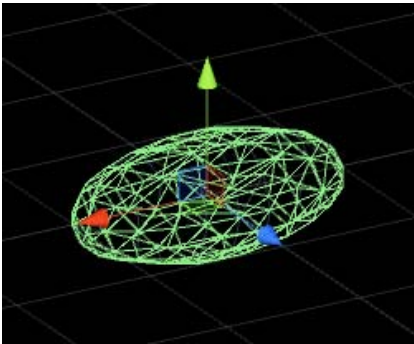
Challenges

- **Simulation**
 - Creating assembly of non-spherical particles
 - Due to the complexity introduced by non-spherical particle shapes, an efficient random assembling method is needed
 - Computationally Intensive
 - Large computational domain to correctly represent a statistically significant sample size of randomly oriented particles
 - Fine grid to resolve the geometry and flow near particle surfaces
- **Data Processing and Analysis**
 - Large amount of data
 - Development of general correlations – identifying important parameters

Outline

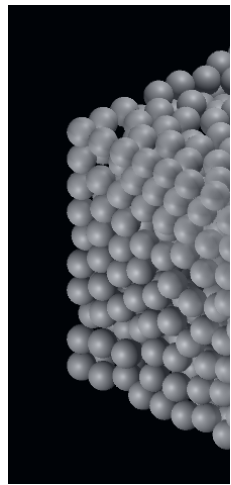


Generate particle assembly in PhysX

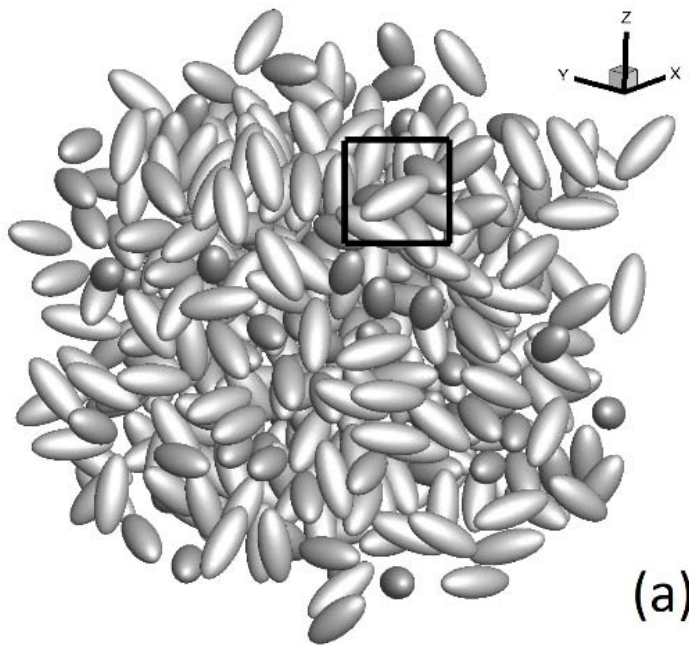


PhysX is a computer software that provides an approximate simulation of certain physical systems, such as rigid body dynamics (including collision detection).

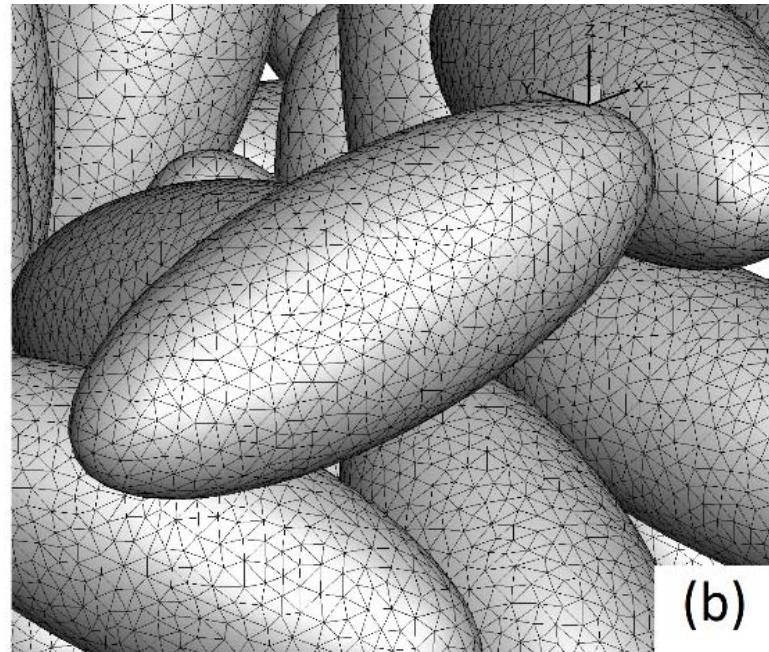
Example - Particle assembly



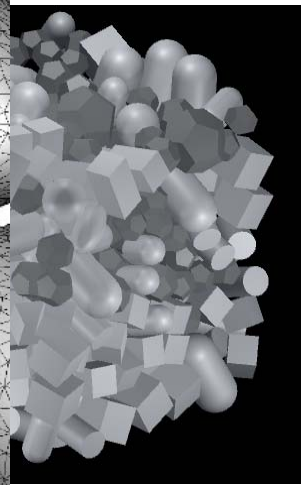
spl



(a)



(b)



mixed spheres, capsules,
dodecahedron, cubes, cuboid,
cylinders with random size.

Fluid governing equations

Incompressible, temperature independent properties

Continuity:

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

Momentum:

$$\frac{\partial u_i}{\partial t} + \frac{\partial (u_j u_i)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left\{ \frac{1}{Re_{ref}} \left(\frac{\partial u_i}{\partial x_j} \right) \right\}$$

Energy:

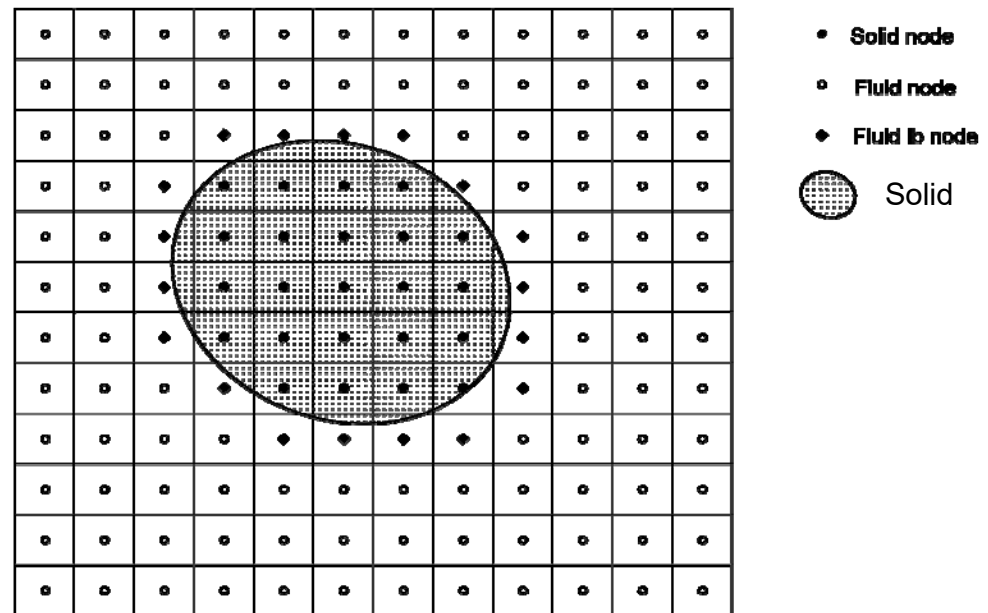
$$\frac{\partial T}{\partial t} + \frac{\partial (u_j T)}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\frac{1}{Re_{ref} \cdot Pr_{ref}} \frac{\partial T}{\partial x_j} \right)$$

Boundary conditions
will be introduced later
with the fluid grid

Immersed boundary method

Major steps:

1. Define node-types: fluid, solid and IB node
2. Obtain IB node velocity, pressure and temperature based on the fluid state and boundary condition
3. Governing equations are solved for all fluid nodes in the domain



Approach--Summary

Choose
particle
geometry

Create
CAD file
for particle

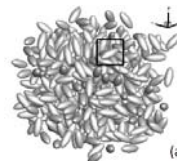
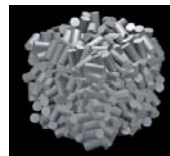
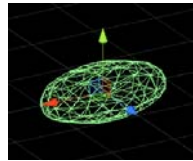
Create
surface
mesh for
packing

Create
particle
assembly
in PhysX

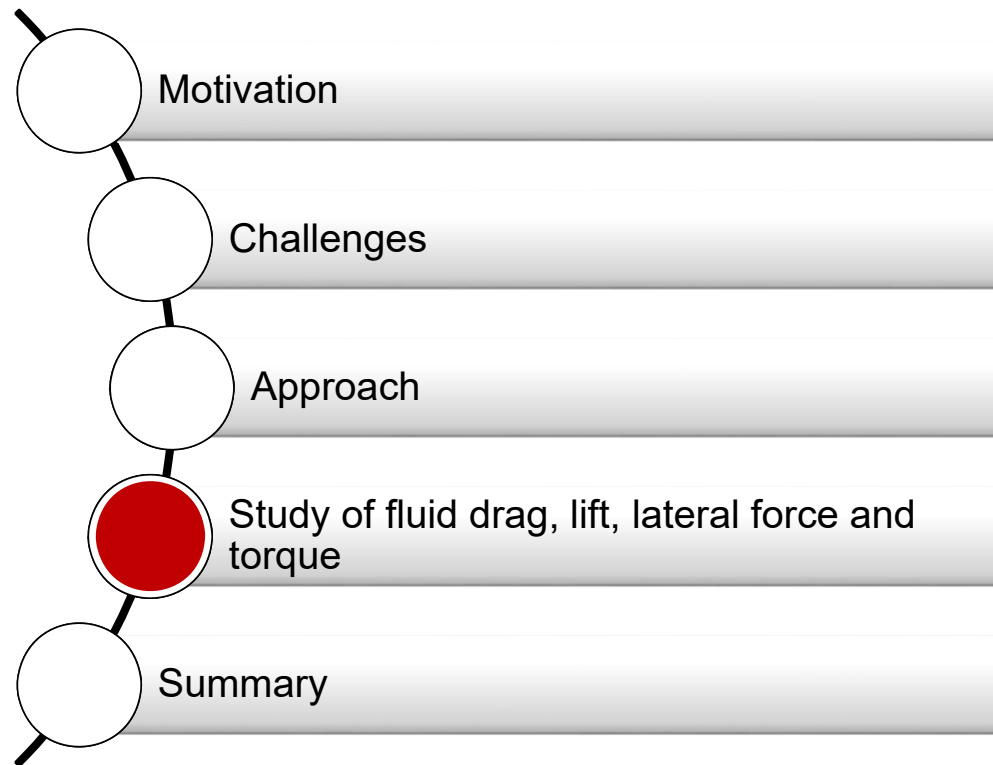
Create
surface
mesh for
assembly
of particles

Simulate using
GenIDLEST

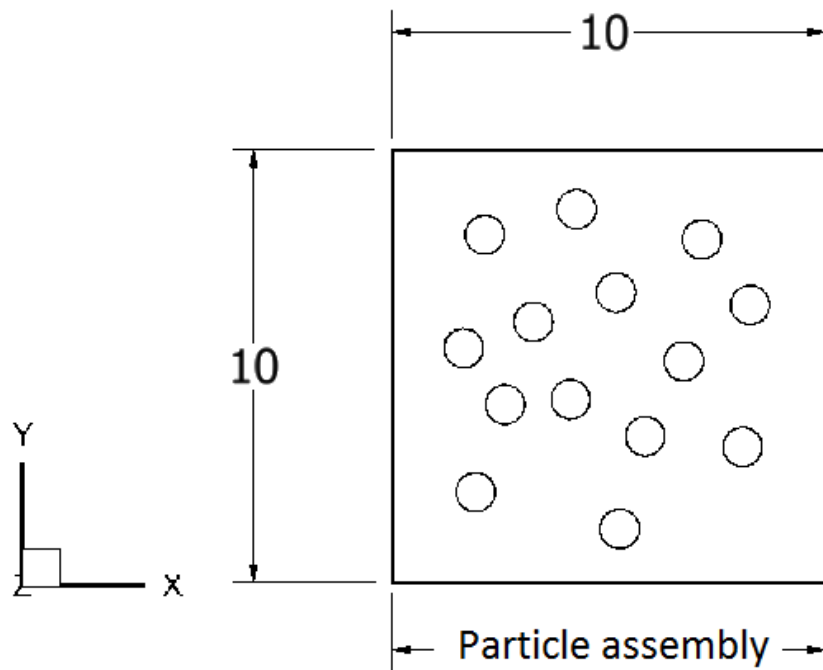
Post-
process



Outline

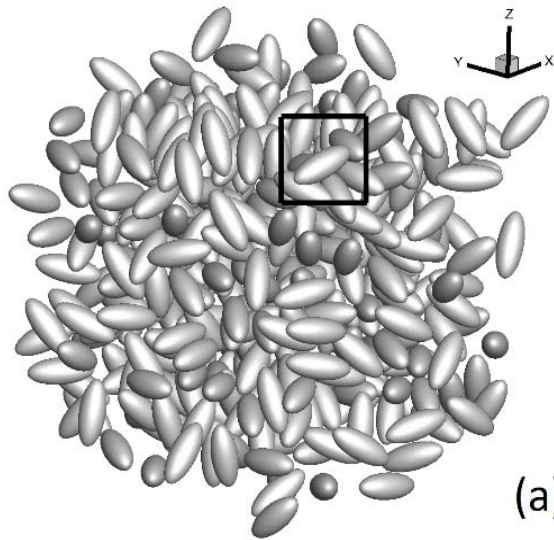


Computation model



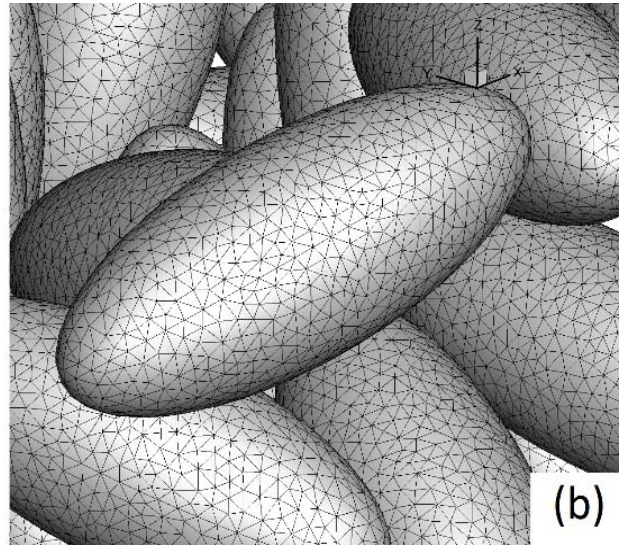
- Fluid domain is a $10D_{eq} \times 10D_{eq} \times 10D_{eq}$ cubic box with periodic boundary condition applied on all three directions
- A pressure source term is added in the x-direction momentum equation to induce flow.
- Forces and torque on the particles are calculated when the flow reaches steady state
- **Ellipsoid: solid fraction tested from 0.1 to 0.35**
- **Reynolds numbers of 10, 50, 100 and 200** based on the superficial velocity and equivalent spherical diameter
- **3 different random assemblies** are tested for each solid fraction and Reynolds number.

Grid Particulars



(a)

20% solid fraction

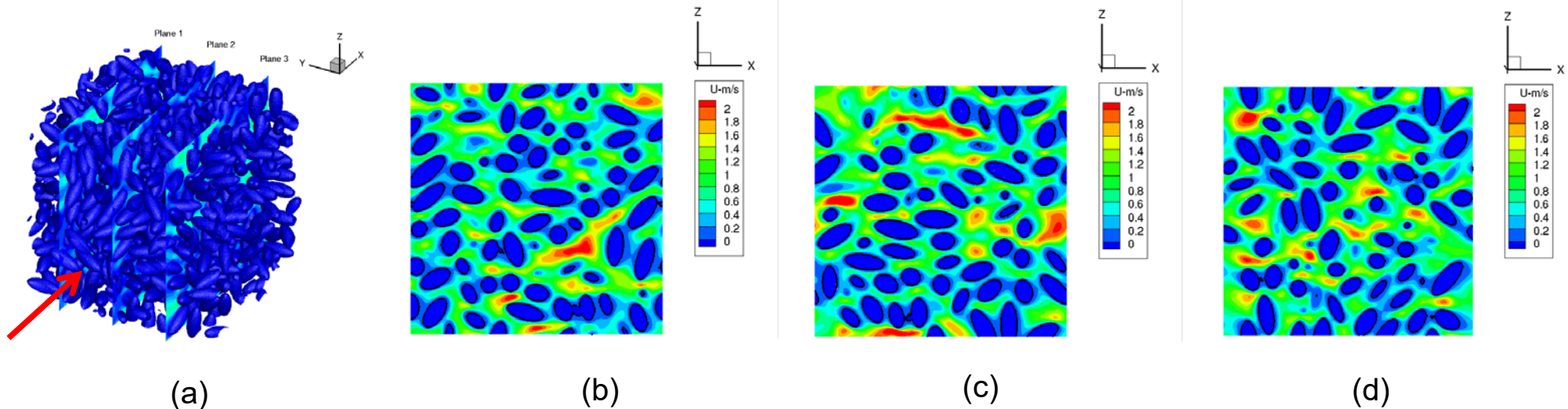


(b)

		Ellipsoid
Geometry parameter	Semi-major	0.921
	Semi-minor	0.368
Sphericity ψ		0.887
D_{eq}		1
Number of particles (N)	$\phi = 10\%$	191
	$\phi = 20\%$	382
	$\phi = 30\%$	573
	$\phi = 35\%$	669

- The background mesh is a uniformly distributed structured mesh with $\Delta x = \Delta y = \Delta z = 0.025D_{eq}$ (based on a grid independent study)
- Total $400 \times 400 \times 400$ cells along x,y and z directions
- 100 processors, 36 to 48 hours

Velocity field in assembly of ellipsoids

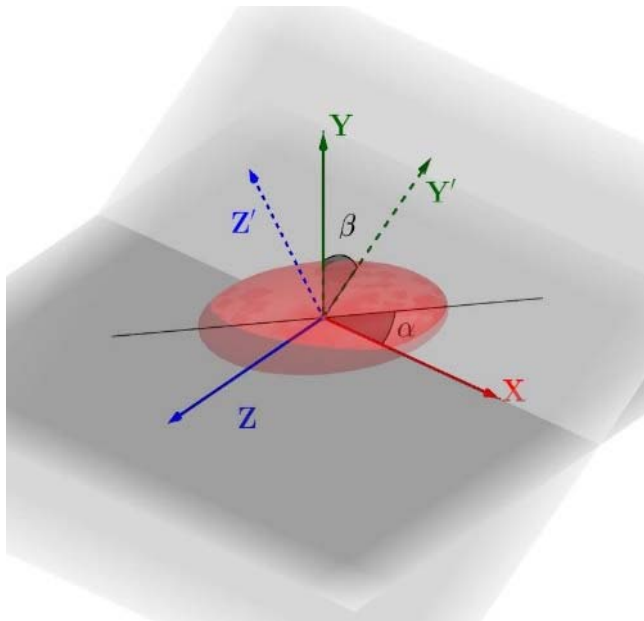


Velocity field for Re of 10, solid fraction of 30%: (a) 3D view; (b) - (d) y planes at different locations

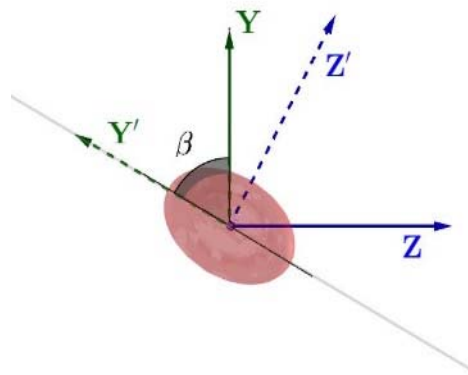
$$\text{Average force } \vec{F}_{g-s} = \frac{1}{N} \sum_{i=1}^N \vec{F}_i$$

$$\text{Non-dimensionalized } F = \frac{\vec{F}_{g-s}}{3\pi\mu D_{eq}U}$$

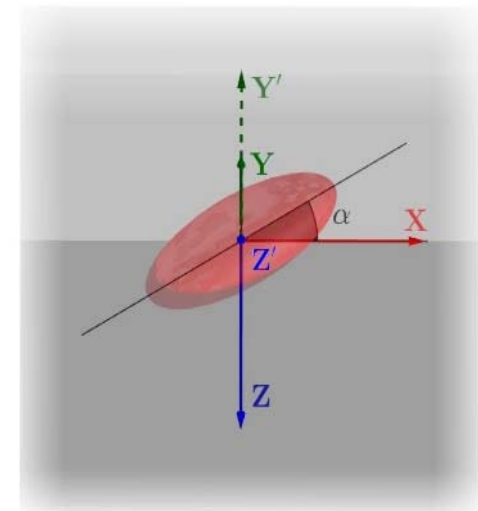
Global and local coordinate system



(a)

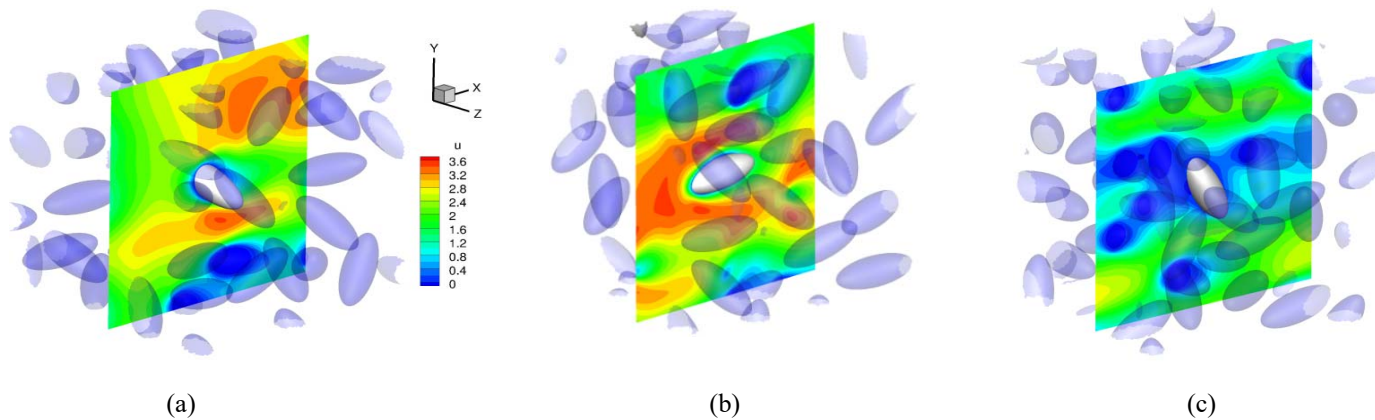


(b)



(c)

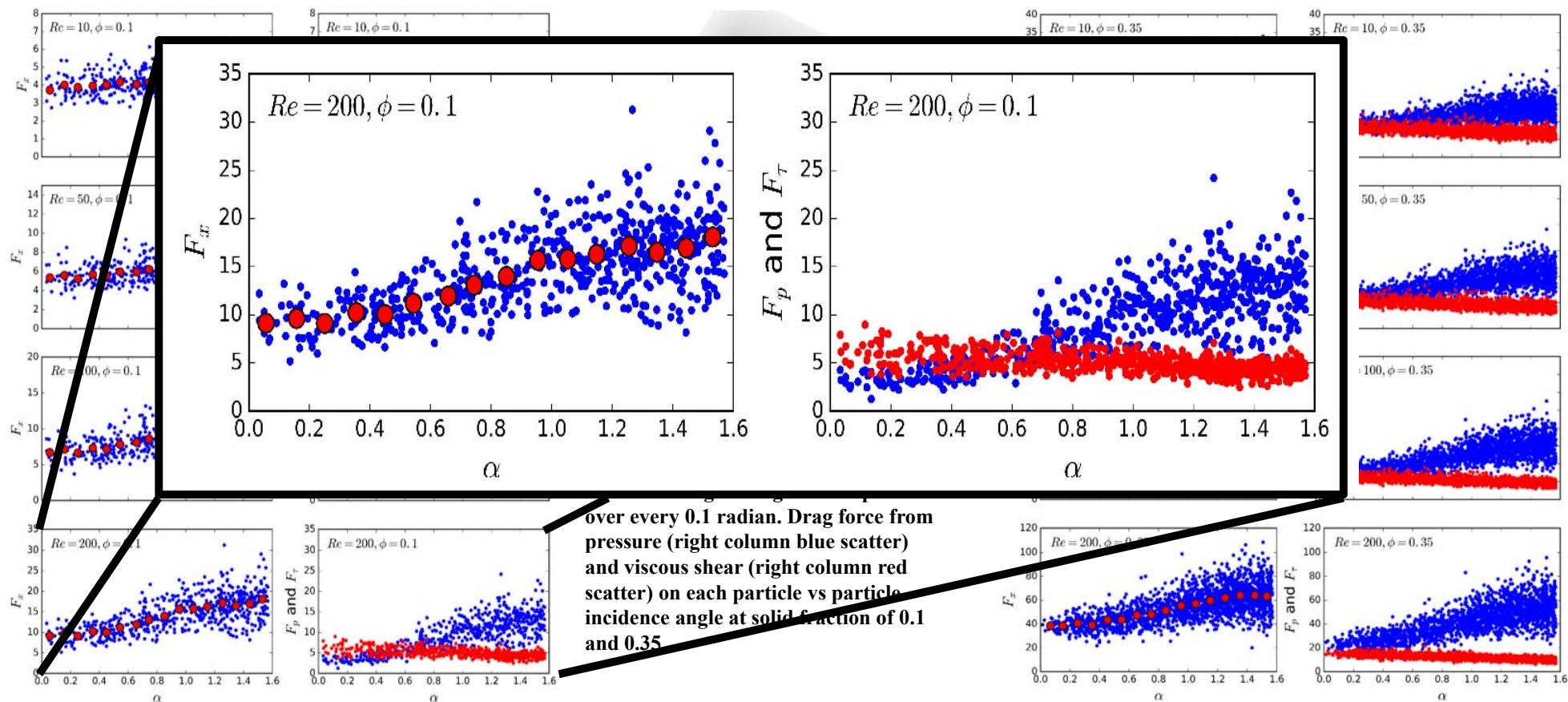
Force affected by local flow field and particle orientation



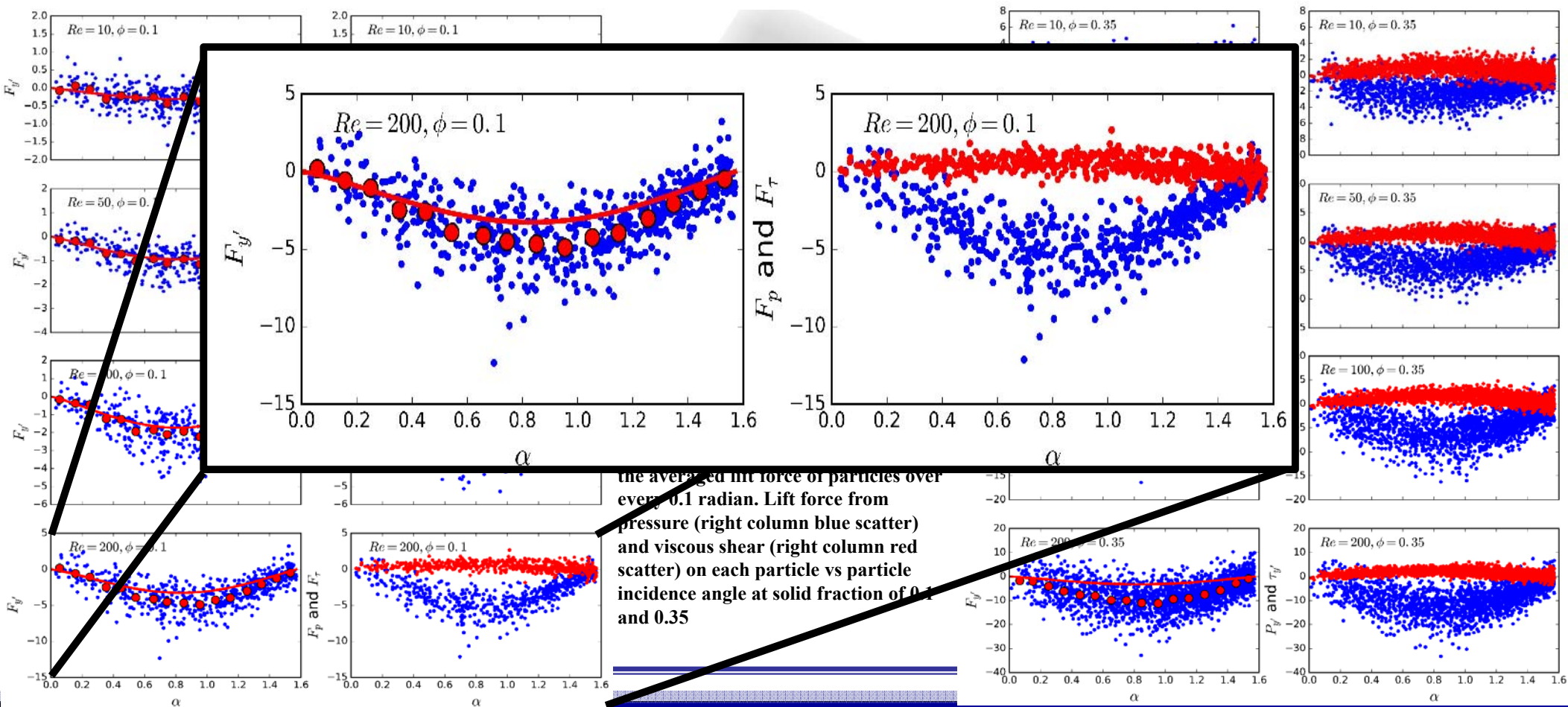
Drag force on ellipsoid in assembly at $Re=10$ and solid fraction of 0.1, (a) $F= 7.69$, $\alpha =1.15$ rad; (b) $F = 6.7$, $\alpha =0.11$ rad; (c) $F=3.59$, $\alpha=1.15$ rad.

For an ellipsoid in **isolation**, the corresponding drag forces are 1.72 and 1.25 for a particle oriented at 1.15 radian and 0.11 radian, respectively.

Drag force variation



Lift force variation



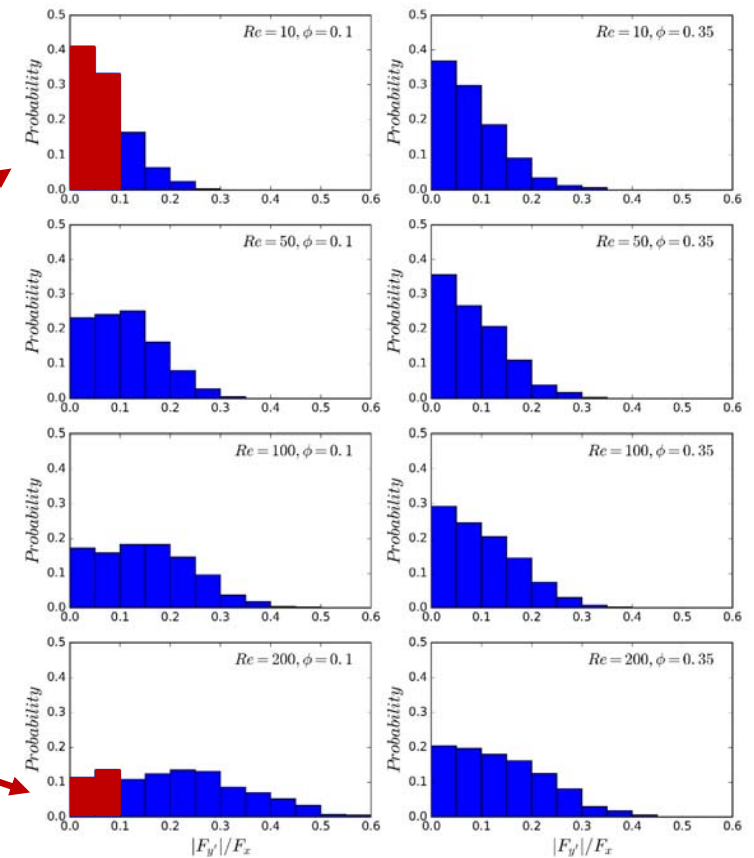
Lift force compared to drag force

The probability histogram of the ratio between magnitude of the lift force over the drag force on each particle in assembly for solid fractions 0.1 and 0.35.

Lift force is significant

~72% of particles, lift force magnitude is <10% of the drag force

~22% of particles, lift force magnitude is <10% of the drag force



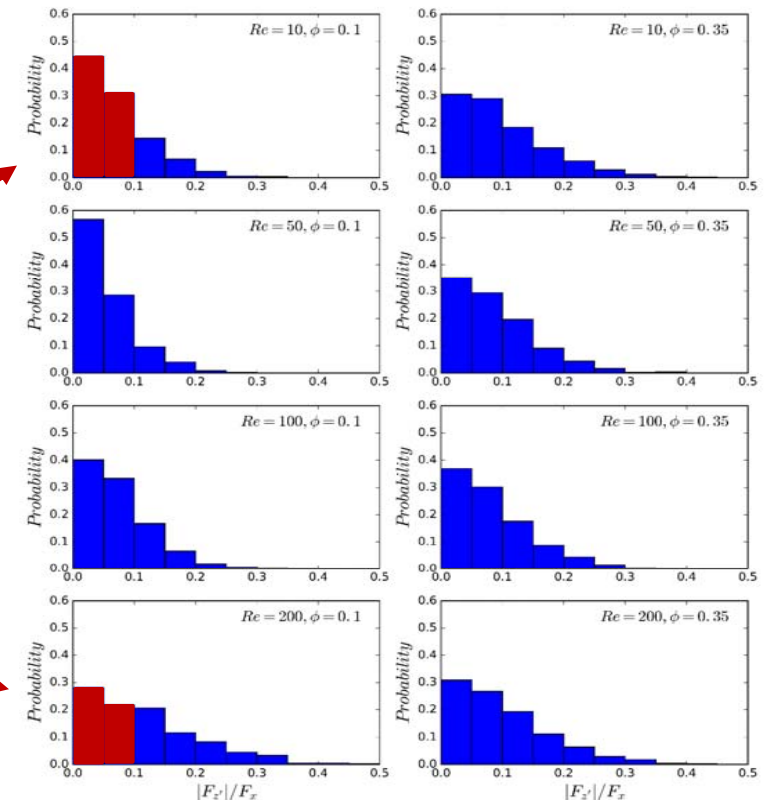
Lateral force compared to drag force

The probability histogram of the ratio between magnitude of the lateral force over the drag force on each particle in assembly for solid fractions 0.1 and 0.35.

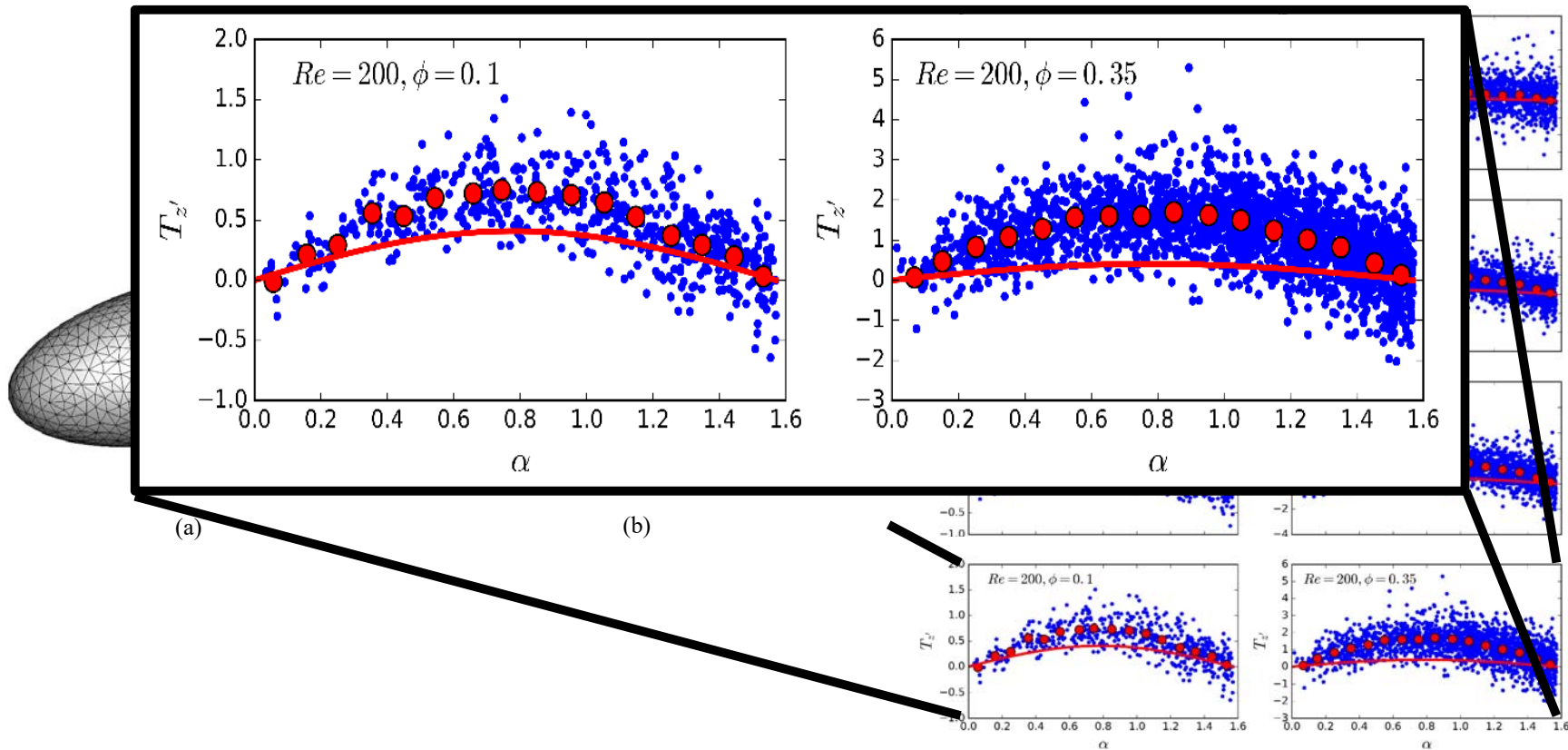
Lateral force is significant

~73% of particles, lateral force magnitude is <10% of the drag force

~48% of particles, lateral force magnitude is <10% of the drag force



Torque coefficient



Summary and Conclusions

- The drag, lift force, and torque coefficient for ellipsoidal particles show a clear dependency on the incidence angle of the flow.
- The drag, lift, lateral forces, and torque coefficients are very sensitive to the local flow conditions and exhibit large variations under the same conditions of Reynolds number and void fraction.
- Comparing to the drag force on each particle at the same Reynolds number and solid fraction, the lift force and lateral force are significant. Neglecting these forces in reduced-order simulations can lead to errors in resolving particle dynamics.
- More advanced sub-scale models may be necessary to resolve the large local sub-grid flow driven perturbations imposed on the mean values.

Thank You!!