Heat Transfer in Assemblies of Spherical and Ellipsoidal Particles

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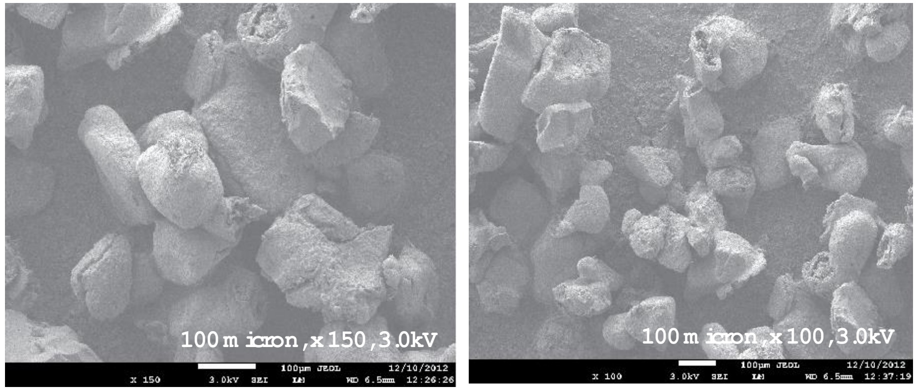
Motivation

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

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



Particles in chemical reactor

Courtesy: Mehrdad Shahnam, NETL

Biomass

Courtesy: Shandong Union Biomass Energy

Catalyst in chemical reactors

Courtesy: GLP inc

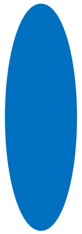
Tablet coating

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

Heat transfer significantly affected by particle shape

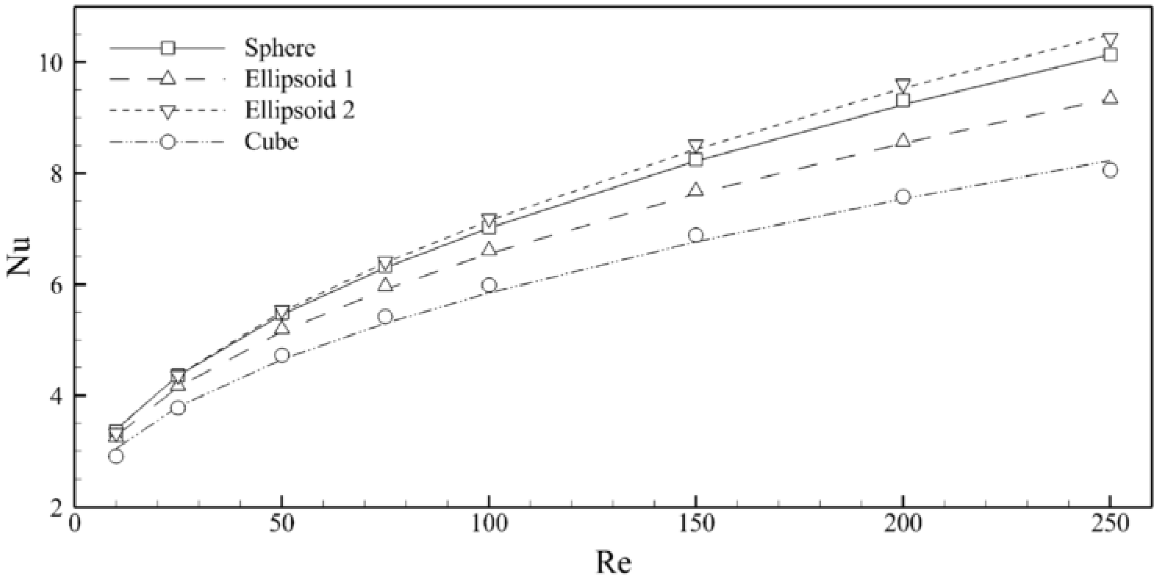
cube

Ellipsoid 1



Ellipsoid 2

Single particle Nusselt number coefficient



From:A. Richter, P A Nikrityuk. Drag forces and heat transfer coefficients for spherical, cuboidal and ellipsoidal particles in cross flow at sub-critical Reynolds numbers. International journal of heat and mass transfer. 2012 P1343 1354

Although the effects of particle shape on heat transfer **in assembly** have already been widely recognized, very few studies have been carried out to quantify the differences.

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

Numerical modeling approaches

Two fluid model (TFM)

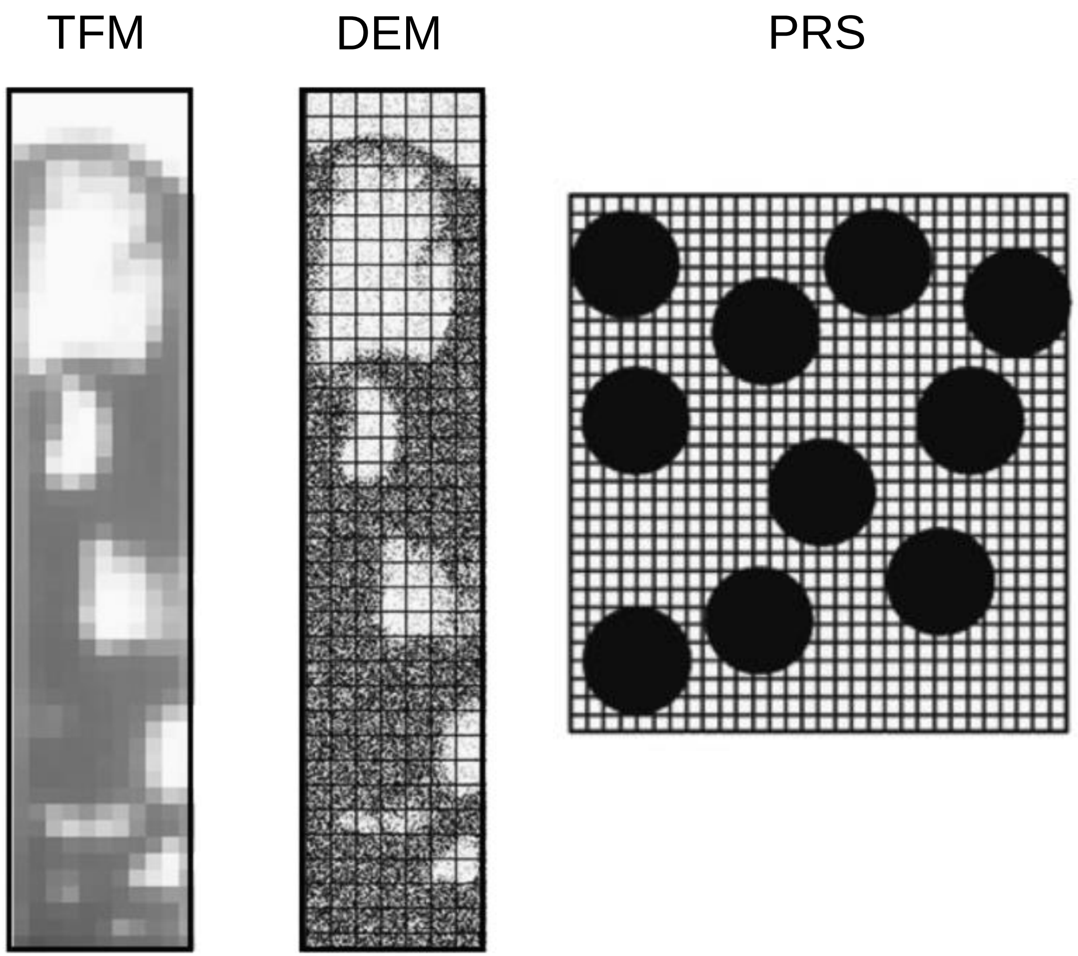
- Particle treated in the continuum as an interpenetrating medium
- Constitutive relationships for interaction between phases

Discrete element method (DEM)

- Fluid motion described by N-S equation
- In fluid, particles are treated as point mass
- Particle motions described by Newton's second law in a Lagrangian framework
- Modeled fluid-particle interaction forces and energy transfer

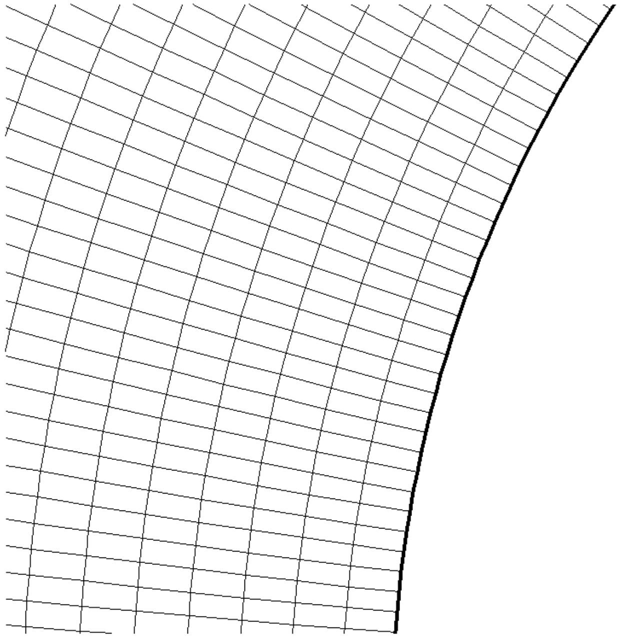
Particle resolved simulation (PRS)

- Particle geometry is resolved in fluid
- No-slip boundary condition set at the fluid-particle interface
- Fluid force and heat transfer is calculated based on the resolved fluid field

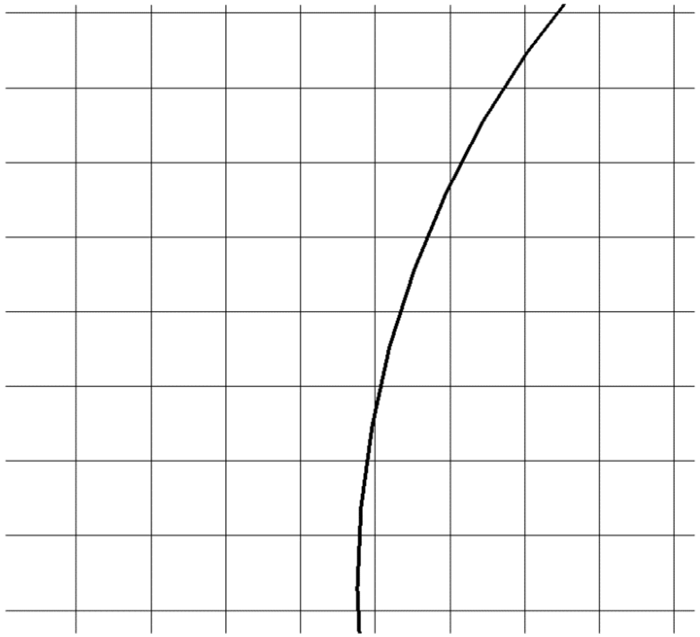


Courtesy: Review of direct numerical simulation of fluid–particle mass, momentum and heat transfer in dense gas–solid flow

Immersed Boundary Method

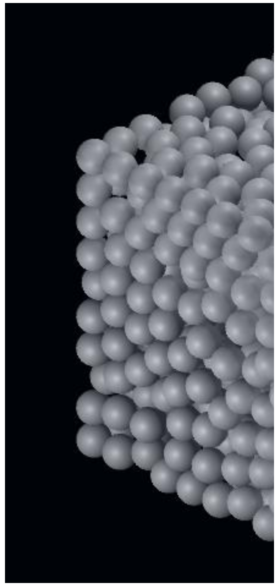


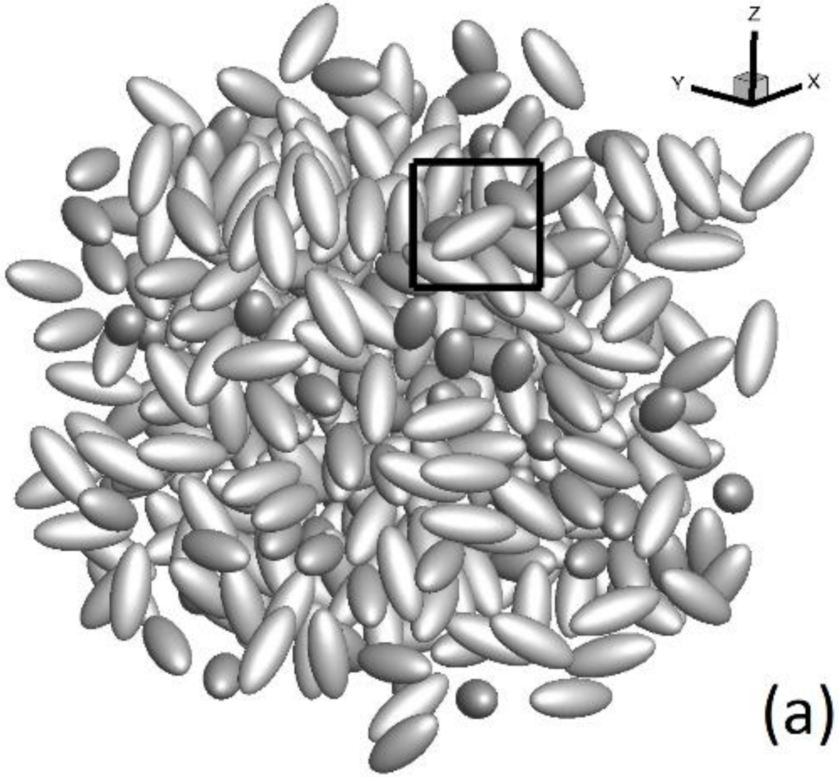
Curvilinear body-fitting grid around a circular surface

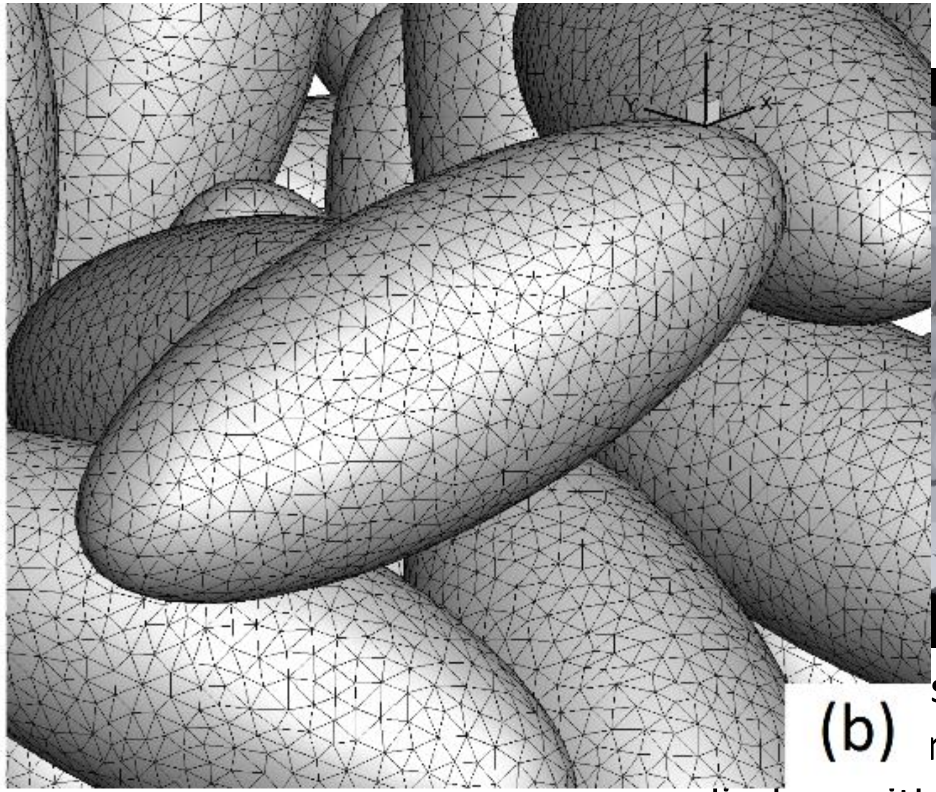


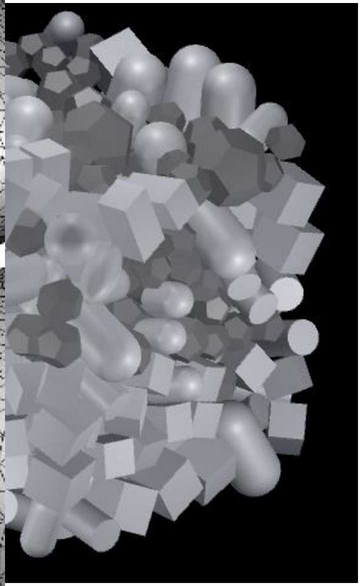
Body non-conforming cartesian grid and an immersed boundary

Generate particle assembly in PhysX







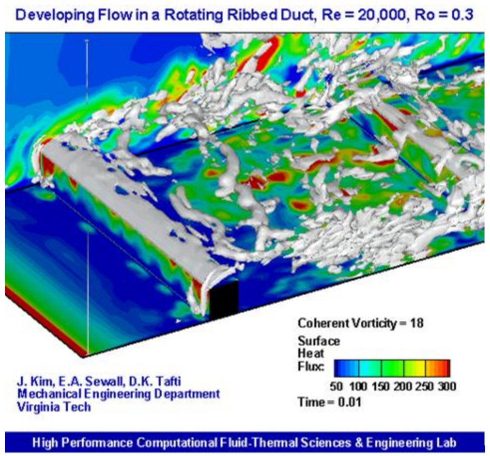


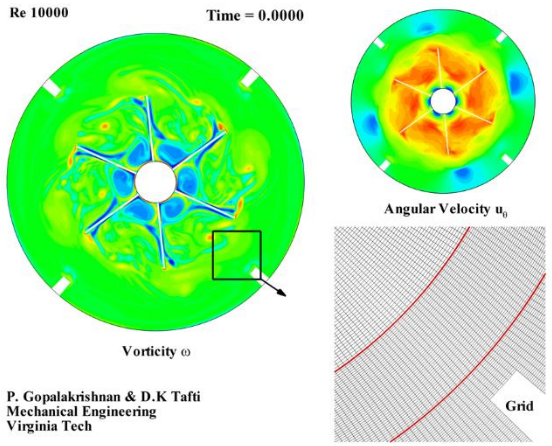
sp

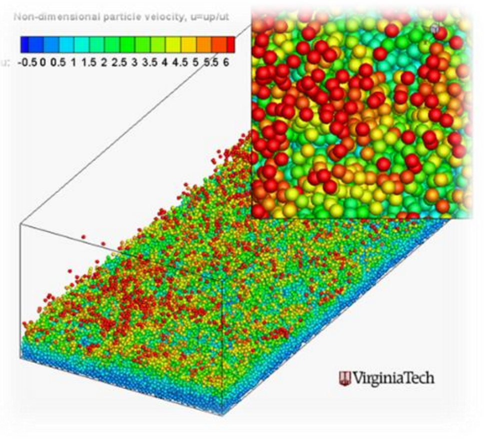
s, capsules,
n, cubes, cuboid,
cylinders with random size.

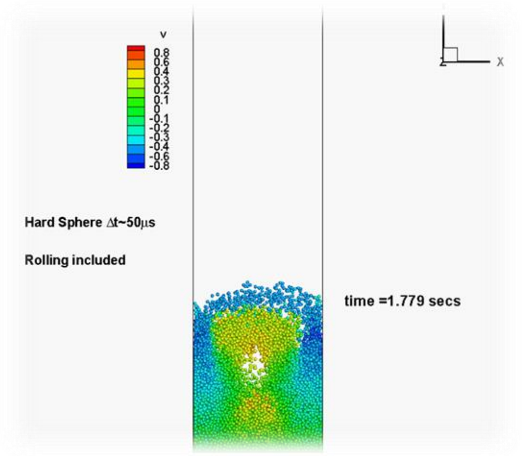
GenIDLEST

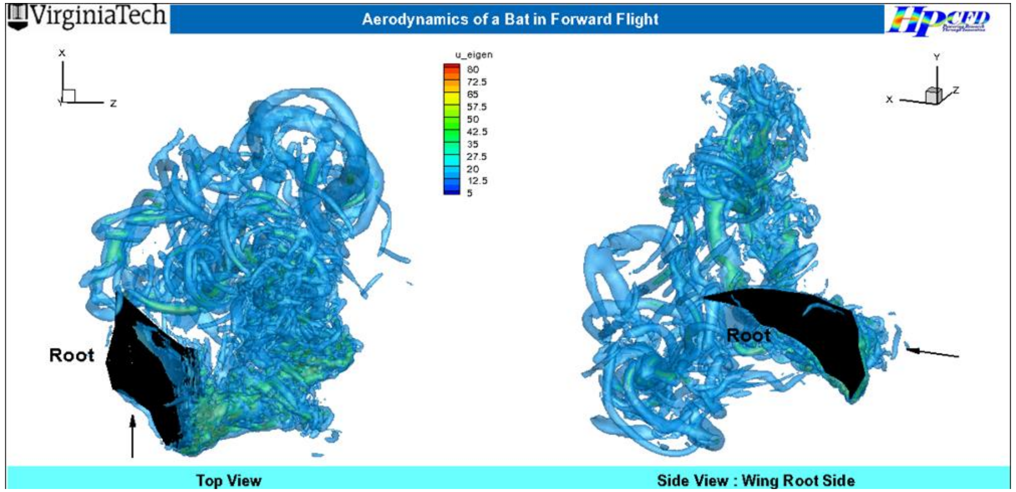
- Generalized Incompressible Direct and Large Eddy Simulation of Turbulence
- Non-staggered finite volume code used a variety of applications
  - Multi-block curvilinear coordinates
  - Temperature dependent property variation
  - Turbulence modeling
  - Immersed boundary
  - Particulate flow modeling
  - Dynamic mesh movement
  - Discrete element method











Fluid governing equations

Incompressible, temperature independent properties

Continuity:

$$\frac{\partial \mathrm{u}_i}{\partial x_i} = 0$$

Momentum:

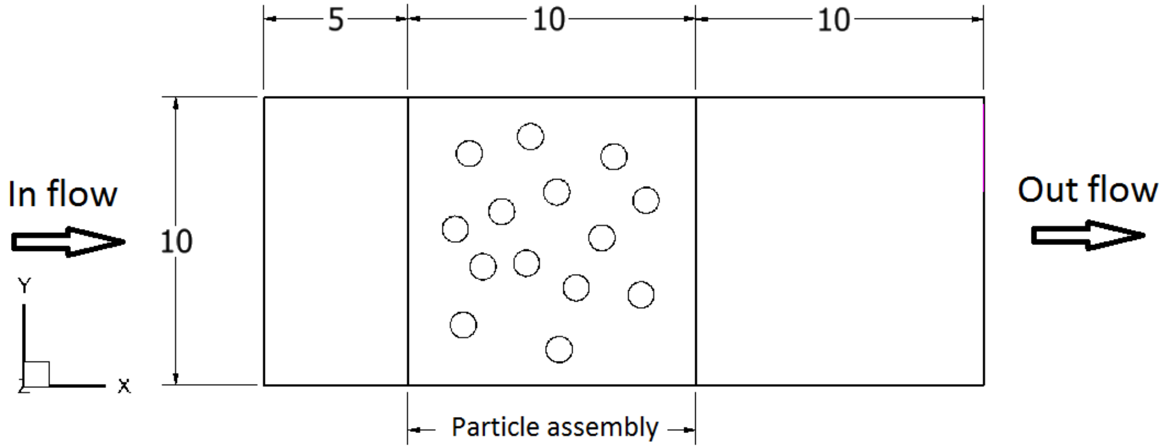
$$\frac{\partial u_i}{\partial \mathrm{t}} + \frac{\partial (u_j u_i)}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left\{\frac{1}{Re_{ref}}\left(\frac{\partial u_i}{\partial x_j}\right)\right\}$$

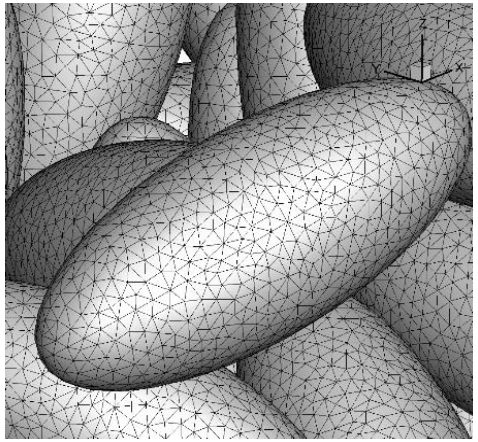
Energy:

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

Boundary conditions will be introduced later with the fluid grid

Computational model for study heat transfer

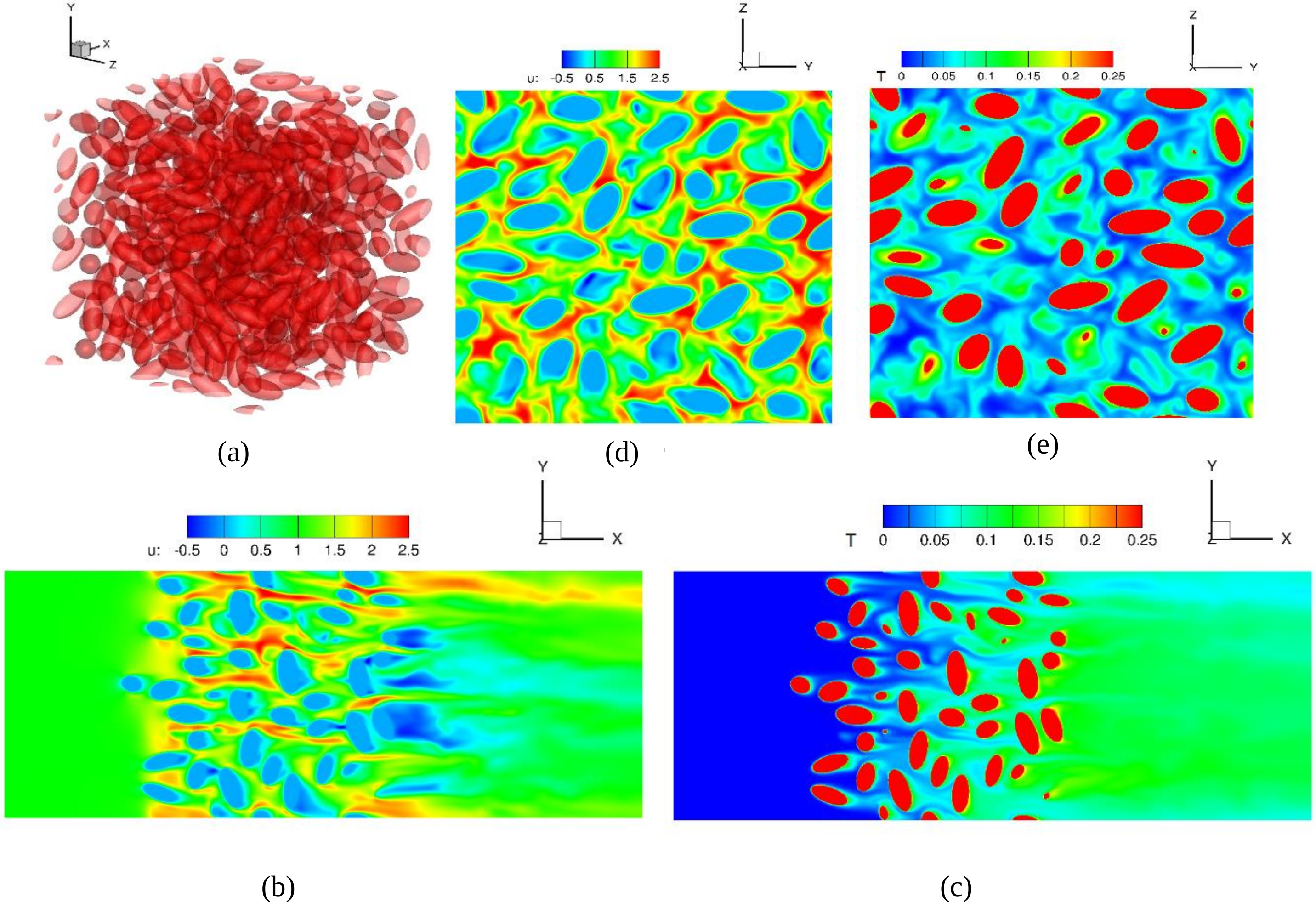




		Sphere	Ellipsoid
Shape parameter		Diameter = 1	Semi-major 0.921
			Semi-minor 0.368
Sphericity		1	0.887
D_{eq}		1	1
Number of particles (N)	$\phi = 10\%$	191	191
	$\phi = 20\%$	382	382
	$\phi = 30\%$	573	573
	$\phi = 35\%$	669	669

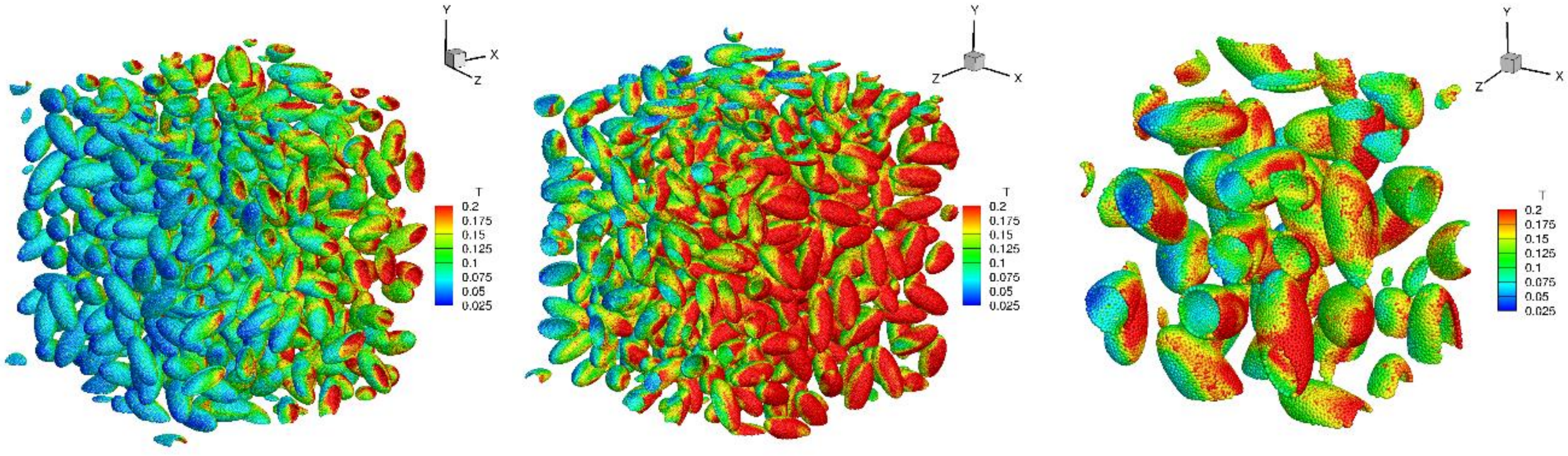
- Constant heat flux boundary condition is set at the particle surfaces
- The background mesh is a uniform distributed structured mesh in the particle assembly region with $\Delta x = \Delta y = \Delta z = 0.025$ based on a grid independency study
- Reynolds number of 10, 50, 100 and 200 based on the superficial velocity and equivalent spherical diameter.
- Prandlt number is set to 0.74

Velocity and temperature field of assembly of ellipsoid



Simulation result of ellipsoidal particle assembly at solid fraction of 20%, Reynolds number of 200: (a) 3D view of assembly; (b) u velocity at X-Y plane (Z = 0); (c) temperature distribution at X-Y plane (Z = 0); (c) u velocity on Y-Z plane at X = 0; (e) temperature distribution on Y-Z plane at X = 0.

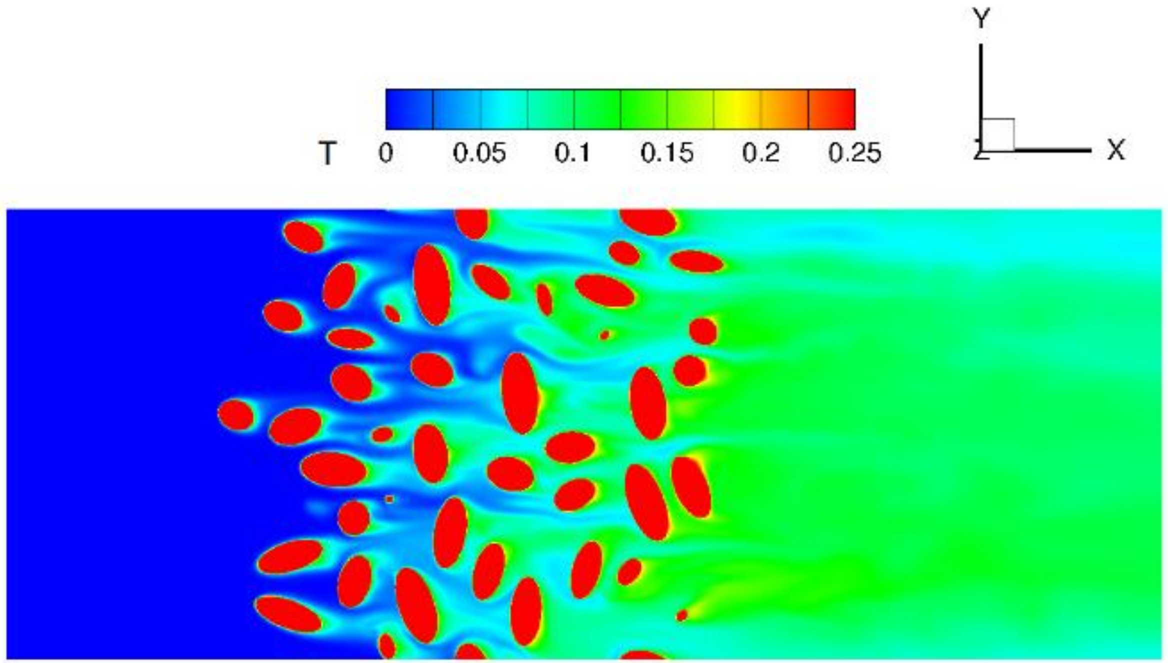
Temperature distribution at the particle surface

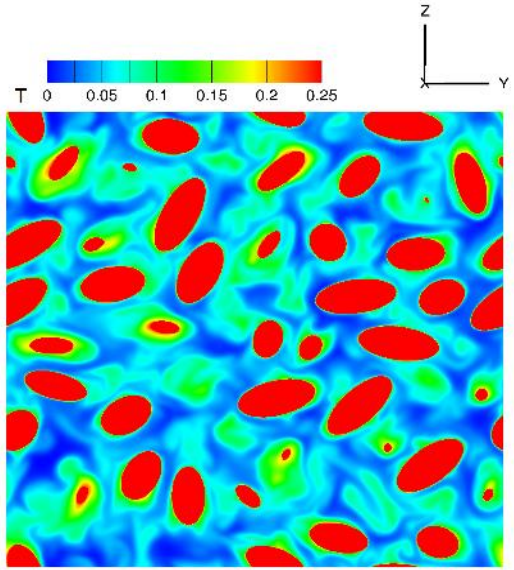


(a) (b) (c)

Temperature at the immersed surface of ellipsoidal particles at solid fraction of 20%, Reynolds number of 200.(a) quarter front view;(b) quarter back view; (3) partial enlarged detail.

Nusselt number calculation



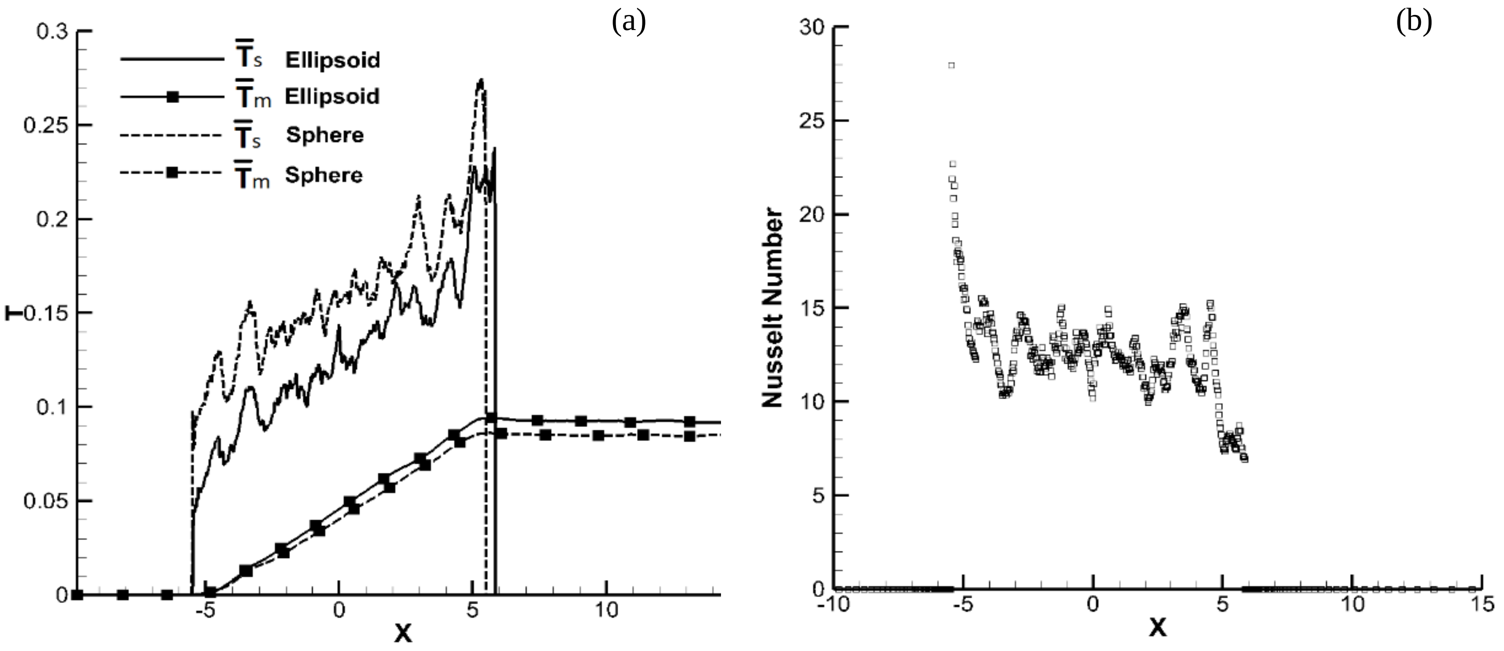


$$\overline{T_s}(x) = \frac{1}{\Omega}\int_{\Omega} T_S(x)\,\mathrm{d}l$$

$$\overline{T_m}(x) = \frac{\int_{A_f} |u_x| T\,\mathrm{d}A}{\int_{A_f} |u_x|\,\mathrm{d}A}$$

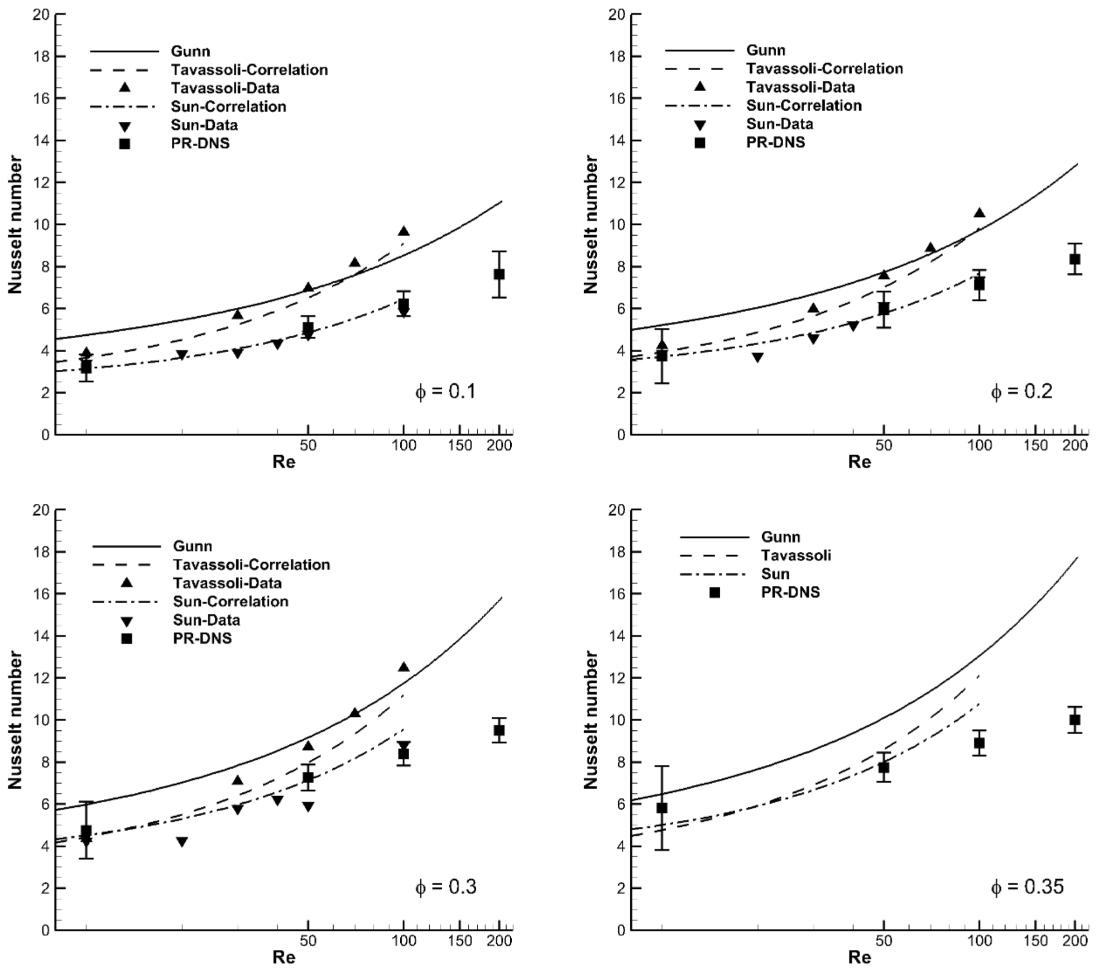
$$Nu(x) = \frac{1}{\overline{T_s}(x) - \overline{T_m}((x)}$$

Surface temperature and Nusselt number



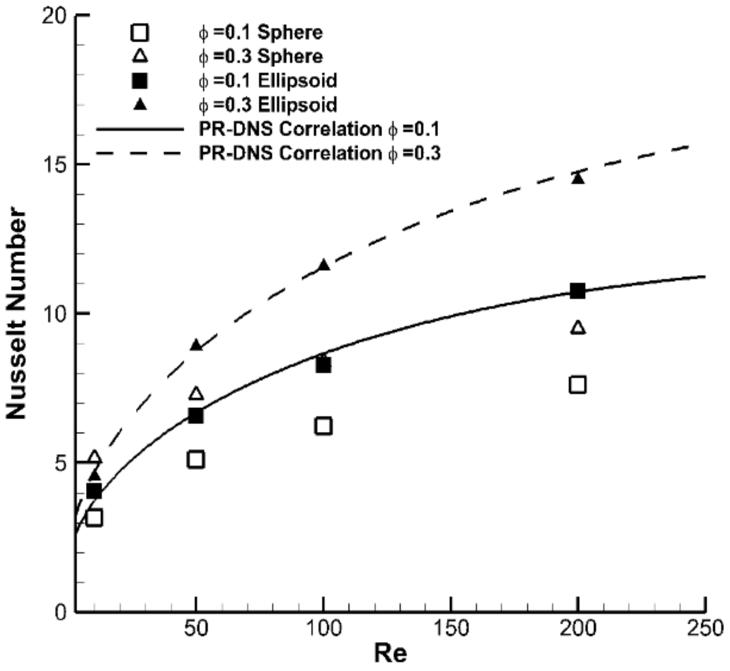
Ellipsoidal particle assembly at solid fraction of 20%, Reynolds number of 200: (a) Average temperature of the particle surface and mixed mean temperature vs X-axis;(b) Nusselt number vs X-axis

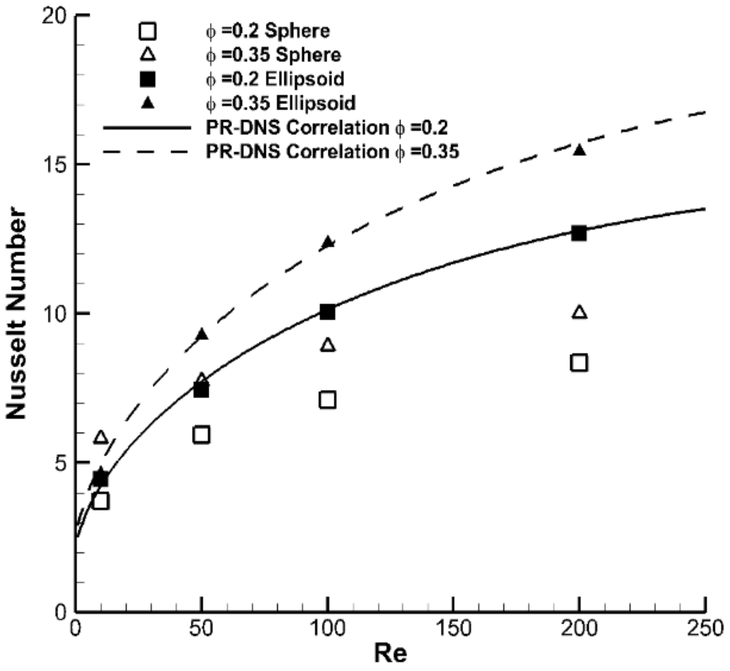
Nusselt number for spherical particles



Nusselt number from current Particle-Resolved simulation compare to correlations and particle resolved simulation data by Sun et al. and Tavassoli.

Nusselt number of ellipsoids and spheres in assembly





$$Nu = (1.49 - 0.885\epsilon + 0.078\epsilon^2)\left(2.458 - 0.042Re^{1.09}Pr^{1/3}\right) + (1.114 - 0.62\epsilon - 0.08\epsilon^2)Re^{0.7}Pr^{1/3}$$

Study of heat transfer--Summary

- Particle resolved simulation for spherical and ellipsoidal particles are performed from Reynolds number of 10 to 200, solid fraction of 0.1 to 0.35
- For each Reynolds number and solid fraction, 3 different random configurations of assembly are tested.
- Sphere vs ellipsoid
  Low Reynolds number, no substantial difference
  High Reynolds number, Nusselt number of ellipsoid ~50% higher than sphere

The results have been published:

Heat transfer in an assembly of ellipsoidal particles at low to moderate Reynolds numbers
L He, DK Tafti - International Journal of Heat and Mass Transfer, 2017, Vol 114, P324-336