Direct Numerical Simulation of Particle Rotation Effects in Gas-Solid Flows Using an Immersed Boundary Lattice Boltzmann Method

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Outline

- Background: Lift force due to particle rotation
- Background: Immersed boundary-Lattice Boltzmann method, from first order to second order
- Drag force and lift force in simple cubic arrays of spheres
- Drag force and lift force in random arrays of spheres
- Open question, how to apply lift force in two-fluid simulations.

Background: Lift force due to particle rotation

- Previously, it was believed that the lift force caused by particle rotation is insignificant compared to the drag force.

  Rotational Reynolds number: $Rer = \omega D^2 / \nu$

- Rubinow & Keller (1961), Stokes flow: $\boldsymbol{F}_D = 6\pi a \mu \boldsymbol{U}[1 + \frac{3}{8}Re + o(Re)]$

  lift-to-drag ratio $F_L / F_D = Rer/24$

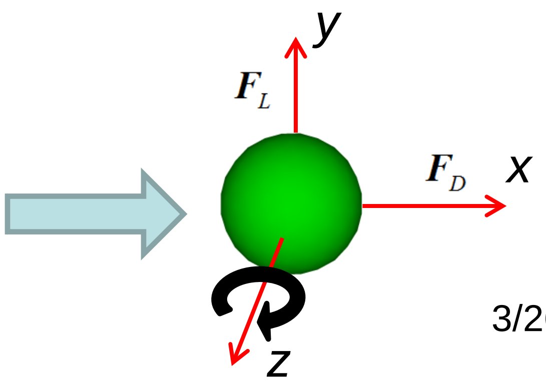
  $\boldsymbol{F}_L = -\pi a^3 \rho \boldsymbol{\omega} \times \boldsymbol{U}[1 + O(Re)]$

- Saffman (1965) mentioned that the lift force due to the rotation is less by an order of magnitude than that due to the shear in the flow.

  $$F_L = 6.46 \nu \rho a^2 U (|\alpha|/\nu)^{1/2} - \frac{11}{8}\rho U \alpha a^3 + \pi \rho U \omega a^3$$

- Yu et al. (2003), simulated *D*=100um, *spin speed*: 10 000 rpm

  lift-to-drag ratio is around 1% (*Rer*=7.0)



Background: Lift force due to particle rotation

- **Recent high-speed imaging show that**
- Wu et al.(2008) measured the particle rotation speed in a cold pilot-scale Circulating Fluidized Bed (CFB) riser. Particle diameter: 0.5 mm.

  Particle rotation speed:

  Average: 300 rev/s Rer=30

  Maximun: 2000 rev/s. Rer=210

- Shaffer et al. (2009) reported the rotation rate of particle in a riser flow. particle size is round 0.5~0.75mm

  Particle rotation speed:

  Average: 22700 rpm Rer=90

  Maximum:90400 rpm Rer=350

- **The importance of the lift force needs to be reevaluated.**

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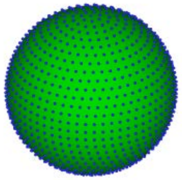
Background: Immersed boundary-Lattice Boltzmann method, from first order to second order



Immersed Boundary Method (IBM)

Advantage:

- The non-slip/non-penetration (ns/np) is easily imposed by adding additional force to the flow in the vicinity of the particle surface
- Does not need regridding when particles are moving

Disadvantage:

- The approximation of ns/np is hard to be exactly imposed.
- Traditional IBM only yields first-order accuracy.

Background: Immersed boundary-Lattice Boltzmann method, from first order to second order

Recent improvement by Breugem (2012)

- Multidirect forcing scheme to reduce the ns/np error (Luo et al. 2007)
- A slight retraction (Hofler and Schwarzer 2000) of the Lagrangian grid from the surface towards the interior of the particles is used to enhance the accuracy of IBM.

Breugem (2012) demonstrated that the improved IBM coupled with traditional incompressible NS-solver gives a second order of convergence

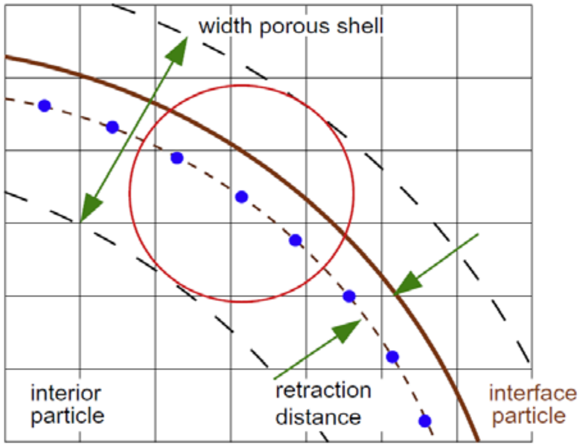


Fig. 3. Illustration of the porous shell covering a solid particle. The dots indicate the position of Lagrangian grid points, which are retracted from the actual interface (the solid line) with a fraction of the Eulerian grid spacing (about $0.3\Delta x$ in this case). The circle depicts the range of action of the regularized Dirac delta function.

Background: Immersed boundary-Lattice Boltzmann method, from first order to second order

Our contribution: embed the improved IBM into LBM

- Using the classic fourth order Runge-Kutta scheme to advance the position, the linear momentum and angular momentum of the particle.
- In the framework of LBM, we can not directly get the flow information at the fractional time step between $n\Delta t$ and $(n+1)\Delta t$. We get the flow information by simple extrapolation:

$$\boldsymbol{u}^{n+\alpha} = \boldsymbol{u}^{n} + (rhs^{n} + \boldsymbol{f}^{n+1})\alpha\Delta t / \rho^{n}$$

$$\rho^{n+\alpha} = \rho^{n} - \nabla \bullet (\rho^{n}\boldsymbol{u}^{n+\alpha})\alpha\Delta t$$

- It is demonstrated, for the first time, that the IB-LBM has the capacity to resolve the translational and rotational motion of particles with the second-order accuracy. (*submitted to the journal of computational physics*)

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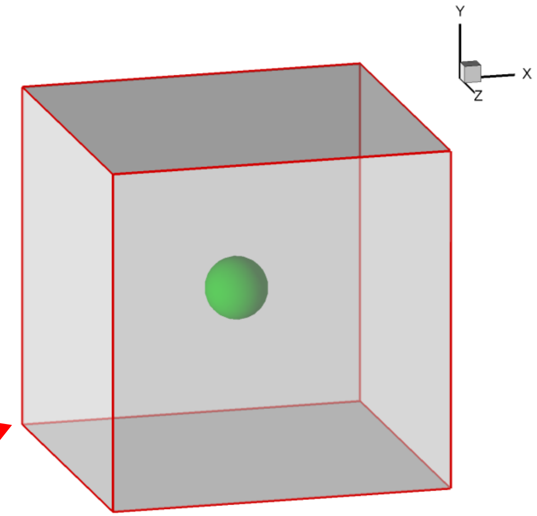
Drag force and lift force in simple cubic arrays of spheres

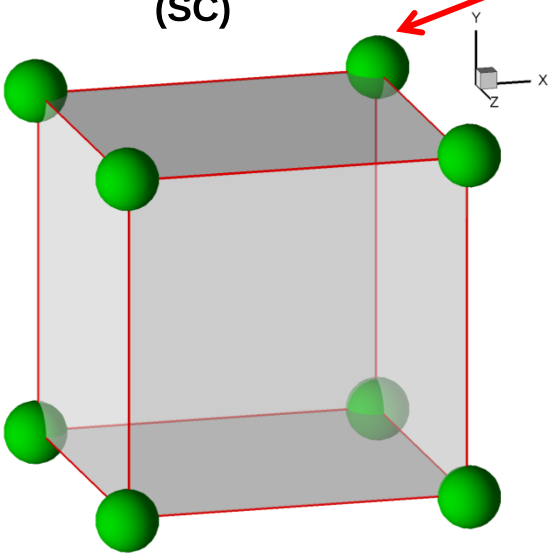


Three ordered configurations

- Theoretical results of the drag force can b configuarations. (Zick & Homsy 1982)

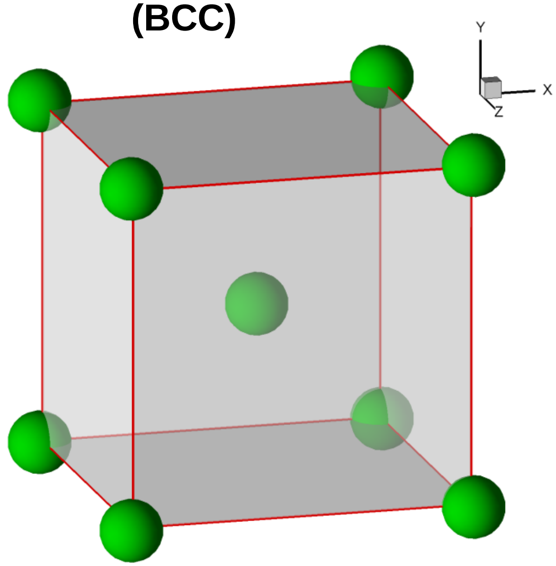
Simple-cubic packing

(SC)



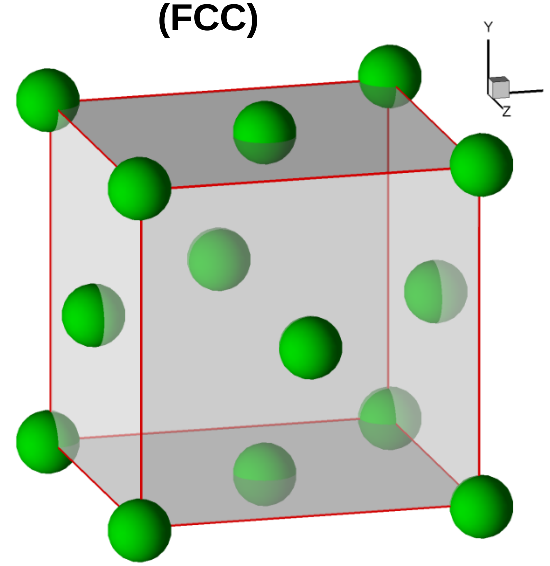
Body-centred cubic packing

(BCC)



Face-centered cubic packing

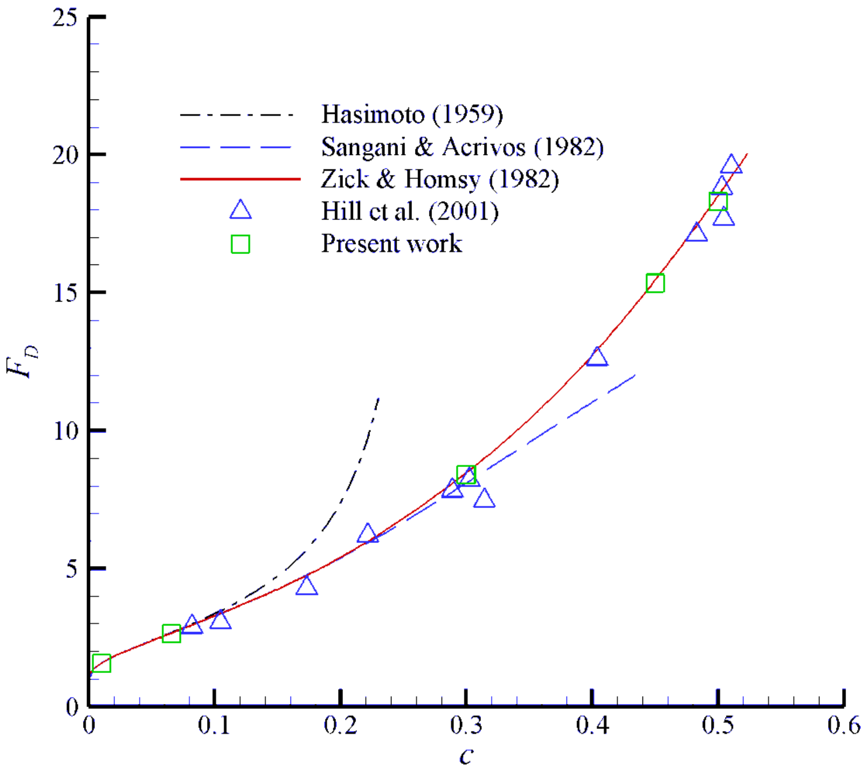
(FCC)

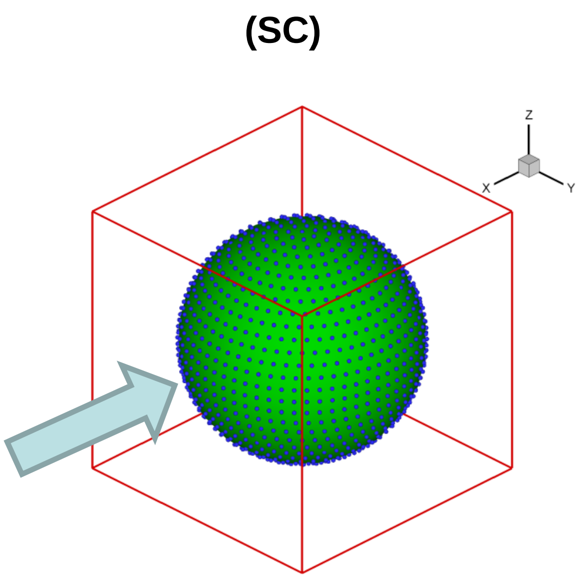


Drag force and lift force in simple cubic arrays of spheres

Validation of our simulation

- The drag force at various solid volume fraction (c) agree well with theoretical results.
- Position fixed, particle Reynolds number <0.2, flow driven by uniform pressure gradient.



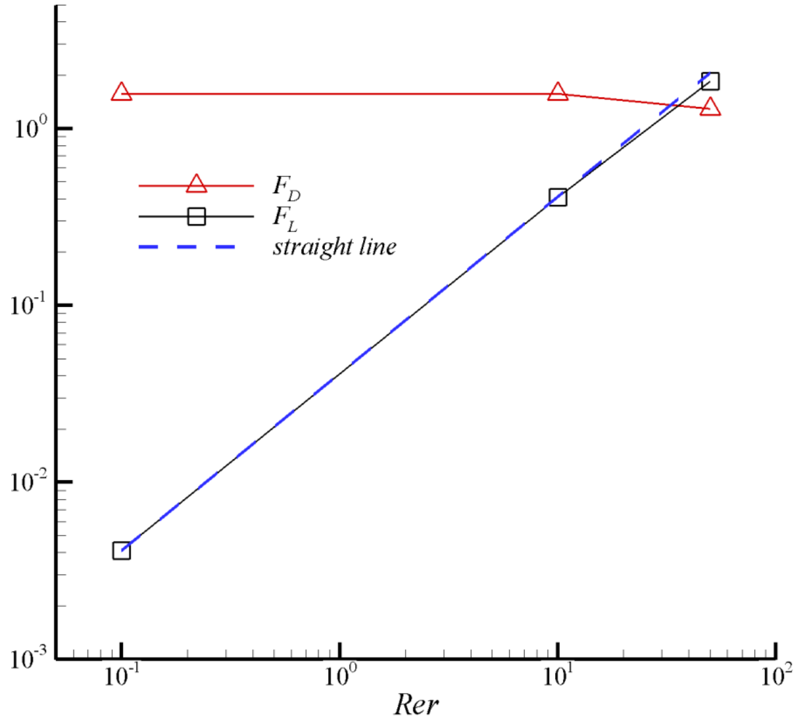


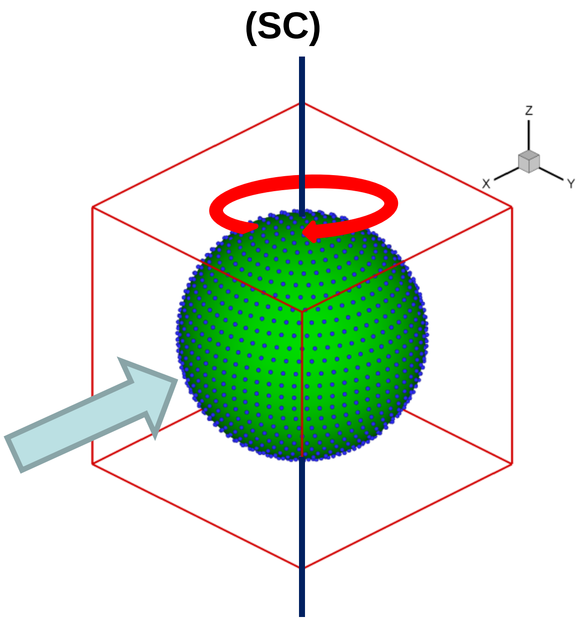
Drag force and lift force in simple cubic arrays of spheres

Lift force caused by particle rotation (rotating axis is perpendicular to the flow direction)

- The lift force at various solid volume fraction (c).

c=0.01



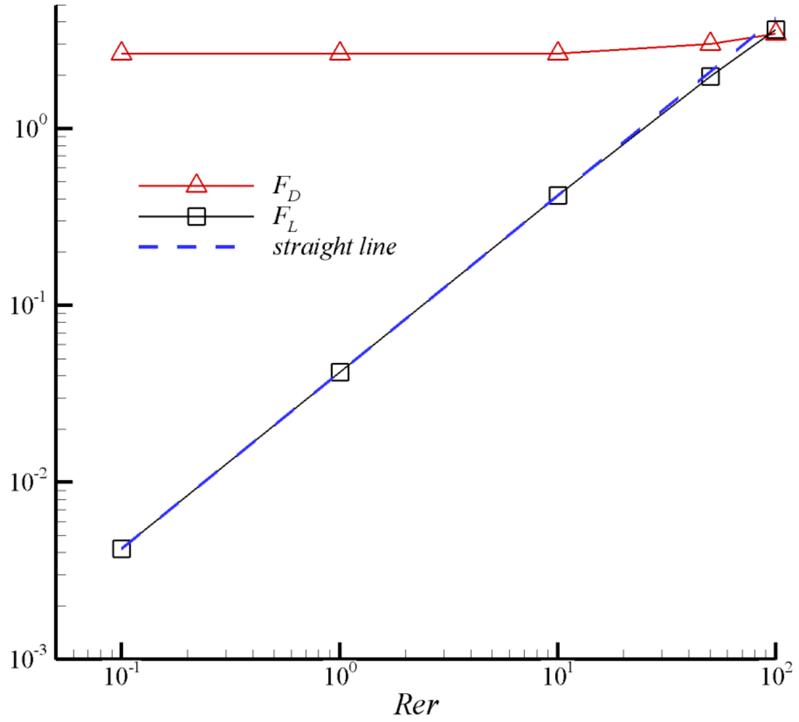


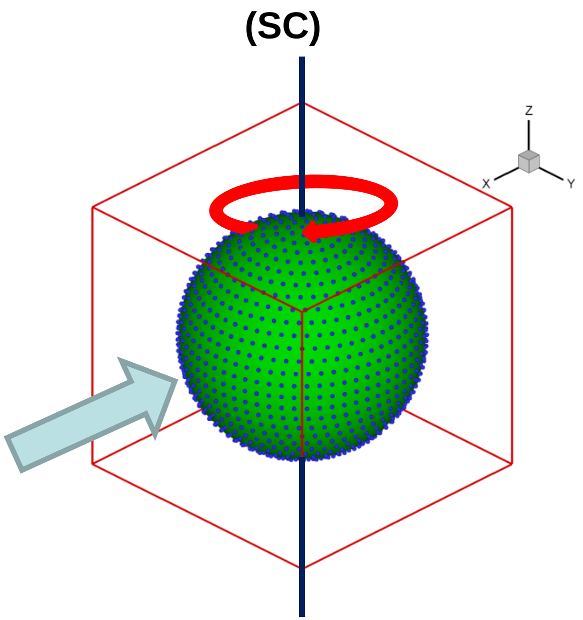
Drag force and lift force in simple cubic arrays of spheres

Lift force caused by particle rotation (rotating axis is perpendicular to the flow direction)

- The lift force at various solid volume fraction (*c*).

c=0.065



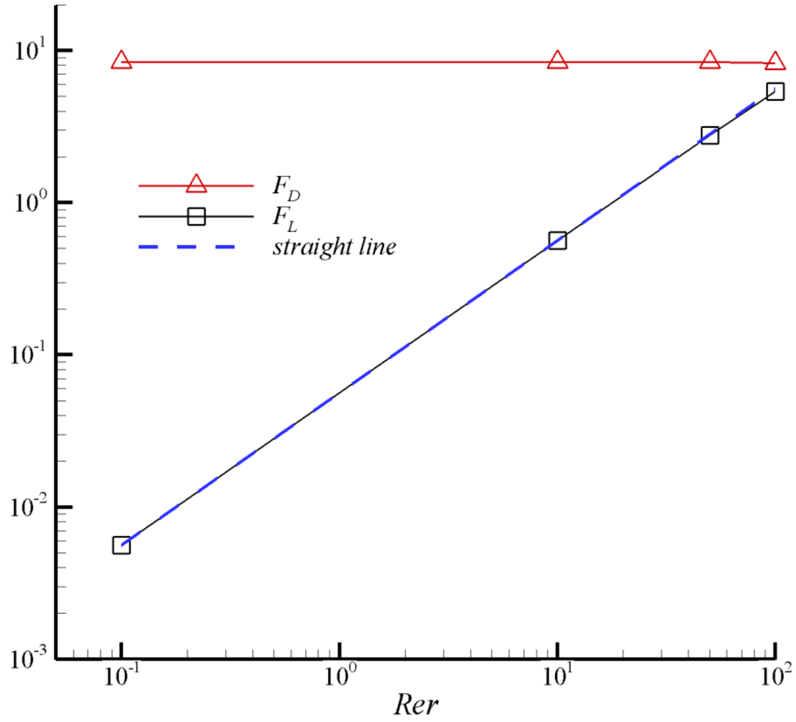


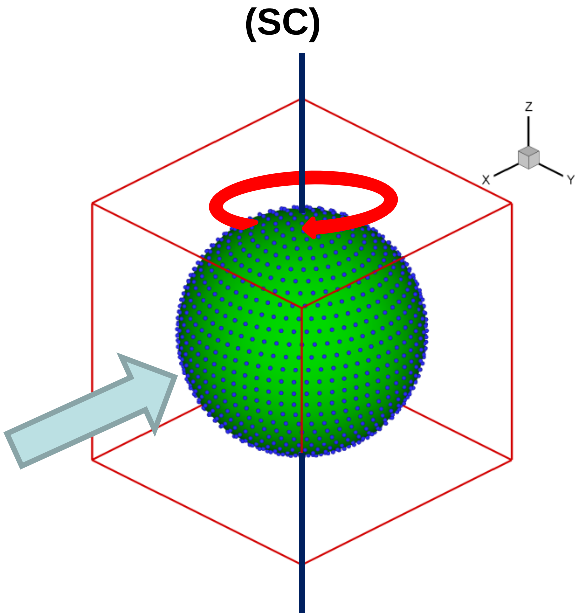
Drag force and lift force in simple cubic arrays of spheres

Lift force caused by particle rotation (rotating axis is perpendicular to the flow direction)

- The lift force at various solid volume fraction (*c*).

c=0.3



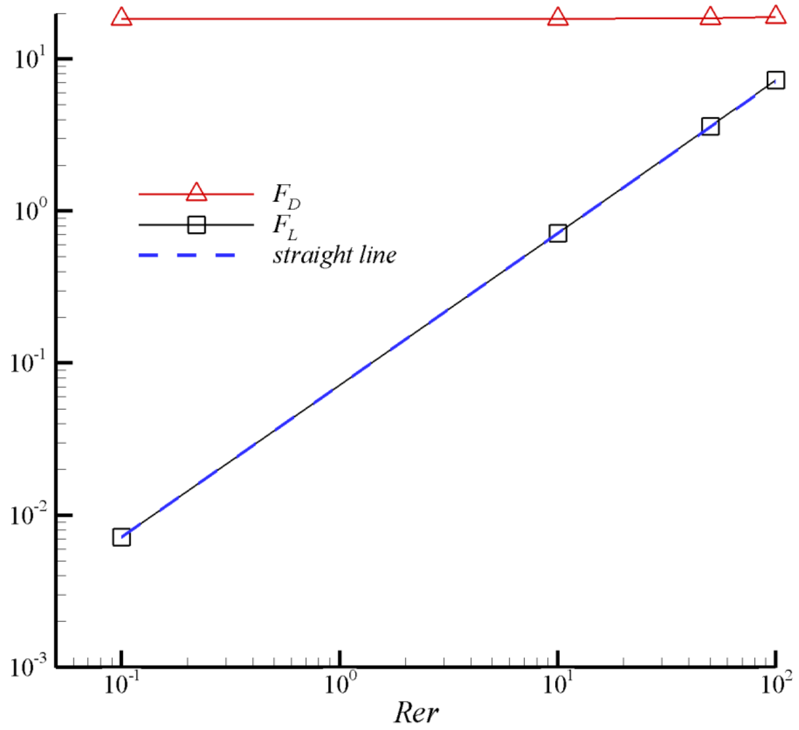


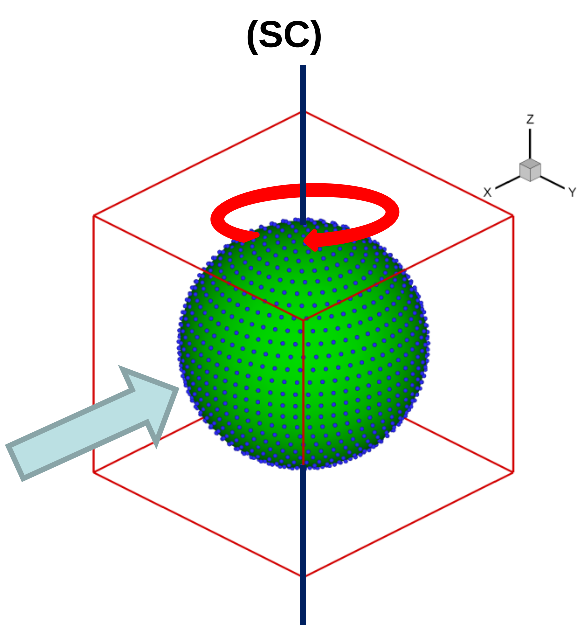
Drag force and lift force in simple cubic arrays of spheres

Lift force caused by particle rotation (rotating axis is perpendicular to the flow direction)

- The lift force at various solid volume fraction (*c*).

c=0.5





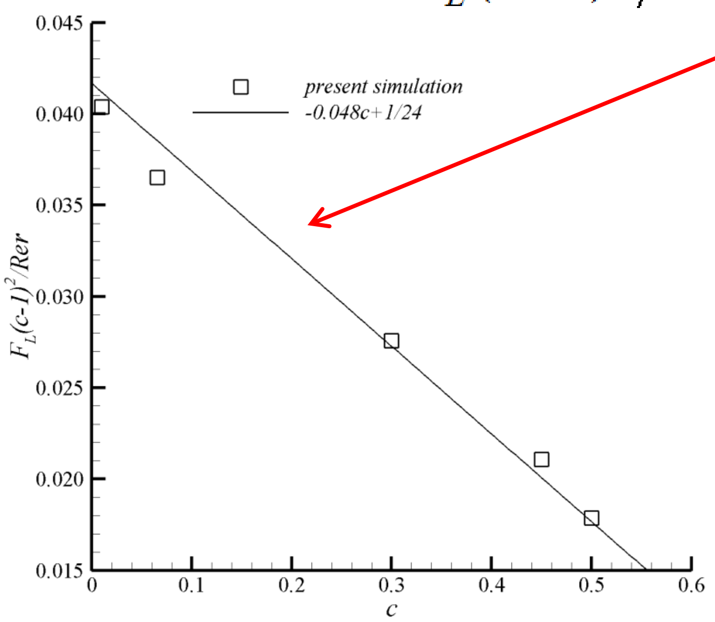
Drag force and lift force in simple cubic arrays of spheres

Lift force caused by particle rotation (rotating axis is perpendicular to the flow direction)

- Based on the simulation results and the theoretical value for $c \rightarrow 0$ (Rubinow & Keller (1961)). The lift force at various solid volume fraction (c) can be expressed as(Rer<100)

$$F_L = Rer(-0.048c + 1/24)/(1-c)^2$$

$$F_L(1-c)^2/Rer = (-0.048c + 1/24)$$



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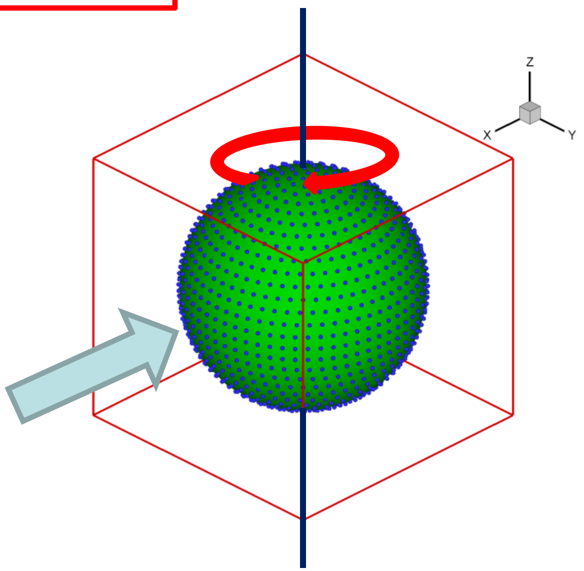
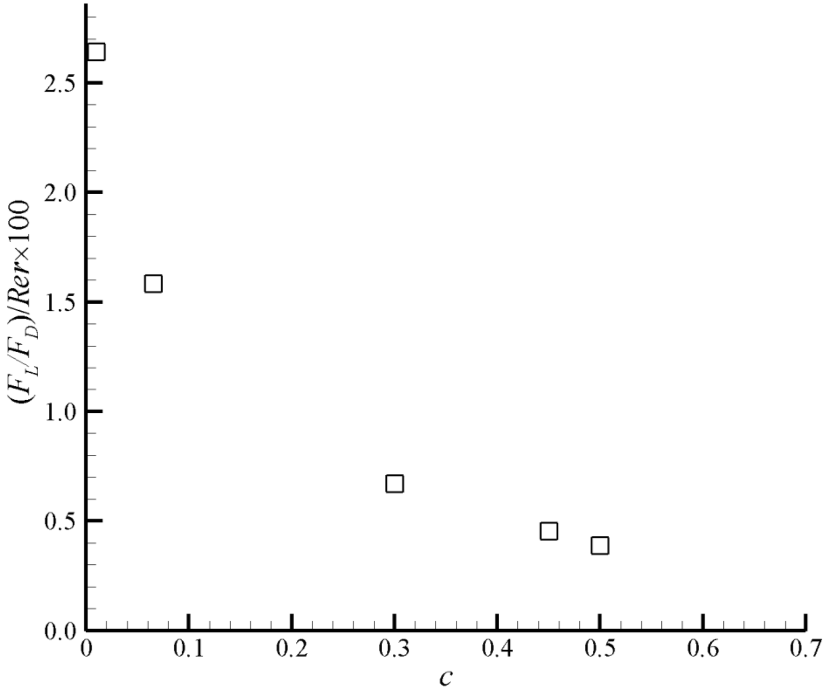
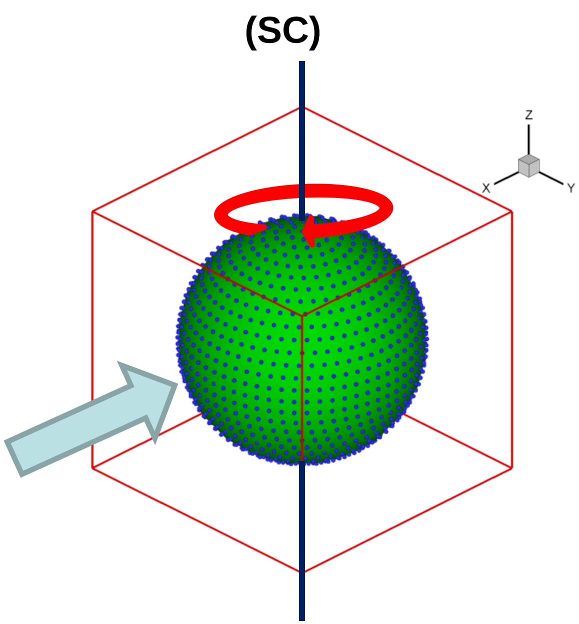


Drag force and lift force in simple cubic arrays of spheres

The ratio of the lift force to the drag force

- *c*=0.01,Rer=1, $F_L/F_D \approx$ 2.6%, Rer=10, $F_L/F_D \approx$ 26%, Rer=100, $F_L/F_D \approx$ 260%
- *c*=0.3, Rer=1, $F_L/F_D \approx$ 0.67%, Rer=10, $F_L/F_D \approx$ 6.7%, Rer=100, $F_L/F_D \approx$ 67%
- *c*=0.5, Rer=1, $F_L/F_D \approx$ 0.39%, Rer=10, $F_L/F_D \approx$ 3.9%, Rer=100, $F_L/F_D \approx$ 39%
- For intermediate and dense system, the lift force became significant when Rer>30.





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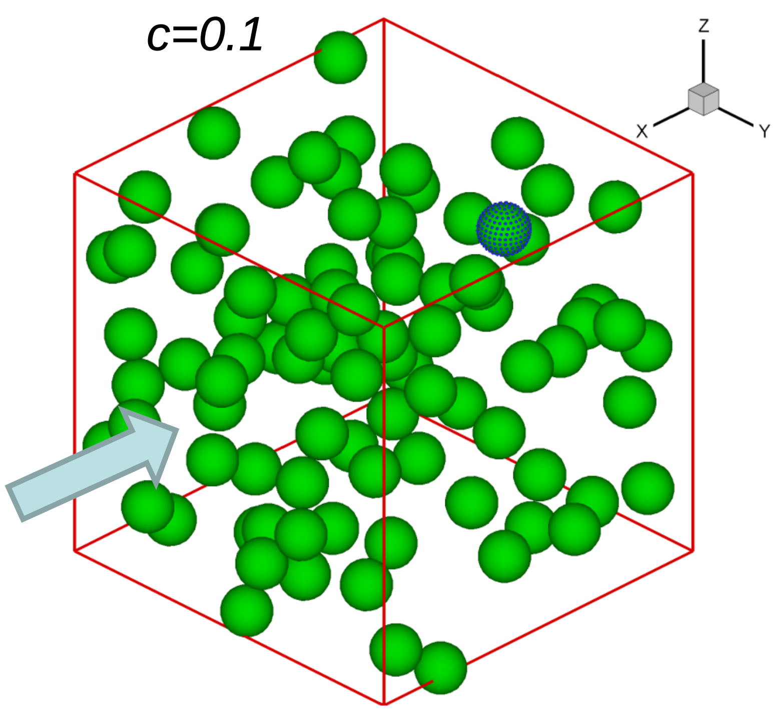
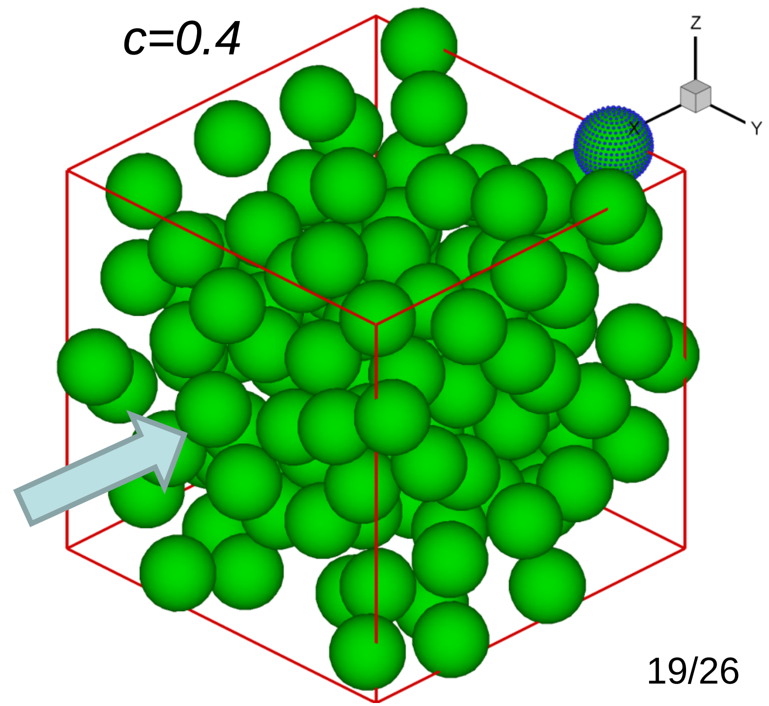
Drag force and lift force in random arrays of spheres

Random configuration

- Random configuration is generated by means of a standard Monte Carlo procedure for hard spheres.
- Many configurations should be simulated to yield accurate results
- For each configuration, three simulations can be done by letting the flow enter the domain in different directions



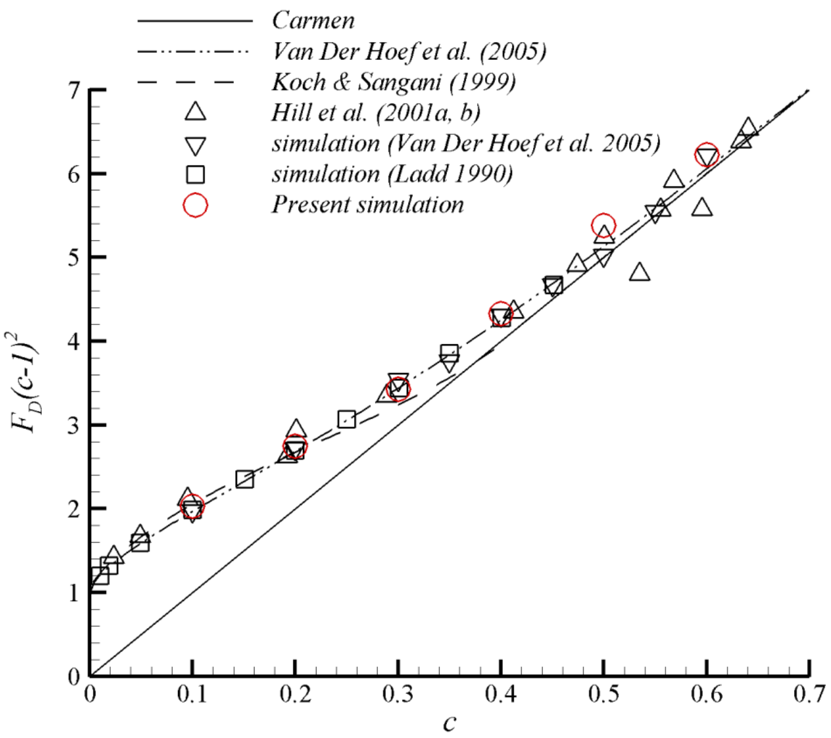


Drag force and lift force in random arrays of spheres

Drag force without particle rotation

- Agree with previous simulation results as well as the fitting expression proposed by Van Der Hoef et al.(2005)

$$F_D = 10\frac{c}{(1-c)^2} + (1-c)^2(1+1.5\sqrt{c})$$

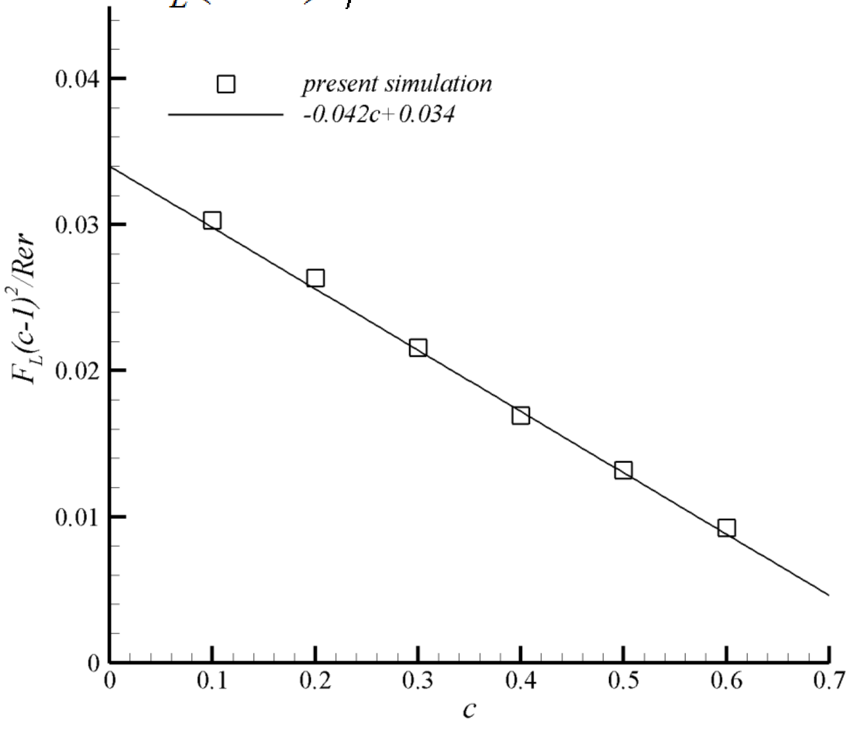


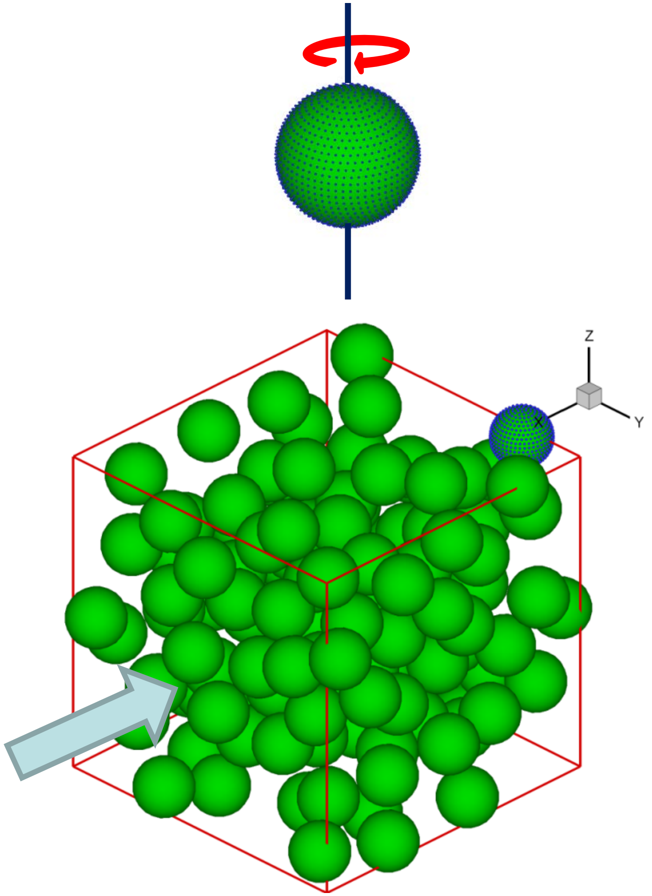
Drag force and lift force in random arrays of spheres

Drag force and lift force in the presence of particle rotation

- Similarly to the results in SC configuration, $F_L(1-c)^2/Rer$ is linearly dependent on *c*.
- The drag force does not change appreciably.
- Based on our simulation results:

$$F_L(1-c)^2/Rer = -0.042c + 0.034$$

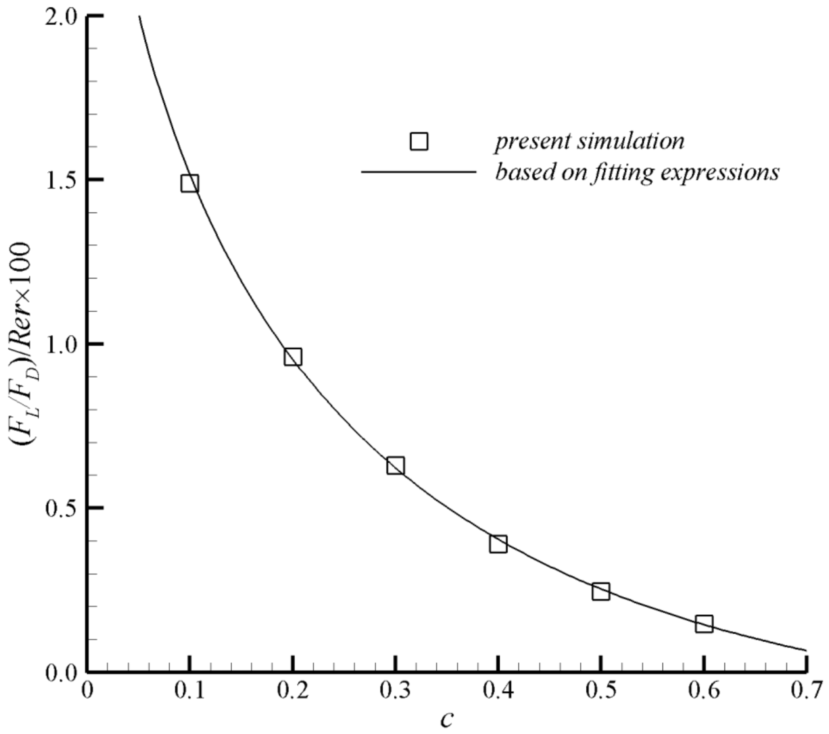




Drag force and lift force in random arrays of spheres

The ratio of the lift force to the drag force

- To reach F_L/F_D =10%, Rer needed for various *c*:
- *c*= 0.1 0.2 0.3 0.4 0.5 0.6
- Rer= 6.7 10.4 15.9 25.6 40.8 67.4
- For c<0.3, the lift force became significant when Rer>10
- For close packing system, the lift force became significant when Rer>50



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Open question, how to apply lift force to two-fluid simulations.

How to obtain the mean rotating speed of the particles?

The first approach (Lun 1991; Jenkins & Zhang 2002**)**

- Typical two-fluid governing equations include, conservation equations for
  - mass
  - translational momentum
  - translational granular temperature
  - rotational momentum
  - rotational granular temperature

The second approach(Lun 1991; Jenkins & Zhang 2002; Sun & Battaglia 2006)

- Do not add additional equations, let the mean rotating speed of spheres be equal to half the vorticity of their mean velocity
- The conservation of rotational granular energy is approximately satisfied by requiring that the rate of dissipation of rotational granular energy equal to zero. Then the rotational granular temperature can be determined in terms of the translational granular temperature.

Concluding Remarks

- LBM and IBM is coupled through the classical fourth order Runge-kutta scheme. The overall accuracy reaches second-order.
- The drag force and the lift force are calculated both in ordered arrays and random arrays. The computed drag force is in good agreement with existing theories and published numerical results. Based on the simulation results, lift laws are proposed for the SC configuration and random configuration, respectively.
- It is found that the lift force can be very significant relative to the magnitude of the drag force when the rotational Reynolds number is within the range of the practical gas-solid flow systems.
- Two approaches that can include the lift force in two-fluid simulations are discussed.

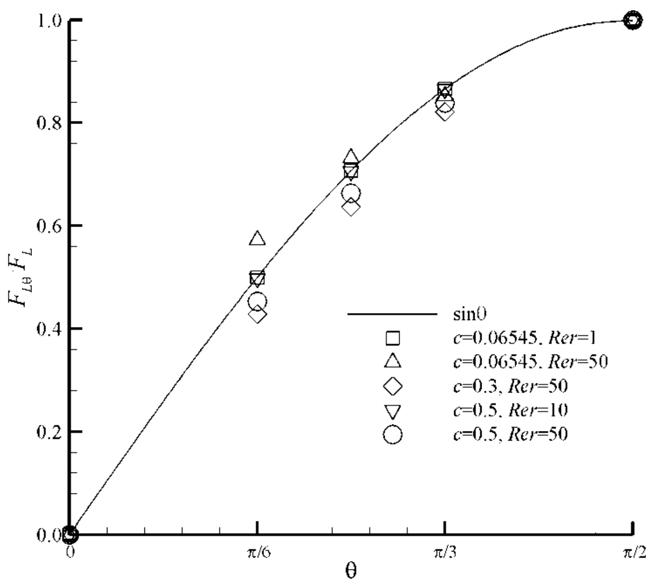
Acknowledgement

- The work is supported by the U.S. Department of Energy Grant FE0007520.

Drag force and lift force in simple cubic arrays of spheres

- The effect of the angle between the rotating axis of the sphere and the flow direction is also explored

$$F_L|_\theta = F_L|_{\theta=\pi/2}\sin\theta$$



(SC)