A General Drag Model for Assemblies of Non-Spherical Particles Created With Artificial Neural Networks (ANN)

Project Award Number DE-FE0031894

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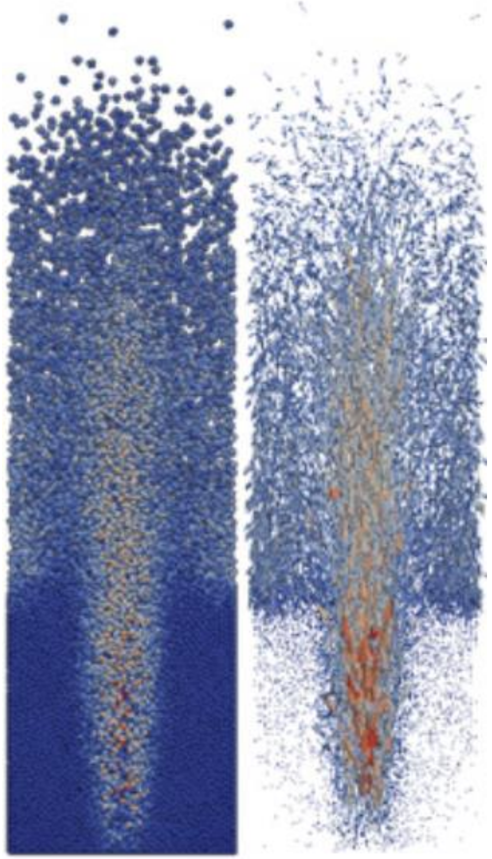
Technical background

- Equation of motion of a particle:

$$m\frac{d\vec{V}}{dt} = \sum\vec{F}$$

- Particle drag determines the movement of particles in particulate flows. It is the key to the modeling and understanding of all phenomena associated with the momentum, heat and mass transfer to the surroundings in all particulate processes (e.g., the process in a fluidized bed reactor).



Technical background – continue

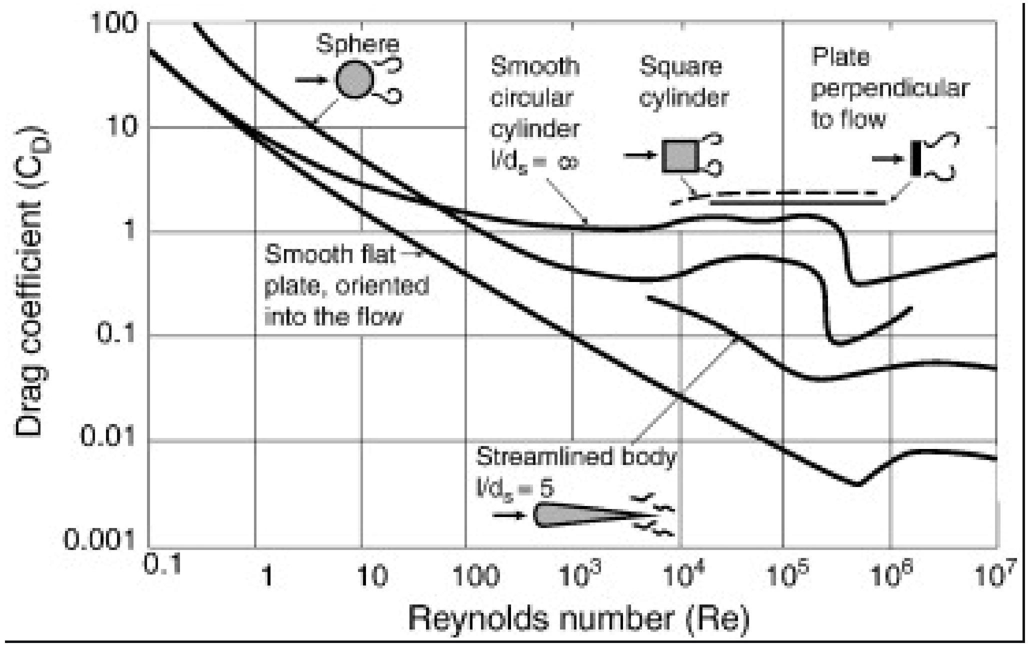
- The studies on the non-spherical particle drag in the literature are very limited.
- Most simulation packages currently use the drag models of spherical particles.

Gidaspow drag correlation

$$\beta_{gm} = \begin{cases} \frac{3}{4} C_D \frac{\rho_g \varepsilon_g \varepsilon_m |\mathbf{u}_g - \mathbf{u}_m|}{d_{pm}} \varepsilon_g^{-2.65} & \varepsilon_g \geq 0.8 \\ \frac{150 \varepsilon_s (1-\varepsilon_g) \mu_g}{\varepsilon_g d_{pm}^2} + \frac{1.75 \rho_g \varepsilon_m |\mathbf{u}_g - \mathbf{u}_m|}{d_{pm}} & \varepsilon_g < 0.8 \end{cases}$$

$$C_D = \begin{cases} 24/\mathrm{Re}\left(1 + 0.15\,\mathrm{Re}^{0.687}\right) & \mathrm{Re} < 1000 \\ 0.44 & \mathrm{Re} \geq 1000 \end{cases}$$

$$\mathrm{Re} = \frac{\rho_g \varepsilon_g |\mathbf{u}_g - \mathbf{u}_m| d_{pm}}{\mu_g}$$



Technical background – continue

- The determination of the drag of non-spherical particles presents more challenges than that of spherical particles
  - Non-spherical particles do not have point-symmetry
  - Non-spherical particles cannot be characterized by a single length-scale that determines their sizes and shapes.
  - The drag of non-spherical particles depends on the orientation of the particles with respect to the flow.
  - The wakes behind non-spherical particles can be anti-symmetric even at low Reynolds numbers.

Results: Drag of an ellipsoid (oblate or prolate)

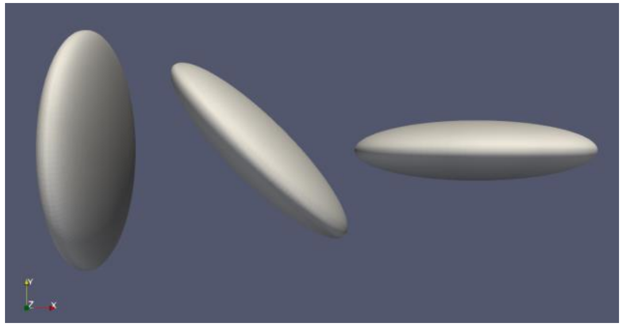
- OpenFoam package has been used to determine drags of ellipsoidal particles.
- Volume equivalent sphere diameter was used as reference for Reynolds number and drag coefficient.
- For an aspect ratios AR, the semi-axis dimensions were determined by:

$$a = \left(\frac{3V_{sph}}{4\pi Ar}\right)^{1/3}, \quad and \quad c = Ar * a.$$

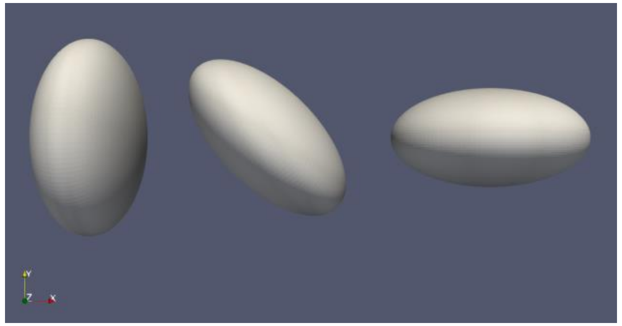
- The sphere and ellipsoids were created in 3D Builder, the objects were then imported into openFoam, and the simulations were computed for a few different incident angles.
- The aspect ratio varies from 0.25 (oblate) to 6 (prolate), and flow Reynolds number varies from 10 to 200.
- We plan to get more results at different Re, AR, and θ and to develop AI model based on these data sets.

Results: Drag of an ellipsoid – continue

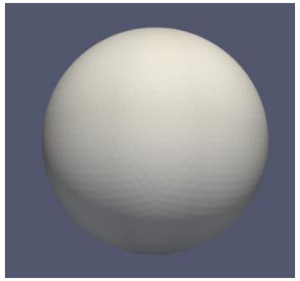
- Configurations of an ellipsoid at different aspect ratio (AR) and different orientation



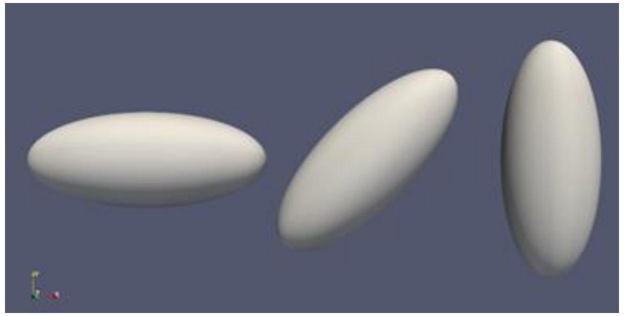
AR=0.25



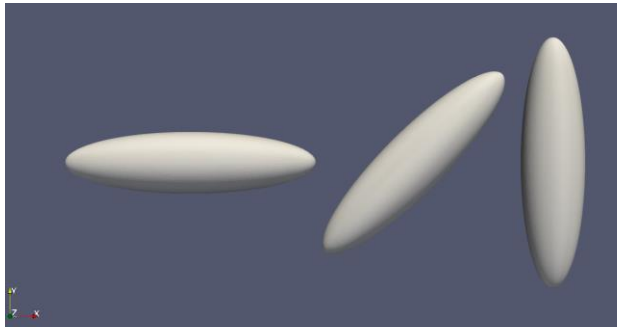
AR=0.5



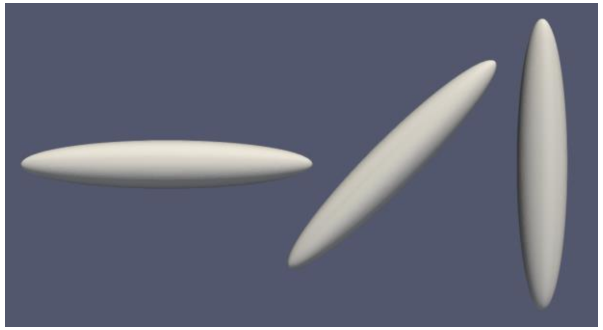
AR=1



AR=2.5



AR=4



AR=6

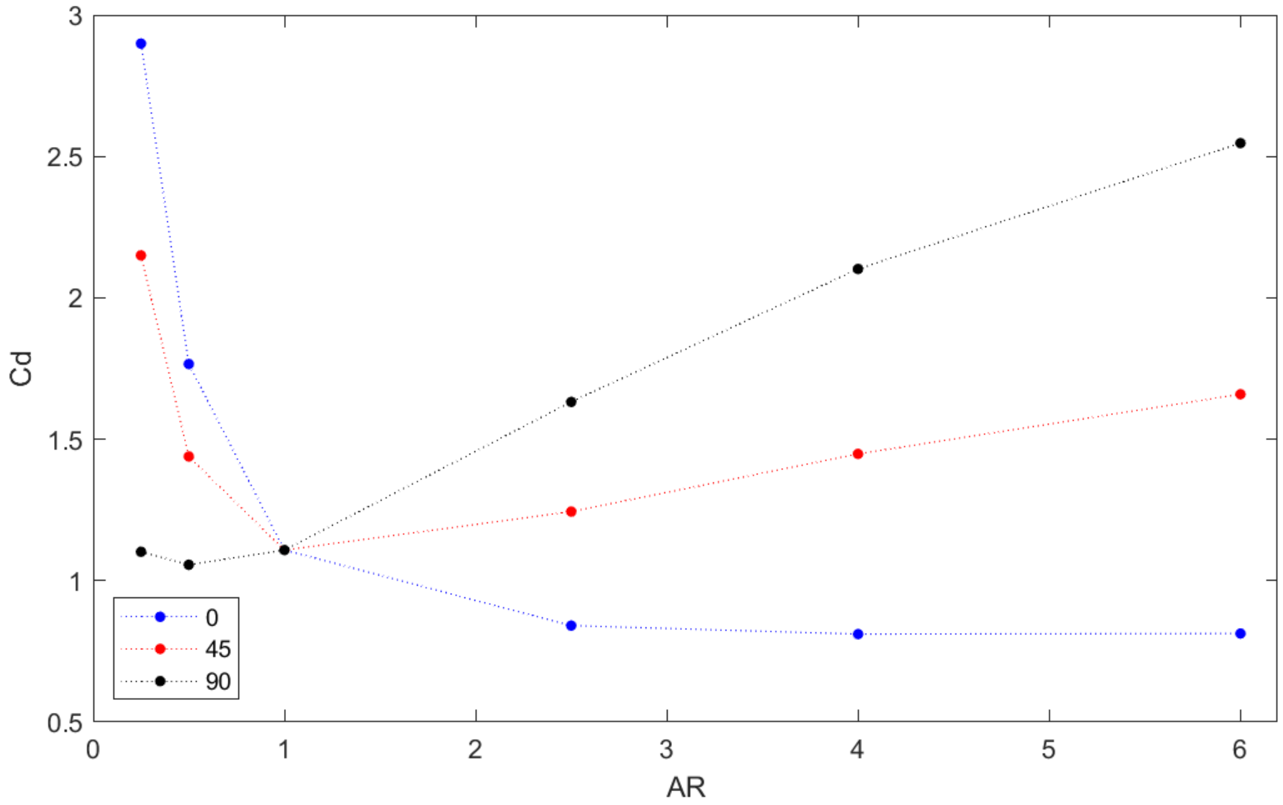
Results: Drag of an ellipsoid – continue

- Simulation results are compared to those obtained by Ke et al. (*)
- Although limited in data points, the values were well within acceptable standards with the largest and smallest deviations being 6.99% and 0.36%, respectively. Graphical visualizations of the results appeared to track with the aforementioned paper.

	Re = 10 (Chunhai Ke et al.)					
theta	0	45	90	0	45	90
Ar	2.5	2.5	2.5	0.5	0.5	0.5
Cd	3.7674	4.4744	5.2983	5.4212	4.7775	4.1791
lit. Cd	4.0504	4.8064	5.5889	5.5681	4.9921	4.4293
% diff.	6.99%	6.91%	5.20%	2.64%	4.30%	5.65%
	Re = 100 (Chunhai Ke et al.)					
theta	0	45	90	0	45	90
Ar	2.5	2.5	2.5	0.5	0.5	0.5
Cd	0.8153	1.1917	1.5940	1.7609	1.3687	1.0010
lit. Cd	0.8674	1.2387	1.6101	1.6937	1.3927	1.0654
% diff.	6.01%	3.80%	1.00%	3.97%	1.72%	6.05%
	Re = 200 (Chunhai Ke et al.)					
theta	0	45	90	0	45	90
Ar	2.5	2.5	2.5	0.5	0.5	0.5
Cd	0.5644	0.8921	1.1907	1.2694	1.0425	0.7298
lit. Cd	0.5623	0.9024	1.1989	1.2356	1.0524	0.7513
% diff.	0.36%	1.15%	0.69%	2.74%	0.94%	2.86%

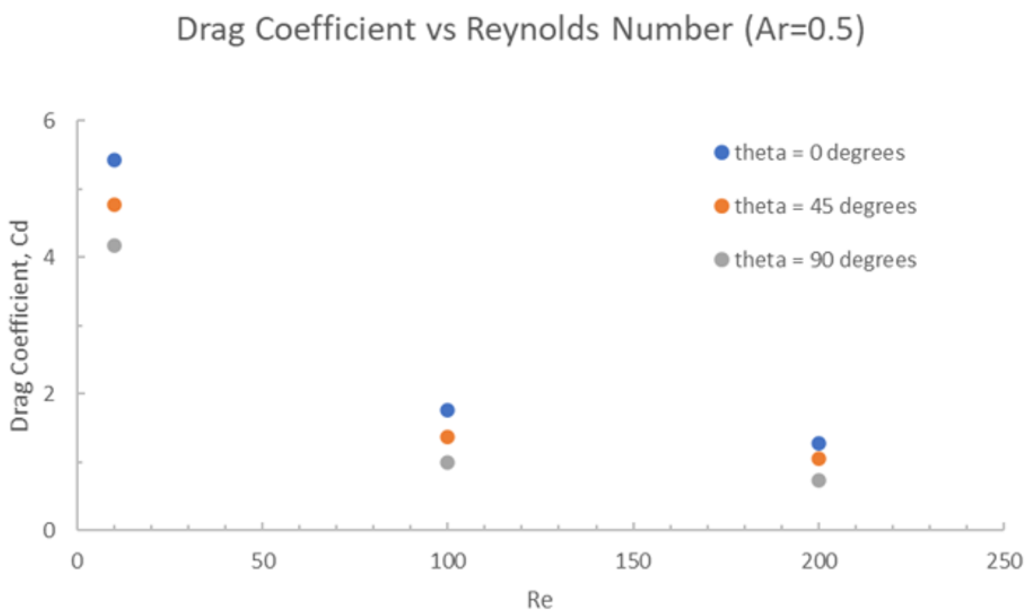
* C. Ke, S. Shu, H. Zhang, H. Yuan and D. Yang, "On the drag coefficient and averaged Nusselt number of an ellipsoidal particle in a fluid," Powder Technology, vol. 325, pp. 134-144, 2018.

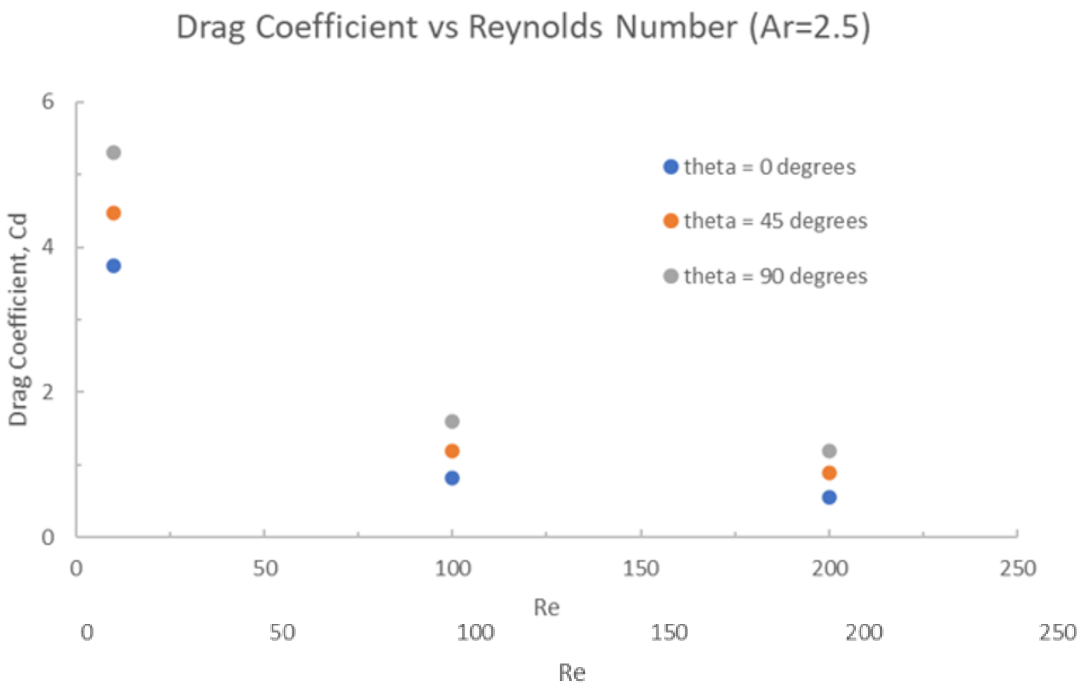
Results: Drag of an ellipsoid – continue



Drag coefficient (Cd) vs. Aspect Ratio (AR) at Re=100

Results: Drag of an ellipsoid – continue

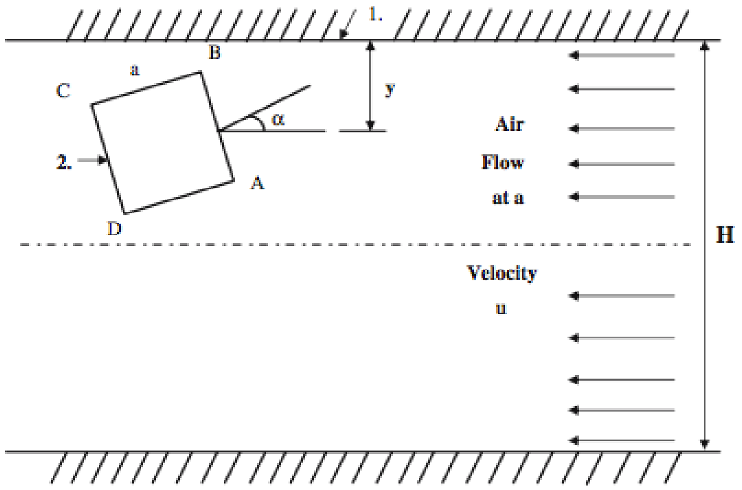




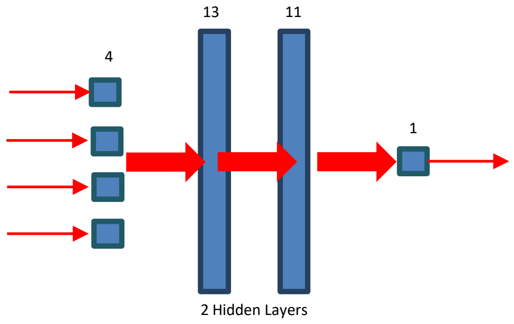
Drag coefficient of an ellipsoid at different Reynolds number (Re) for ab oblate (Ar=0.5) and a prolate (AR=2.5)

Use of TensorFlow to develop ANN model

- As a testing case, a 4-layer ANN model has been developed in TensorFlow using the wind tunnel experimental results of Chakrabary and Brahma (*)
  - Input parameters: Reynolds number, Height-ratio, Attack angle, and Blockage ratio
  - Output parameter: drag coefficient



Experimental setup (*)

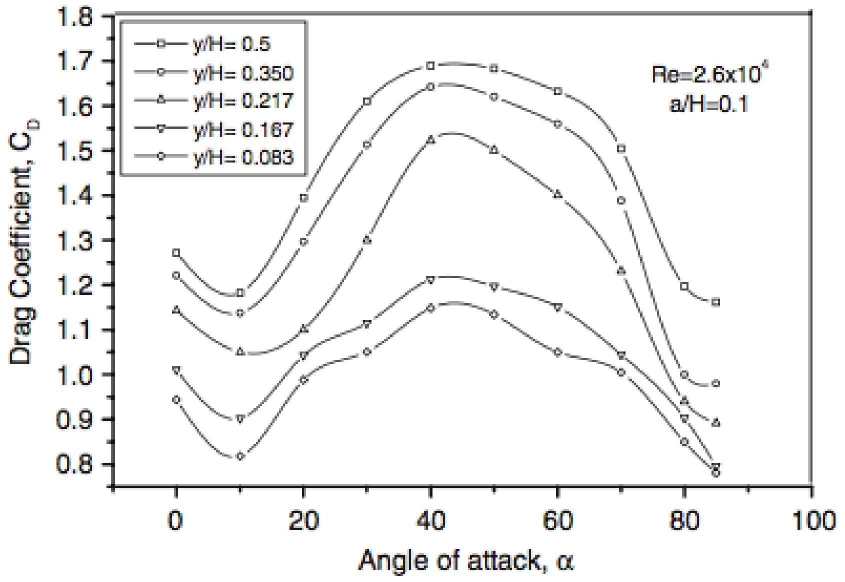


Structure of the ANN model

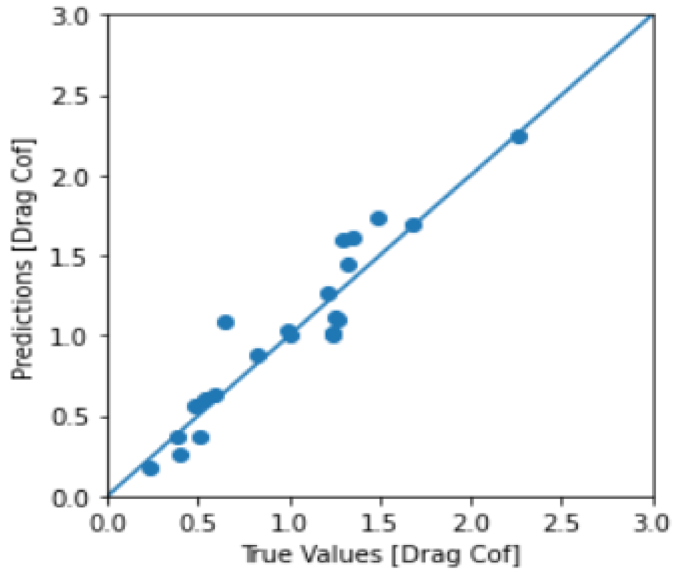
*Chakrabarty D, Brahma R (2008) Effect of wall proximity in fluid flow and heat transfer from a rectangular prism placed inside a wind tunnel, J Heat and Mass Transfer 51:736-746

Use of TensorFlow to develop ANN model

- 100 data points are taken from the graphs of Chakrabary and Brahma paper and separated into two portions, 80% to train, 20% to test the ANN model accuracy.



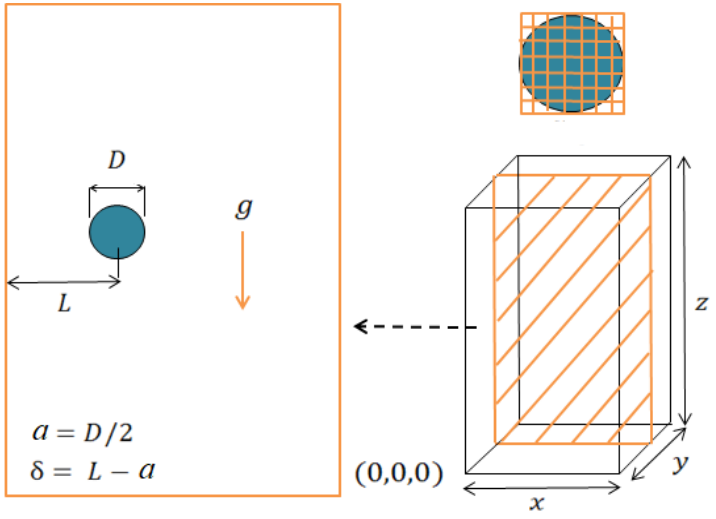
Variation of drag coefficient with angle of attack at different height-ratios of a square prism (Ref.1)

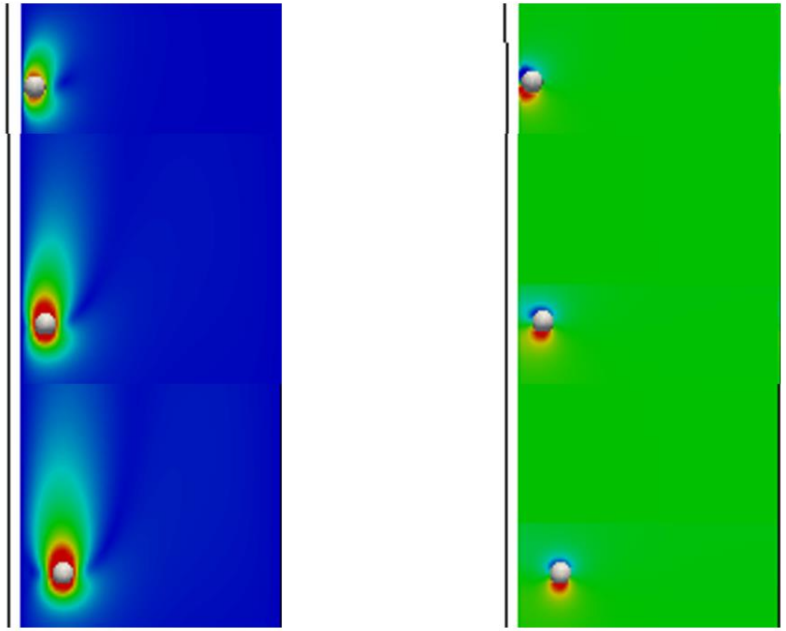


Model of predicted Drag Coefficient vs. Experimental Drag Coefficient

Develop ANN model to predict the wall effect to particle drag

- Input parameters
  - Reynolds number of translation
  - Reynolds number of rotation
  - Distance to the wall
  - Particle shape (to be included in the future)
- Output
  - Drag coefficient
  - Lift coefficient

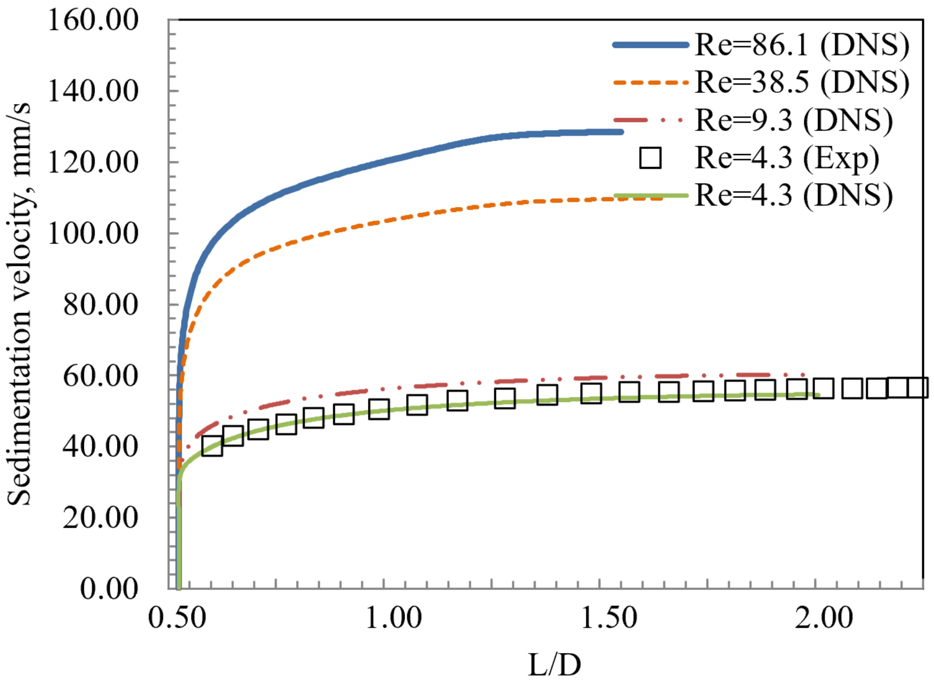


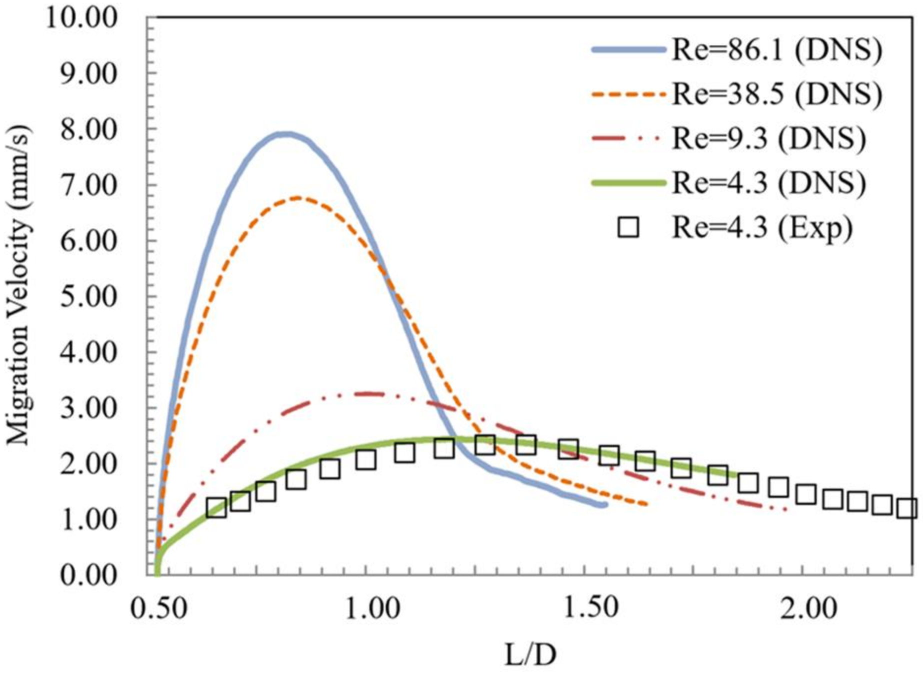


Velocity (left) and pressure (right) distributions around a moving sphere at different Reynolds numbers

Develop ANN model to predict the wall effect to particle drag – continue

- Wall effect to the motion of a particle
  - Simulation results of sedimentation and migration velocities at different Reynolds numbers were compared to the experimental work of Takemura et al.(*) and good agreements were found.

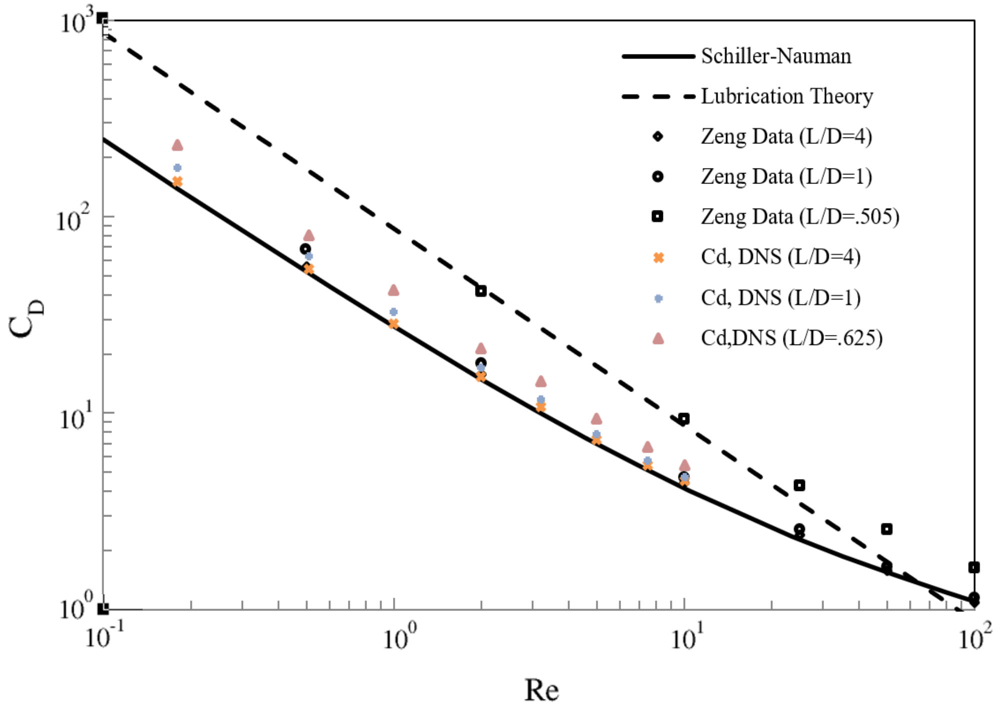




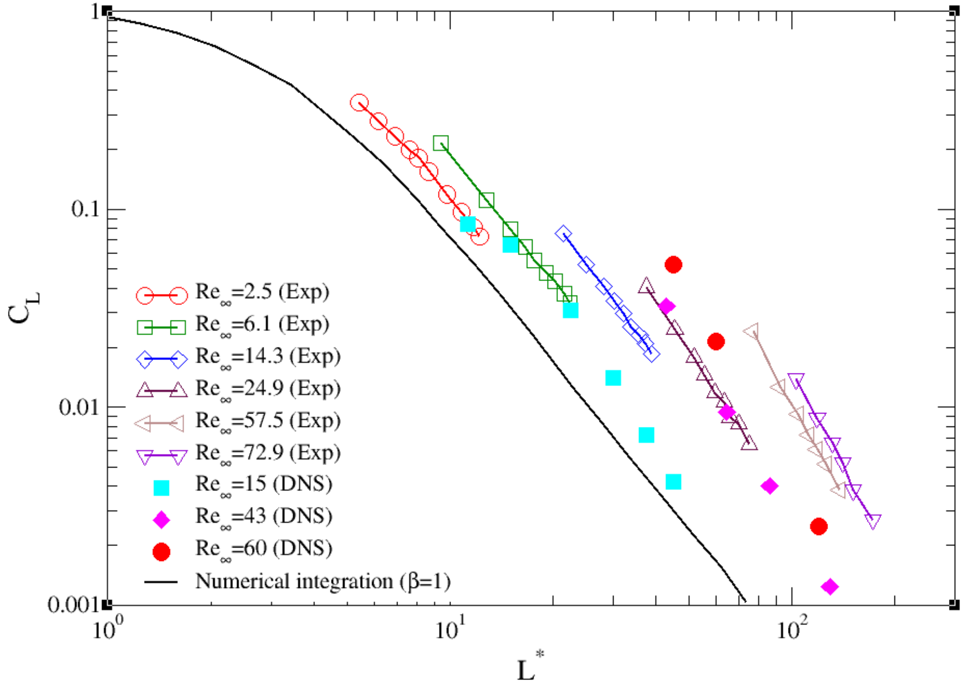
* Takemura, F. and Magnaudet, J., 2003, "The transverse force on clean and contaminated bubbles rising near a vertical wall at moderate Reynolds number." *Journal of Fluid Mechanics*, **495**, pp.235-253.

Develop ANN model to predict the wall effect to particle drag – continue

- **Wall effect to the drag and lift of a particle**



Drag Coefficient versus Reynolds Number. Our DNS results and simulation results of Zeng et al*.



The wall-induced lift coefficient C_L of a rigid sphere, experimental data from Takemura et al. and the lift coefficient for Stokesian flow.

* Zeng, L., Balachandar, S. and Fischer, P., 2005, “Wall-induced forces on a rigid sphere at finite Reynolds number,” Journal of Fluid Mechanics, 536, pp. 1-25

- **Students supported by this project:**
  - **Graduate students: Miguel Cortina, Joshua Corner, Daniel Hinojosa**
  - **Undergraduate student: Andres Leon Islas**

Thank you!

- **Acknowledgment:** “This material is based upon work supported by the Department of Energy Award Number DE-FE0031894.”