

UNSUPERVISED LEARNING BASED INTERACTION FORCE **MODEL FOR NONSPHERICAL PARTICLES IN INCOMPRESSIBLE FLOWS**

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- Project Description and Objectives
- Project Update
- Preparing Project for the Next Steps
- Concluding Remarks

Outline

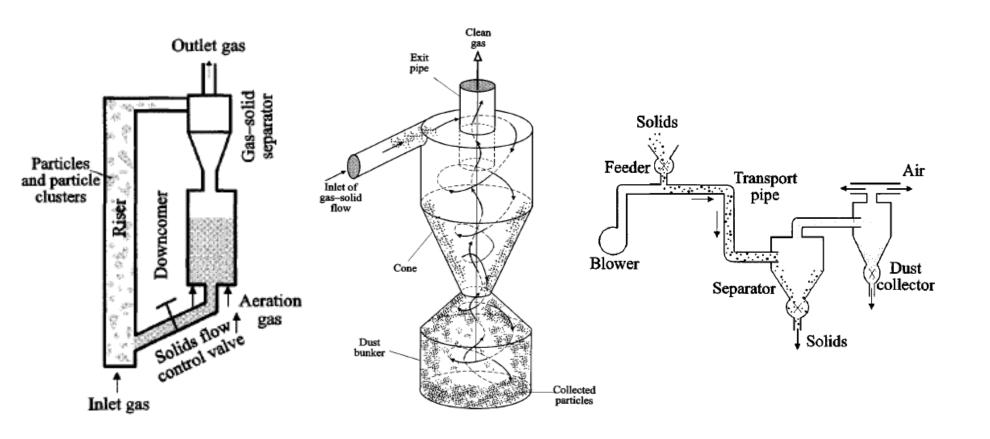
(a) 70

y

60

Gas-Solid system

Interaction forces



> Inputs (Reynolds Number Solid Fraction, Neighboring

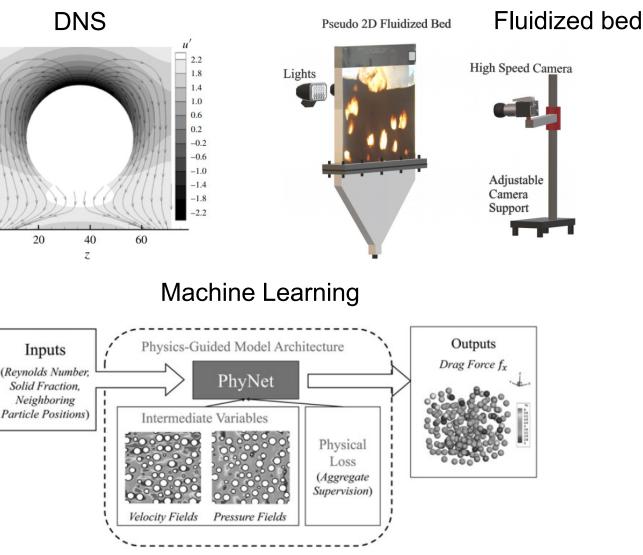
Liang-Shih Fan, Principles of gas-solid flows (1999)

Qiang Zhou et al., Journal of Fluid Mechanics, 765 (2015)

Cesar Martin Venier et al. International Journal of Numerical Methods for Heat and Fluid Flow (2019)

Long He et al., Powder Technology 345 (2019)

Project Description and Objectives





Project Description and Objectives

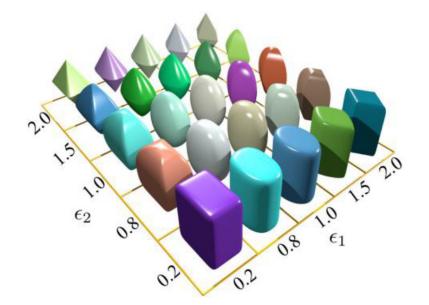
Non-spherical particle

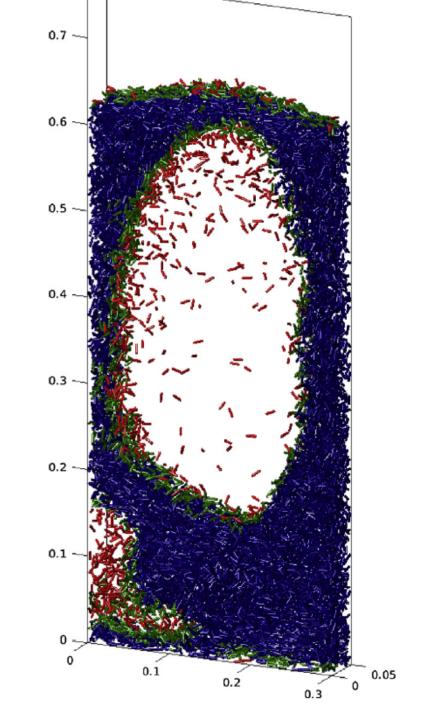
- Difficult to define the geometrical factors sphericity, flatness, elongation and circularity, etc.
- Data for the interaction force between nonspherical particles and the fluids are limited.
- Correlation may be highly-nonlinearity.

Objectives

- Developing a neural network-based force model for a diversity of non-spherical particles.
- From low O(1) to moderate O(100) Reynolds number.
- From low to high volume fraction.

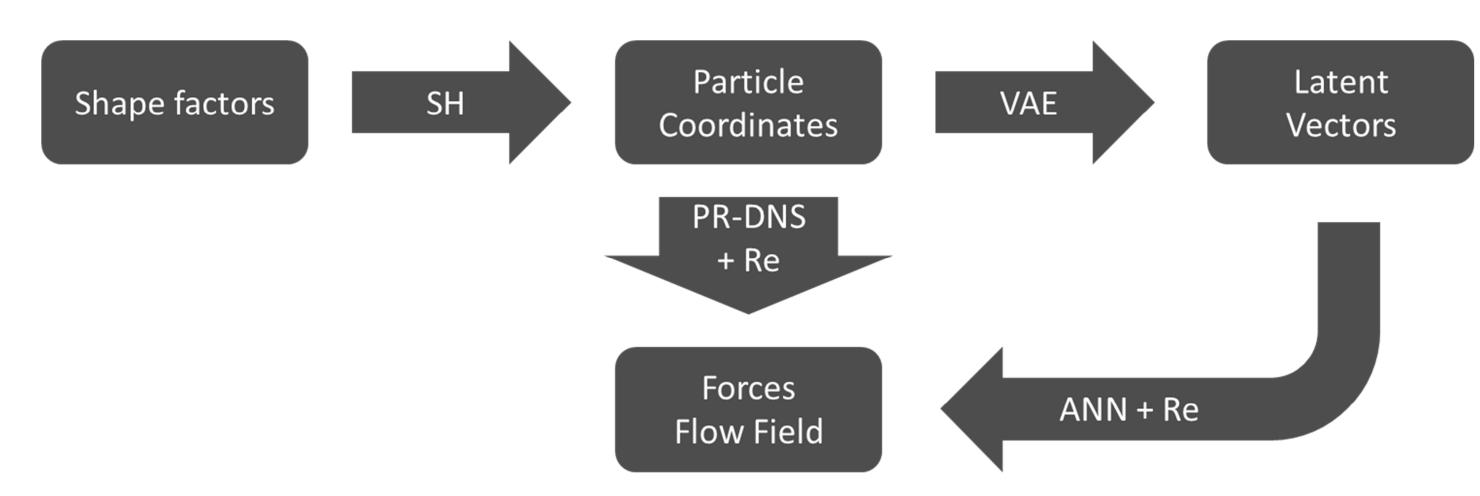
Shiwei Zhao et al., Int J Numer Anal Methods Geomech., 43 (2019) Vinay V. Mahajan et al., Chemical Engineering Science, 192 (2018)











- SH : Spherical Harmonic method
- VAE : Variational Auto-Encoder
- **PR-DNS** : Particle Resolved Direct Numerical Simulation
- ANN : Artificial Neural Network

Project Description and Objectives

The Ohio State University

Tasks	Year 1				Year 2				Year 3			
	10/20	1/21	4/21	7/21	10/21	1/22	4/22	7/22	10/22	1/23	4/23	7/23
PR-DNS development												
Particles Generation & VAE												
Low Re data Collection												
High Re data Collection												
MLP Training												

Current stage

Preliminary tests



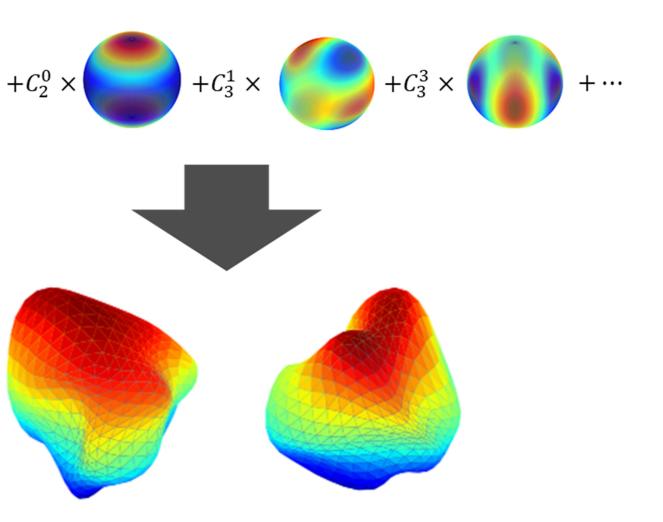
Spherical Harmonic Method

• Spherical harmonic functions

$$\begin{pmatrix} x(\theta,\phi) \\ y(\theta,\phi) \\ z(\theta,\phi) \end{pmatrix} = \begin{pmatrix} \sum_{l=1}^{l_{max}} \sum_{m=-l}^{l} C_{x,l}^{m} Y_{l}^{m}(\theta,\phi) \\ \sum_{l=1}^{l_{max}} \sum_{m=-l}^{l} C_{y,l}^{m} Y_{l}^{m}(\theta,\phi) \\ \sum_{l=1}^{l_{max}} \sum_{m=-l}^{l} C_{z,l}^{m} Y_{l}^{m}(\theta,\phi) \end{pmatrix}$$

 $C_1^0 \times$

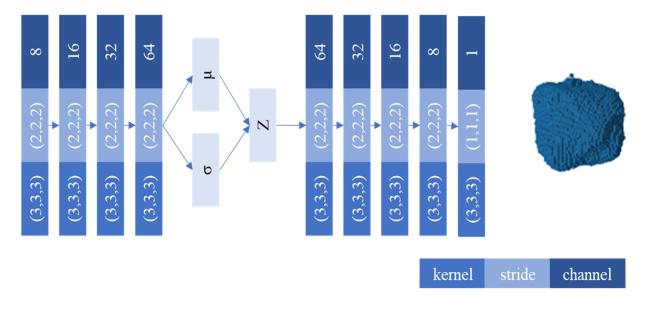
- Few shape factors
 - d : spherical descriptor, roughness
 - *EI* : elongation index
 - *FI* : flatness index
- Randomness



Variational Auto-Encoder

- Voxel input
- Deep CNN layers with ELUs
- Latent vectors with 128 dimension
- 1,200 datasets to train, 400 datasets to validate
- Less than 1% reconstruction error
- For the DNS, new 5,200 particles were generated (error < 1%)



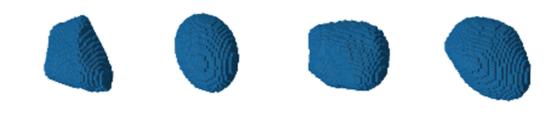


Training Input



Decoded Output



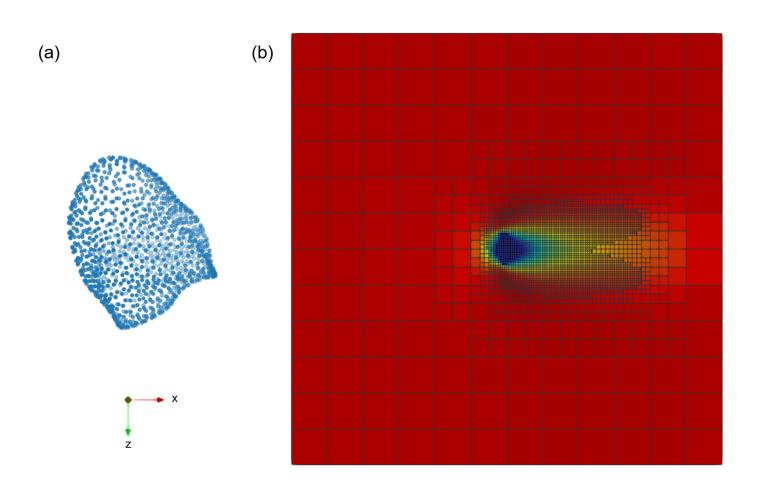


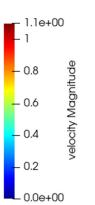


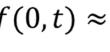


PR-DNS Development

- Simplified Spheric Gas Kinetic Scheme (GKS)
- Immersed boundary Method (IBM) ${}^{\bullet}$
- Adaptive Mesh Refinement (AMR) •



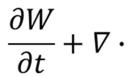




$$\begin{split} \frac{\partial f}{\partial t} + v \cdot \nabla f &= \frac{g - f}{\tau} \\ f &= g - \tau \frac{Df}{Dt} = g - \tau \frac{D}{Dt} (g + f^{neq}) \\ f(0,t) &\approx g(0,t) - \frac{\tau}{\delta t} (g(0,t) - g(-v\delta t, t - \delta t)) \\ F &= \int f(0,t) v \Xi dv , \qquad \Xi = \begin{pmatrix} 1 \\ v \end{pmatrix} \end{split}$$

$$=\begin{cases} \frac{\rho}{4\pi}\\ 0, \end{cases}$$

g



$$if (u - v)^2 = c^2$$

otherwise

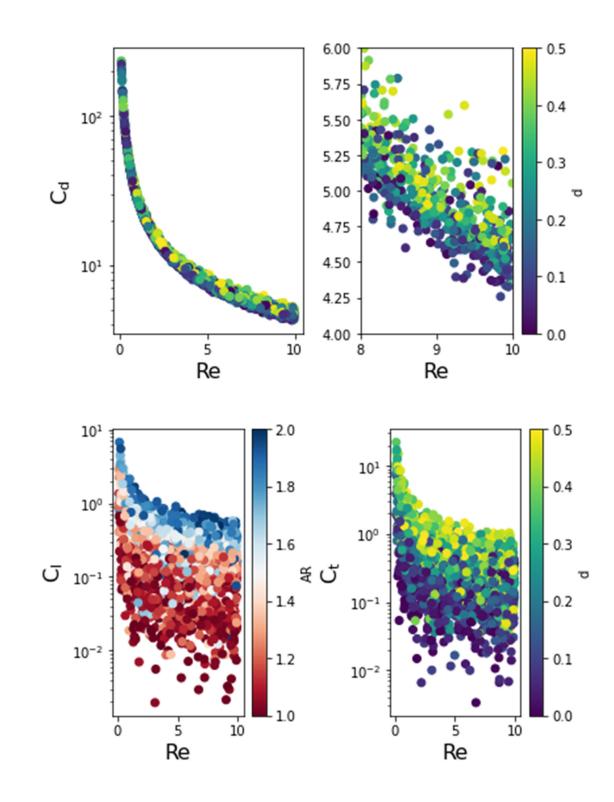
$$F = 0, \qquad W = \begin{pmatrix} \rho \\ \rho u \end{pmatrix}$$

PR-DNS Results

- Re = 0.1~10
- 5,200 datasets in low Re regime
- Show the typical $\operatorname{Re-}C_D$ trend
- MSEs for drag, lift, torque coefficients 380, 0.15, 0.61, respectively
- C_d and C_t depend on d
- C_l depends on AR

$$C_d = \frac{24}{Re} + \frac{4}{\sqrt{Re}} + 0.4 \tag{1}$$

A.A. Kaskas, dissertation (1970)



Project Update

10

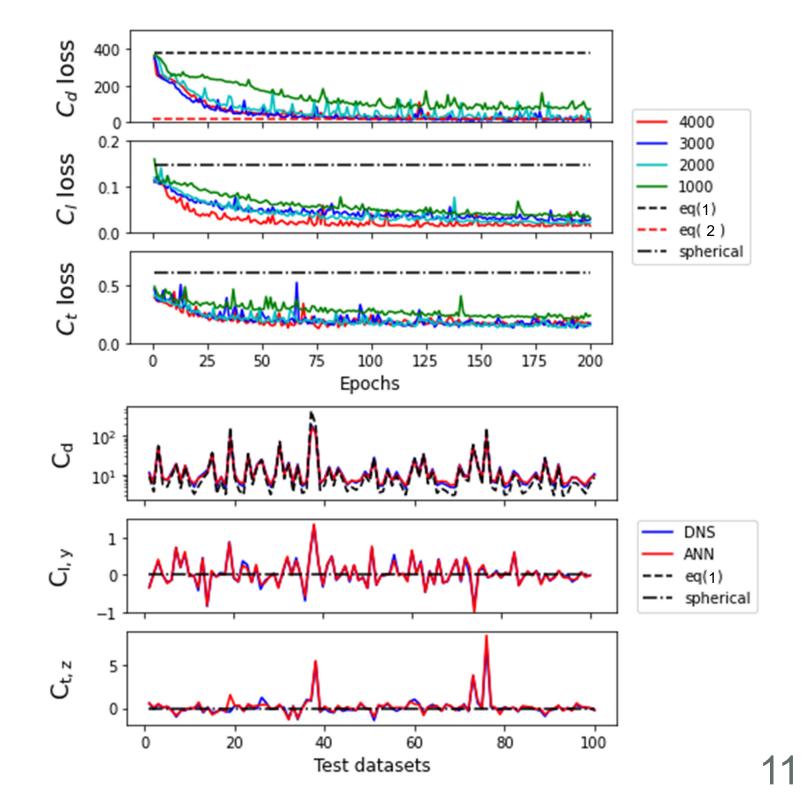
ANN results

- 1,000~4,000 datasets for training and 600 datasets for validation and evaluation
- Two hidden layers with 32, 8 nodes
- MSEs for drag, lift, torque coefficients are reduced to 3%, 7%, 25%, respectively
- MSEs for eq (2) is 21.8 which is comparable to the ANN result (12.7±2.7)

$$C_{d} = \frac{24}{ReK_{1}} \{1 + 0.1118(ReK_{1}K_{2})^{0.6567}\} + \frac{0.4305K_{2}}{1 + \frac{3305}{ReK_{1}K_{2}}}$$
$$K_{1} = \left[\left(\frac{d_{n}}{3D_{eq}}\right) + 2/3\psi^{-0.5}\right]^{-1}, K_{2} = 10^{1.8148(-log\psi)^{0.5743}}$$

(2)

G.H. Gamer, Powder Technology. 77 (1993)





ANN results

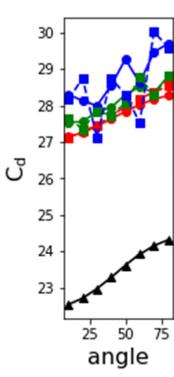
- 3 particles (*d* = 0, 0.25, 0.5)
- More accurate prediction on the lifting force and torque coefficients.

$$C_{d} = \frac{a_{1}}{Re^{a_{2}}} + \frac{a_{3}}{Re^{a_{4}}} + \left(\frac{a_{5}}{Re^{a_{6}}} + \frac{a_{7}}{Re^{a_{8}}} - \frac{a_{1}}{Re^{a_{2}}} - \frac{a_{3}}{Re^{a_{4}}}\right) sin^{a_{9}}(\theta)$$

$$C_{l} = \left(\frac{b_{1}}{Re^{b_{2}}} + \frac{b_{3}}{Re^{b_{4}}}\right) sin^{b_{5}+b_{6}Re^{b_{7}}}(\theta) cos^{b_{8}+b_{9}Re^{b_{10}}}(\theta)$$
(3)

$$C_{t} = \left(\frac{c_{1}}{Re^{c_{2}}} + \frac{c_{3}}{Re^{c_{4}}}\right) sin^{c_{5} + c_{6}Re^{c_{7}}}(\theta) cos^{c_{8} + c_{9}Re^{c_{10}}}(\theta)$$

M. Zastawny, el al., International Journal of Multiphase Flow. 39 (2012)



Project Update

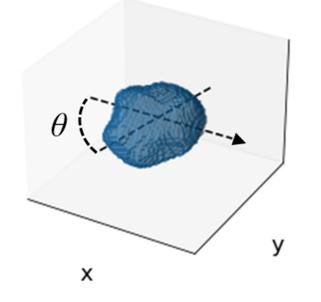
z

50

angle

25

75



0.8

0.7

0.6

0.5

0,0

0.3

0.2

25 50 75

angle

 \overline{O}





Market Benefits/Assessment

MFiX only provides the drag force model for spherical particles Industrial CFD application requires the comprehensive interaction force model

Technology-to-Market Path

This project will provide the interaction force model including lifting force and torque which can be implemented in MFiX

Data for the higher Re regime will be collected

Multi-particle system will be studied to predict the interactive force for the dilute and dense system.

Preparing Project for Next Steps



- This study provide the interaction force model for the non-spherical particle \bullet which is practical in industry.
- In MFiX-DEM, the NN based force can be implemented to obtain the ${\bullet}$ interaction forces.
- Wider range of Re will be studied and the neighboring effect will be included \bullet in the future work for the multi-particle system.

Concluding Remarks

Acknowledgment: "This material is based upon work supported by the Department of Energy Award Number DE-FE0031905."

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Acknowledgement