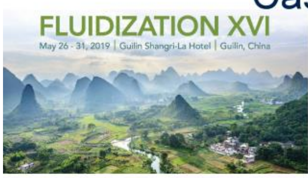
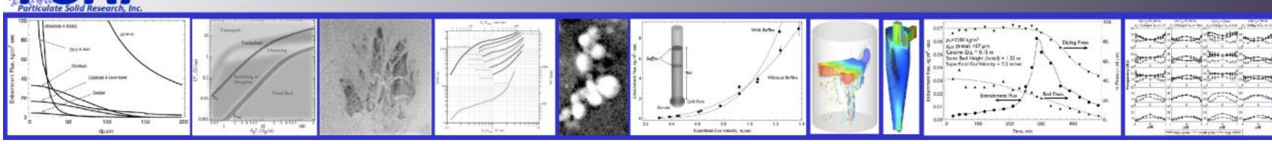
Review of Fluid-Particle Drag Experimental Validation

Casey LaMarche, Ben Freireich, Ray Cocco



Particulate Solid Research, Inc.

PSRI Applying the Fundamentals



Outline

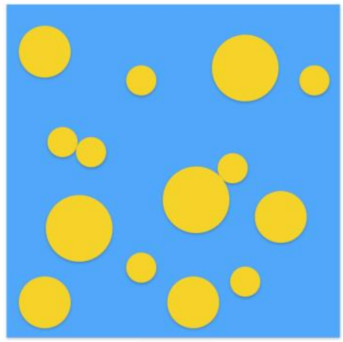
- Problem of interest — What's the question?
- Methods of approach — How has it been answered?
- Verification and Validations — Are the answers any good?
- Summary — So what?

Spectrum of Interactions

Single Particle

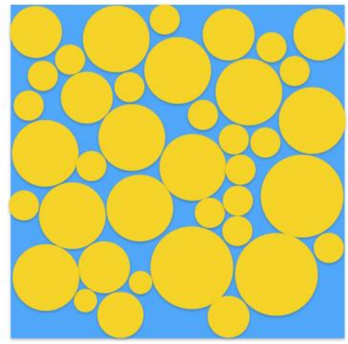
Drag Coefficient

Intermediate?



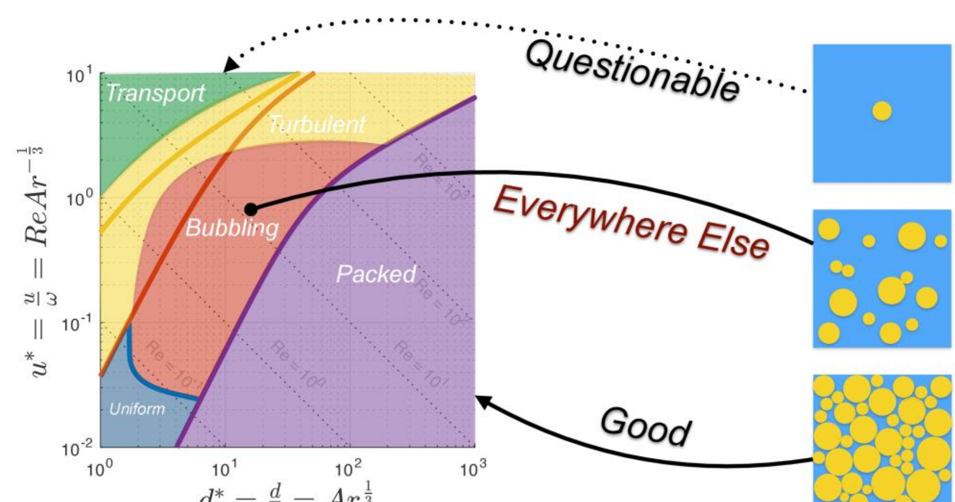
How to transition?

Packed Bed



Pressure Drop

Where Do We Care?



Analytical Single Particle Drag

Stokes/Creeping Flow

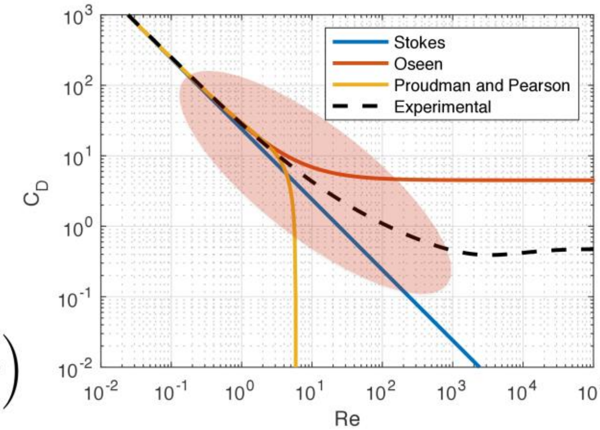
$$C_{\text{Stokes}} = \frac{24}{Re}$$

Perturbed

$$C_{\text{Oseen}} = \frac{24}{Re}\left(1 + \frac{3}{16}Re\right)$$

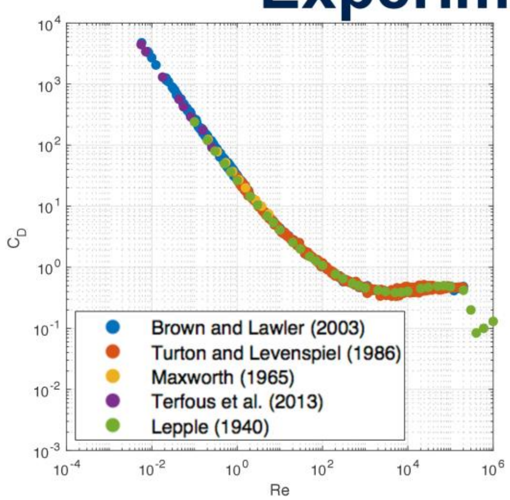
Perturbed²

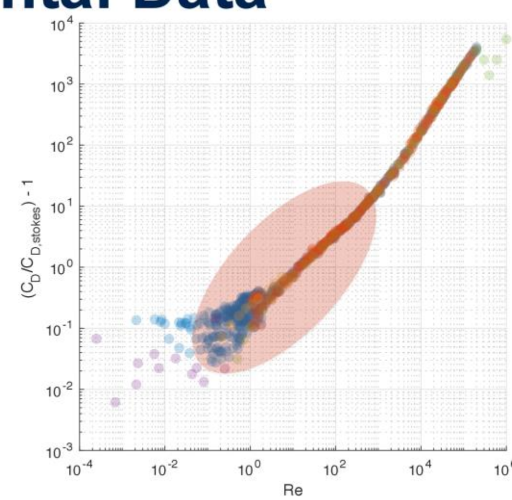
$$C_{\text{P\&P}} = \frac{24}{Re}\left(1 + \frac{3}{16}Re - \frac{9}{160}Re^2 \ln Re\right)$$



Accurate only for Re < 1

Experimental Data





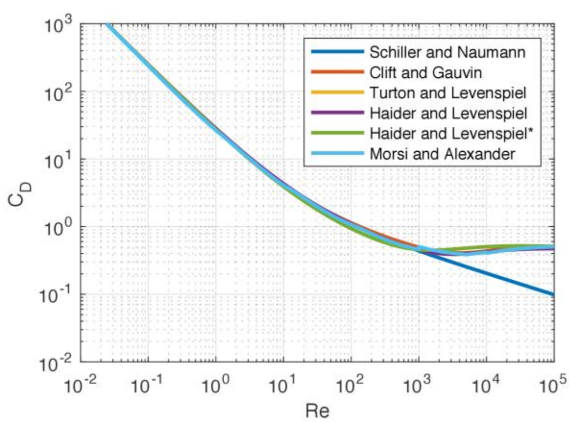
Lots of scatter for Re < 10

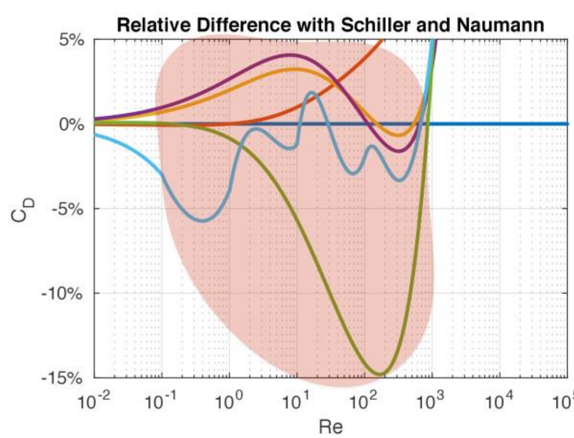
Experimental Correlations

$$C_D = \frac{24}{Re}\left(1 + ARe^{B}\right) + \frac{C}{1 + DRe^{-E}}$$

	A	B	C	D	E
Schiller and Naumann	0.1500	0.6870	0		
Clift and Gauvin	0.1500	0.6970	0.4200	42500.00	1.16
Turton and Levenspiel	0.1730	0.6570	0.4130	16300.00	1.09
Haider and Levenspiel	0.1806	0.6459	0.4251	6880.95	1
Haider and Levenspiel*	0.1402	0.6530	0.4610	2682.50	1

Experimental Correlations





Is single particle known?

Experimental Correlations

$$C_D = \frac{A}{Re}\frac{1-\varepsilon}{\varepsilon^2} + \frac{B}{\varepsilon^2}$$

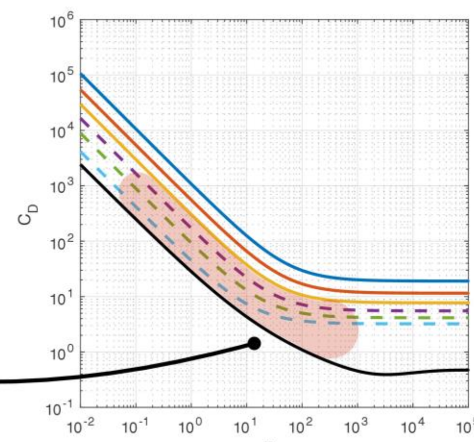
	A	B
Darcy	$1.33 d^2 \kappa^{-1}$	0
Carman-Kozeny	240	0
Ergun	200	2.33
MacDonald et al.	240	2.40
MacDonald et al.*	240	5.28

S.A. Morsi and A.J. Alexander, J. Fluid Mech., 55 (1972) 193

Typical Shape

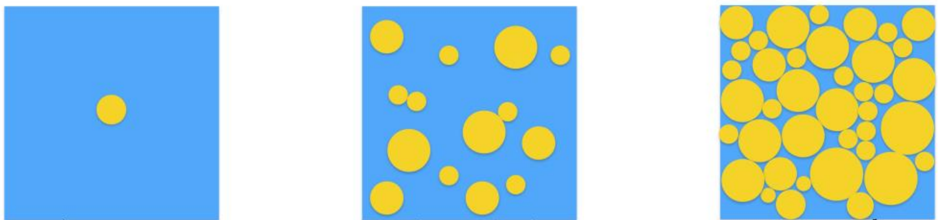
Ergun for 0.10 < ε < 0.44

Haider and Levenspiel



Meaningful only for ε > 0.4

What About the Middle?



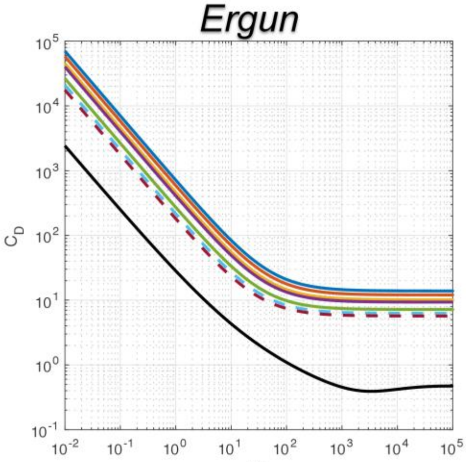
$C_D = C_{D,\text{single}}(Re) f_1(\varepsilon)$

$C_D = C_{D,\text{packed}}(Re, \varepsilon) f_2(\varepsilon)$

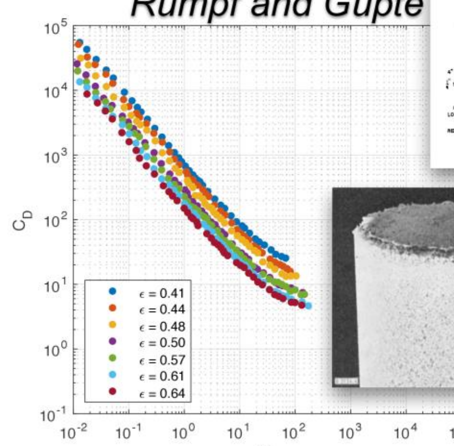
Direct?

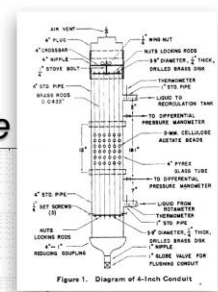
Fixed Array Experiments

Ergun



Rumpf and Gupte

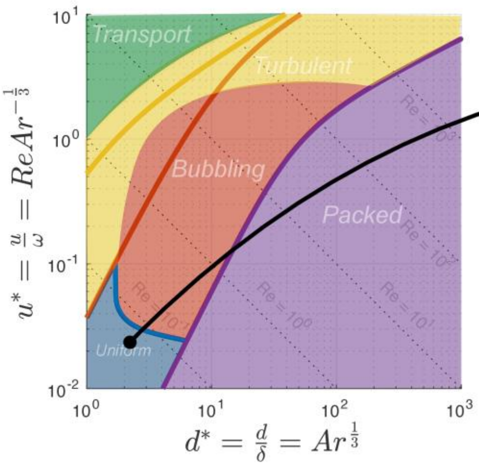




Happel Epstein (1954)

Rumpf and Gupte (1971)

Bed Expansion Experiments



- *Uniformly Fluidize*

Only Here — **Severe Limitation**

- *Force Balance*

$$F_D = F_g - F_b$$

- *Assume Voidage Multiplier*

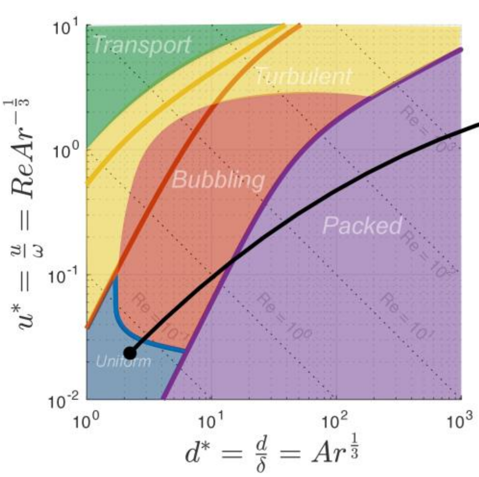
$$F_D = F_{D,\text{single}} f(\varepsilon)$$

Must Assume $C_{D,\text{single}}$

- *Experimentally Determine*

$$f(\varepsilon) = \frac{4}{3}\frac{Ar}{Re} C_{D,\text{single}}^{-1} \approx \varepsilon^{-n}$$

Hindered Settling Experiments



- *Uniformly Fluidize*

Only Here — **Severe Limitation**

- *U = 0 then watch surface drop*

$$U_T = U_{\text{surface}}$$

- *Assume Voidage Multiplier*

$$U_T = U_{T,\text{single}} f(\varepsilon)$$

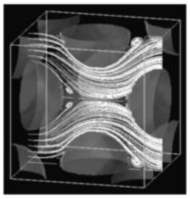
Must Assume $U_{T,\text{single}}$

- *Experimentally Determine*

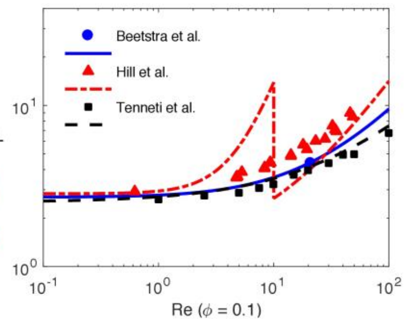
$$f(\varepsilon) = \frac{U_T}{U_{T,\text{single}}} \approx \varepsilon^{-n}$$

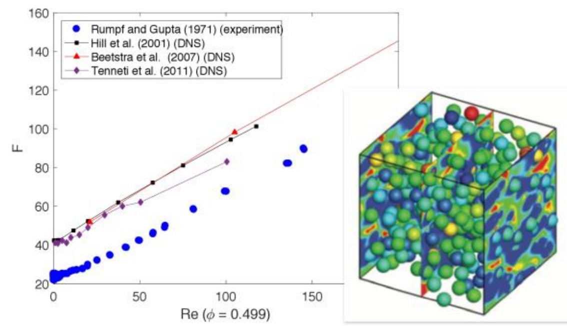
Direct Numerical Simulation

DNS over predicts experiments

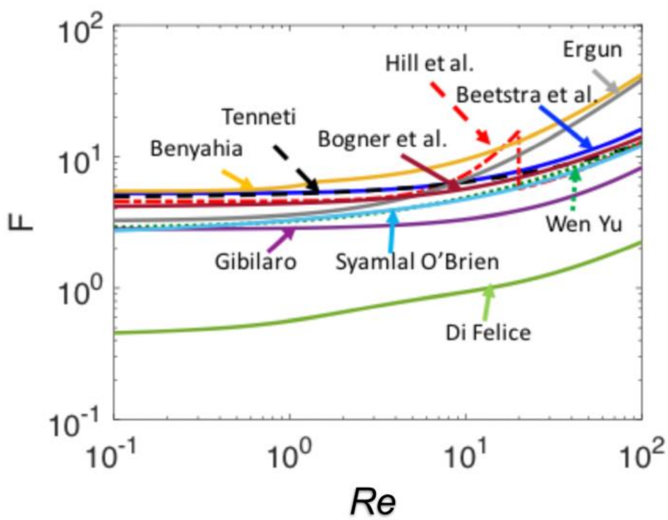


Very limited domain size





Many Common Methods



Large variation

Summary

- Existing drag measurements are limited to:
  - Single particle (dilute)
  - Packed bed (dense)
  - Uniform fluidization
  - Contrived fixed arrays
- Interpolation requires single particle drag law assumption
- Heterogeneous drag prediction (filtering and EMMS) assumes a homogeneous model

There is still space for work here

Acknowledgement

- PSRI Staff
  - Cory Jarvis
  - Bryan Harrison
  - Ryan Foy
- PSRI Membership
  - Clay Sutton
  - Benjamin Amblard
  - Raj Singh

Questions?