ON THE DRAG COEFFICIENT OF NON-SPHERICAL PARTICLES

Gholamhossein Bagheri[1]
Costanza Bonadonna[1]
Irene Manzella[1]
Piero Pontelandolfo[2]
Pierre Vonlanthen[3]
Patrick Haas[2]

[1]Section of Earth Science, University of Geneva, Switzerland
[2]hepia/CMEFE, Geneva, Switzerland
[3]Institut des sciences de la Terre, Lausanne, 1015, Switzerland

Outline

- Introduction
- objectives
- Methodology
  - Analytical solutions ($Re \ll 1$)
  - Settling columns ($10 < Re < 10^3$)
  - Vertical wind tunnel ($10^3 < Re < 10^5$)
- Results

Particle size and shape

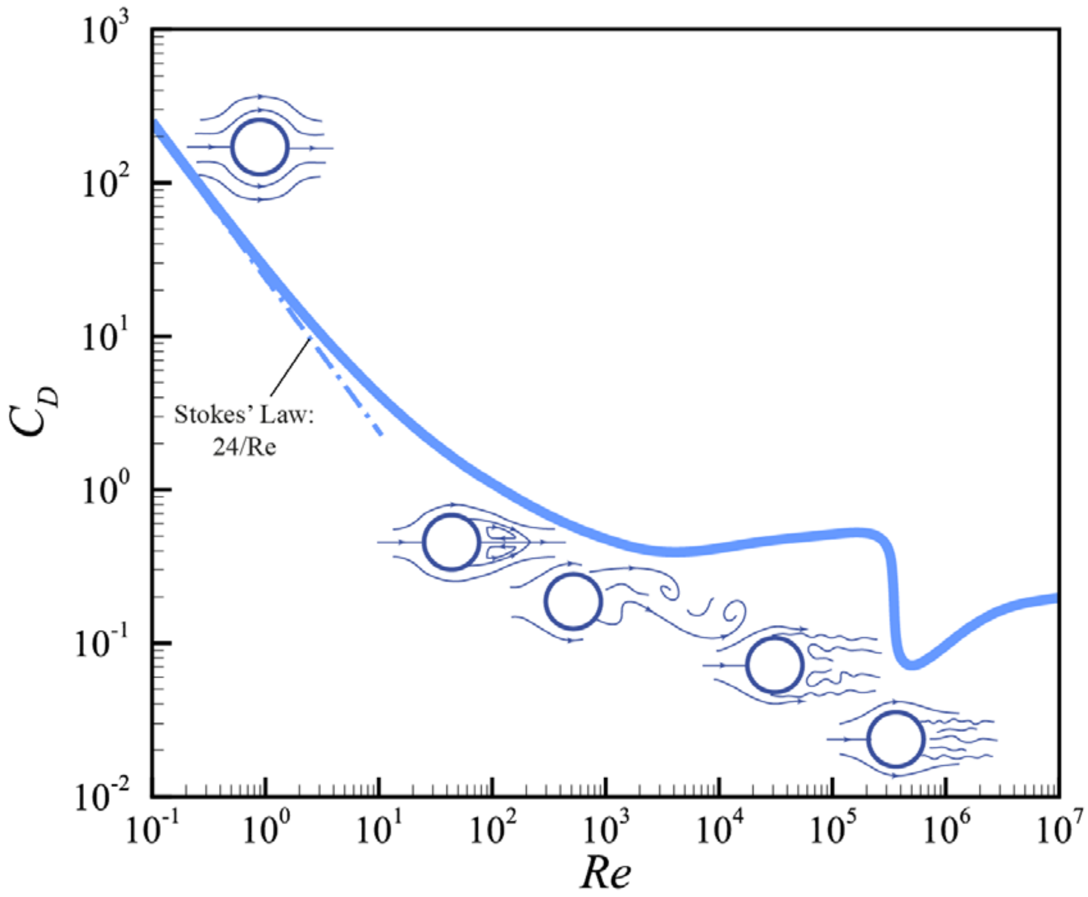
- The most important factors to determine particle velocity and its atmospheric residence time

- Particle terminal velocity can be evaluated if its drag coefficient (C_D) is known

Objectives

- Effect of particle shape and surface vesicularity on the drag force?
- Benchmarking existing models and shape descriptors
- Presenting a new model based on easy-to-measure shape descriptors

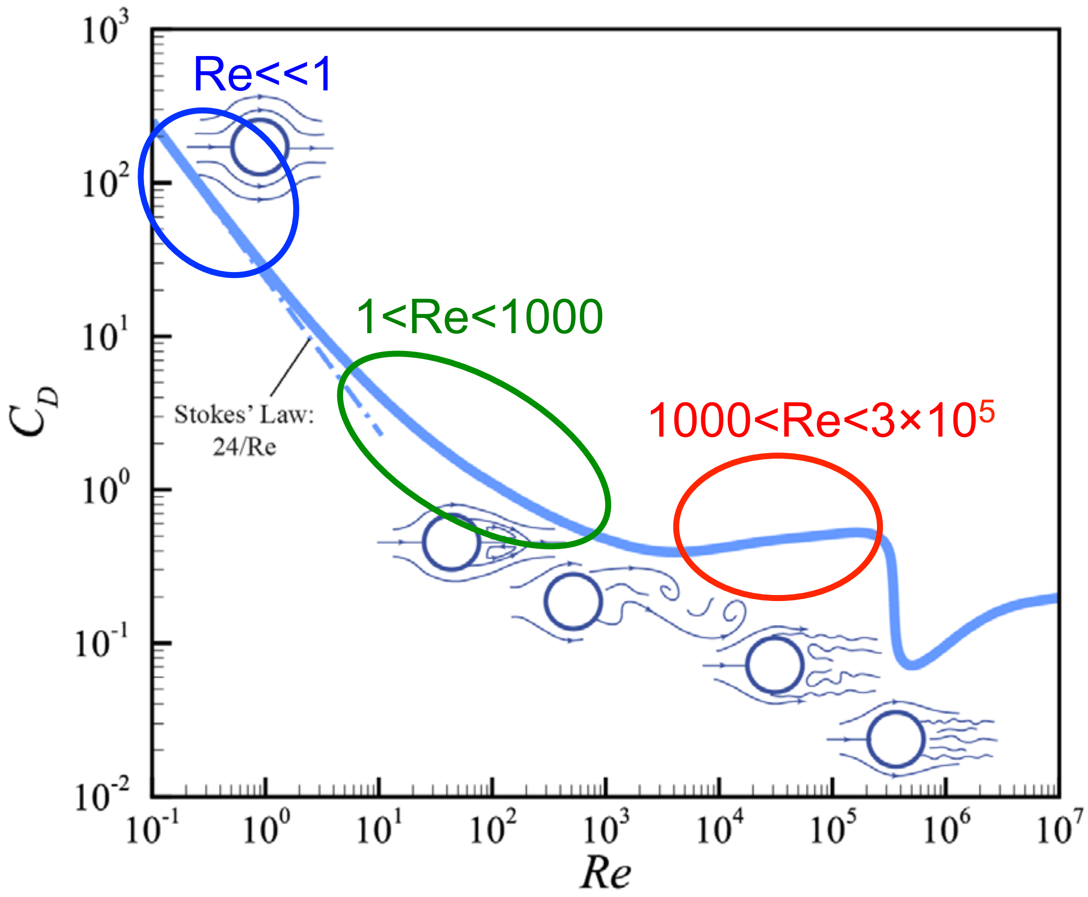
Sphere drag



10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
C_D
Stokes' Law:
24/Re
10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7
Re

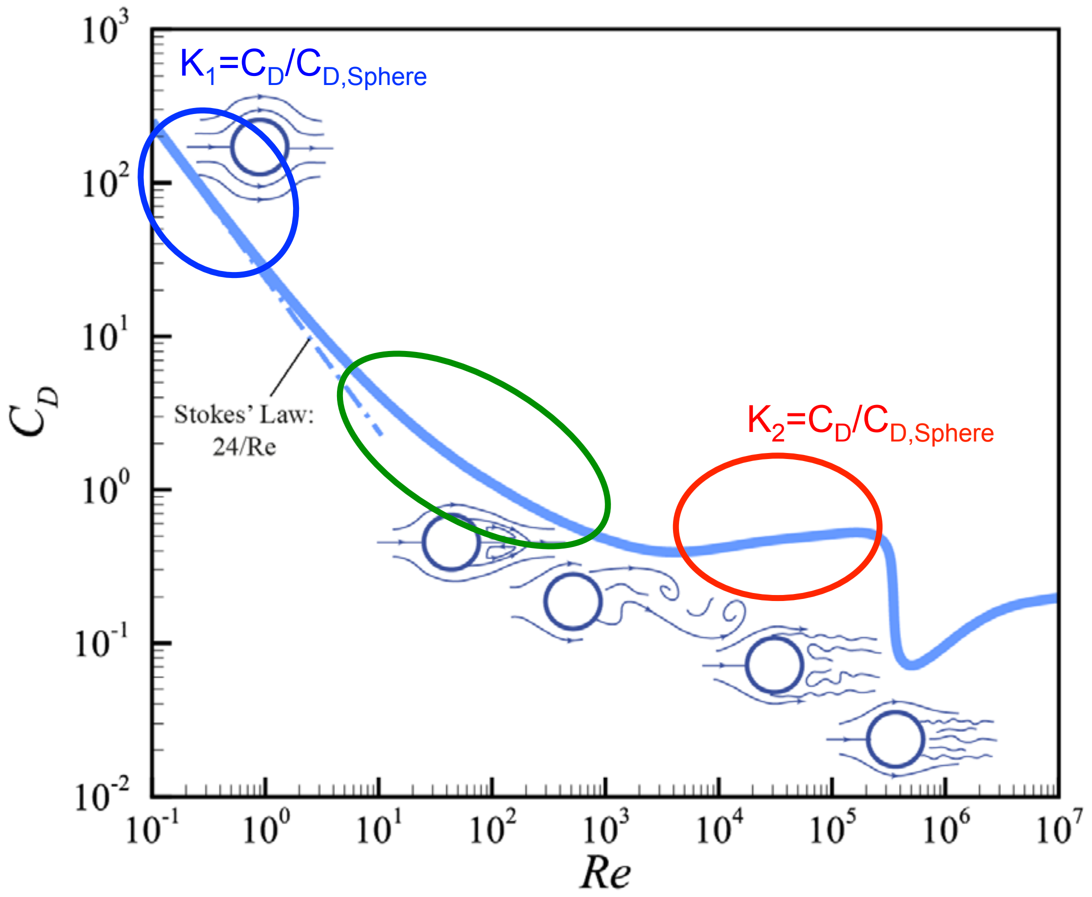
Approaching the problem

- C_D of any arbitrary shape particle at intermediate Re is a function of its C_D at very low Re and very high Re



Approaching the problem

- In other words: $C_D = f$ (Re, K_1, K_2) where K_1 and K_2 are functions of particles shape



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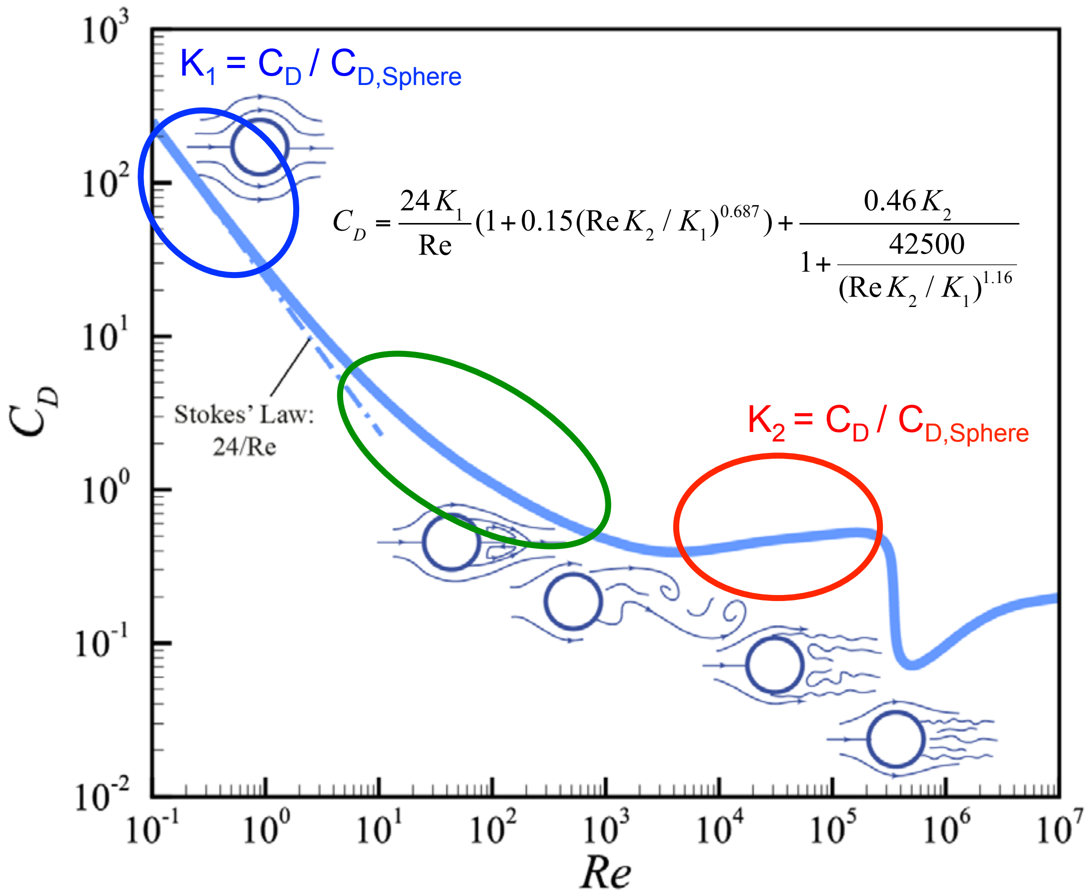
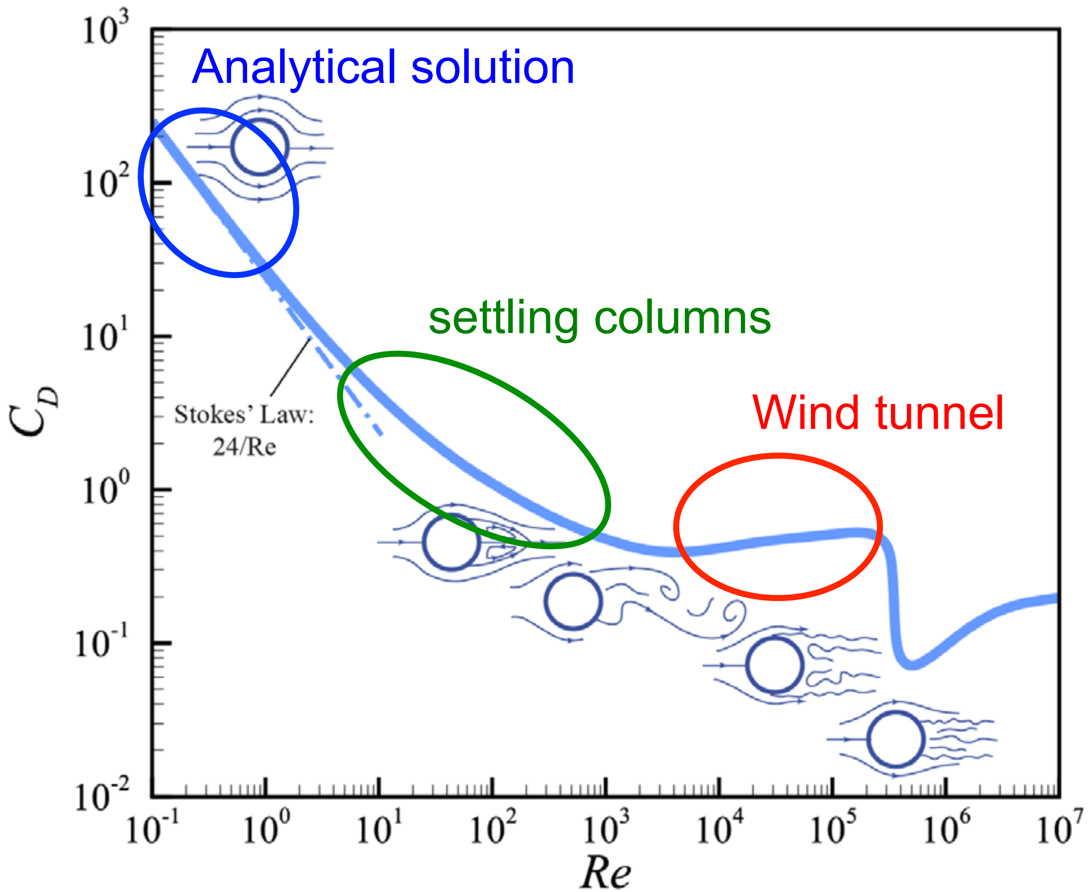
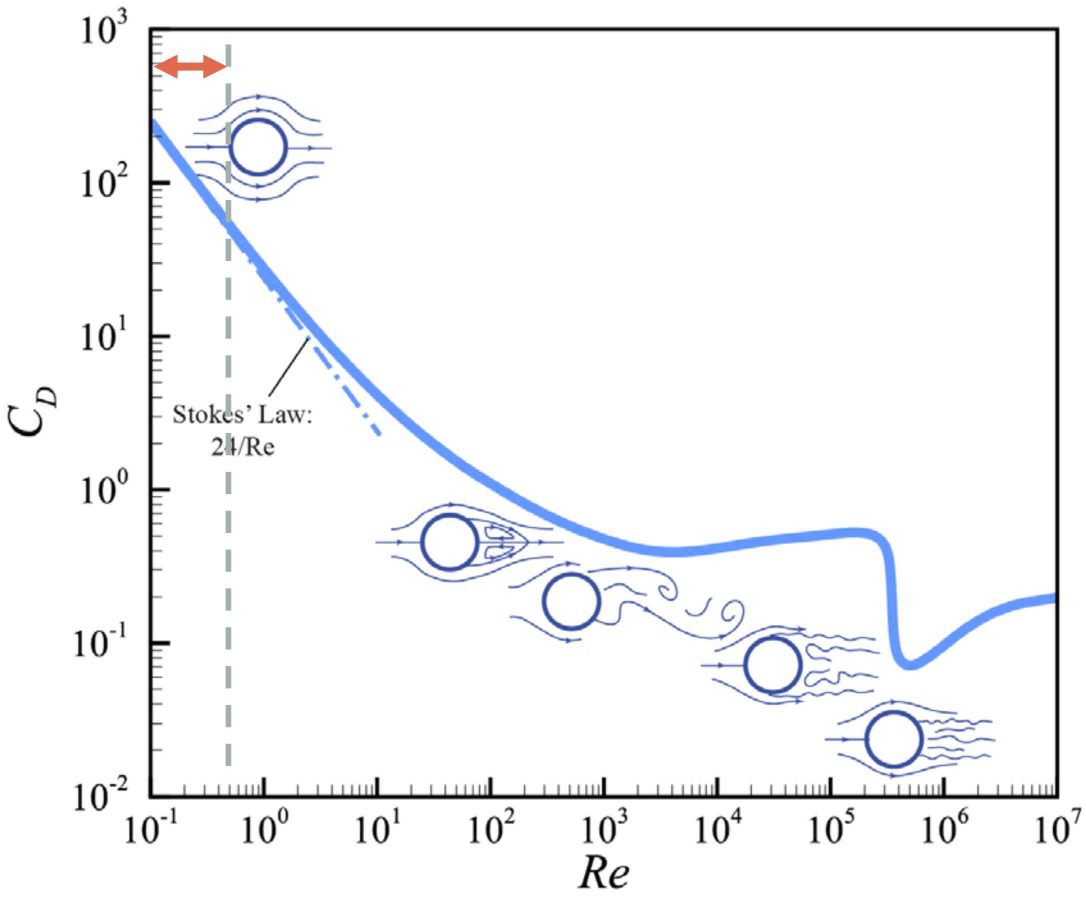


Approaching the problem



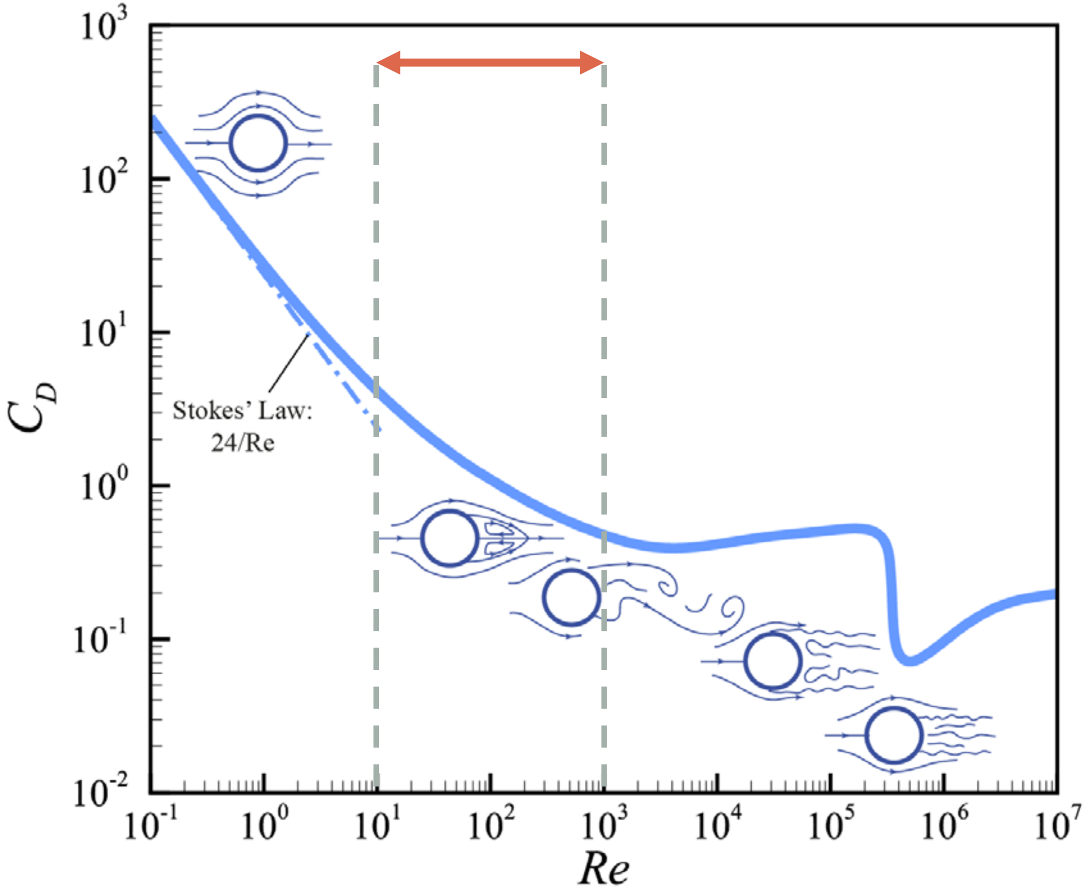
Re<<1

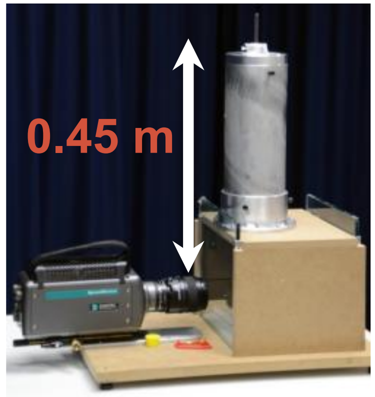
- Analytical solution exists only for sphere and ellipsoid



$10 < Re < 10^3$

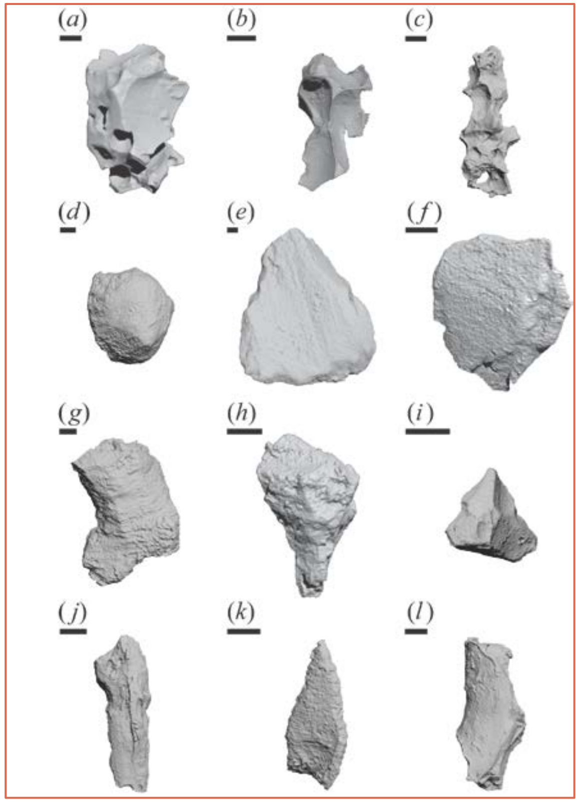
- Experiments in settling columns
- 117 particles (100 volcanic), 150 *μm*< diameter< 1 *mm*





Particle Characterization

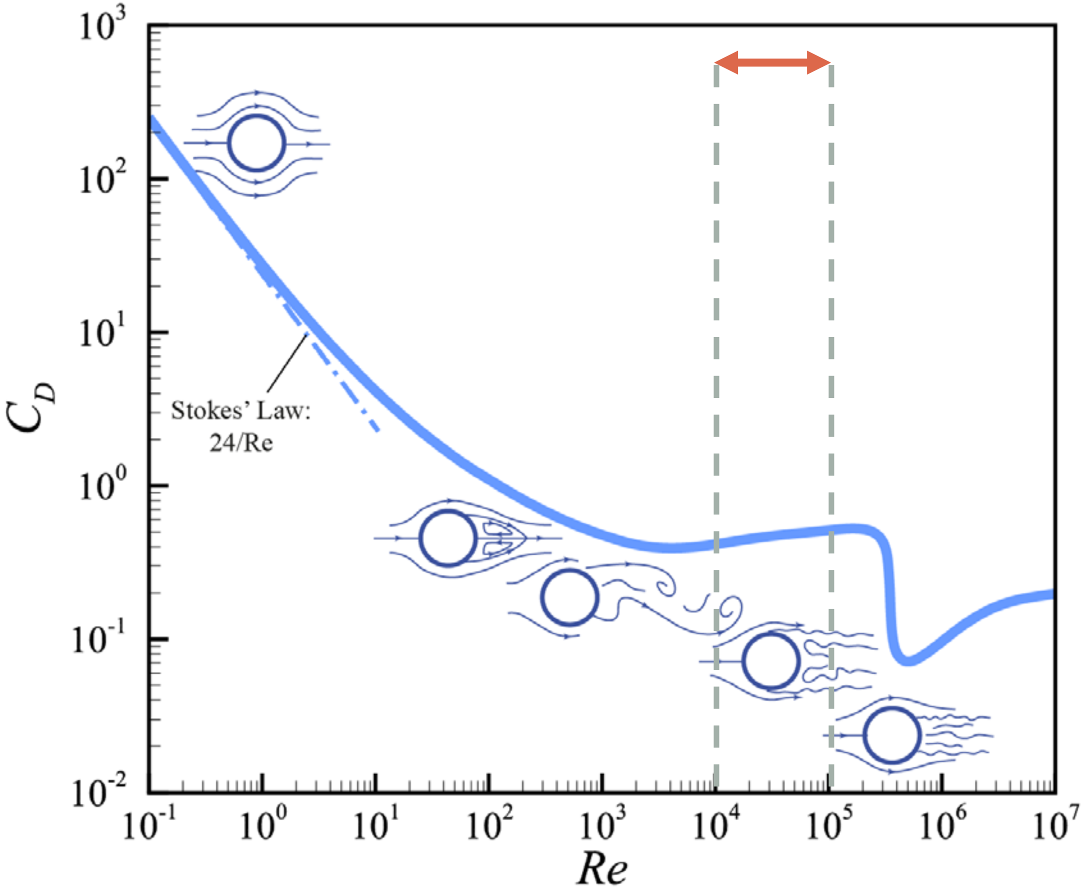
- 117 particles (100 volcanic)
- 150 *μm* < diameter< 1 *mm*
- SEM micro-CT and Image analysis



Bagheri et al., Powder Technology (2014), 270(A)

$10^4 < Re < 10^5$

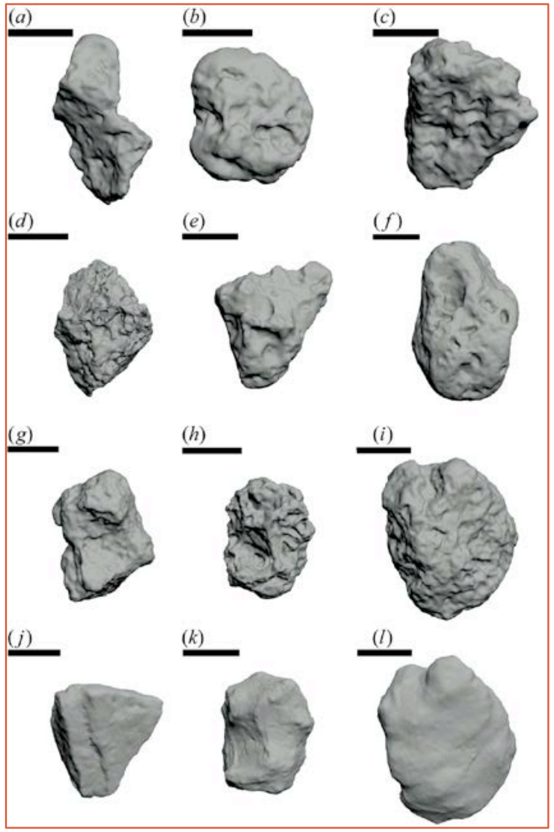
- Experiments in vertical wind tunnel
- 177 particles (116 volcanic), 11 *mm*< diameter< 36 *mm*



Bagheri et al., Rev. Sci. Instrum. (2013), 84 (5)

Particle Characterization

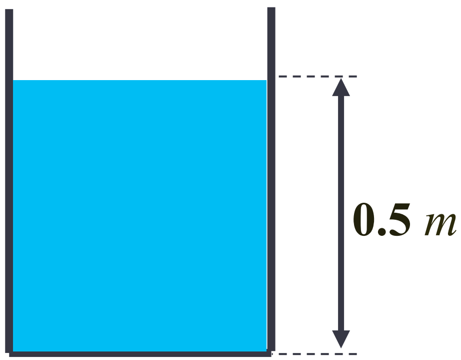
- 177 particles (116 volcanic)
- 11 *mm* < diameter < 36 *mm*
- 3D laser scan and Image analysis



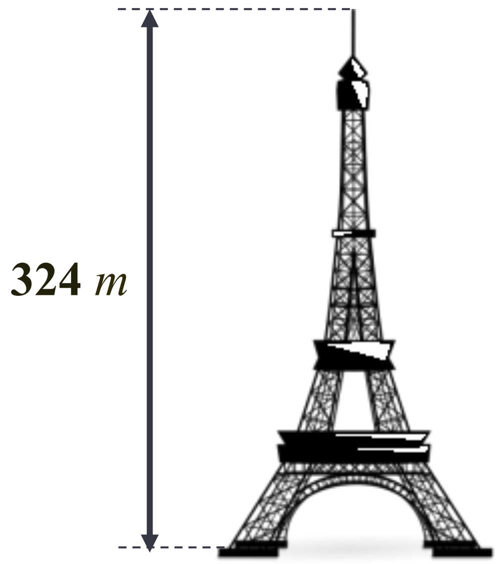
Bagheri et al., Powder Technology (2014), 270(A)

Why vertical wind tunnel?

Falling columns: A **spherical** particle with **diameter of 2 *cm*** and density of 2700 kgm^{-3}

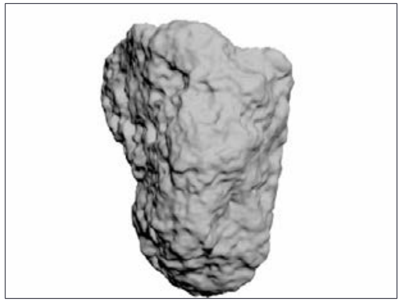


Water (*density ratio* = 2.7)



Air (*density ratio* = 2700)

Particle secondary motion

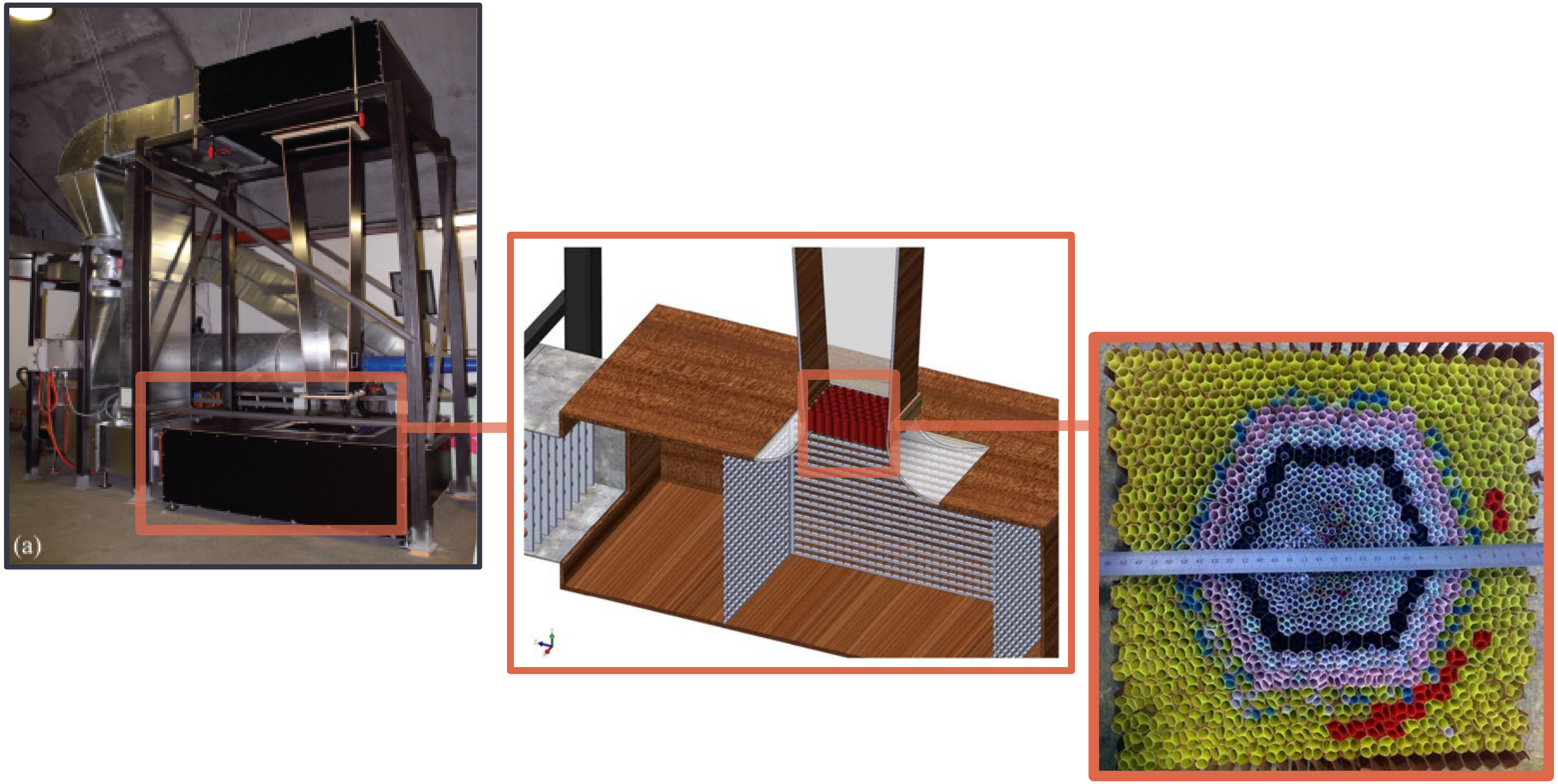


100 *cm*

25 frame per second

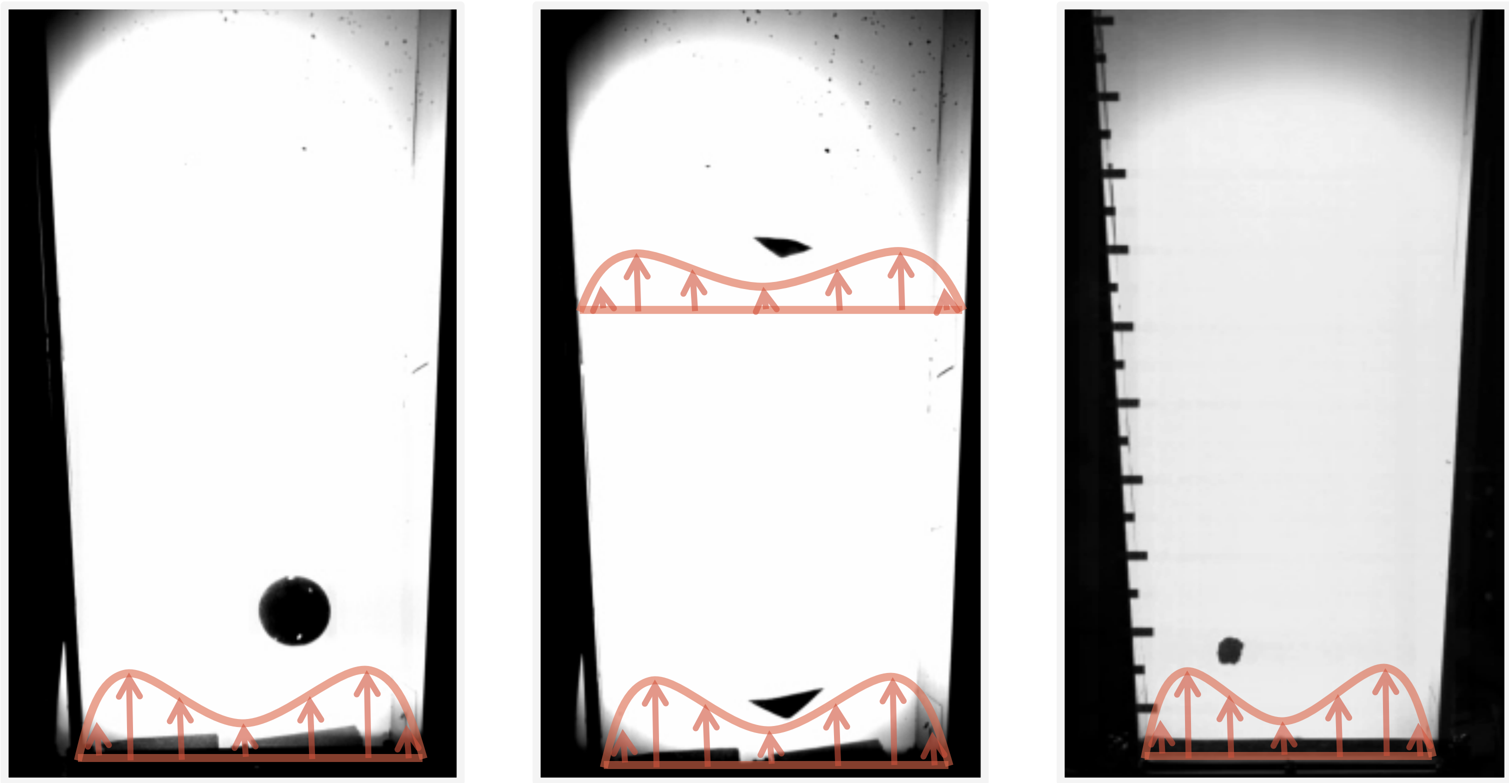
Bagheri et al., Rev. Sci. Instrum. (2013), 84 (5)

Particle secondary motion

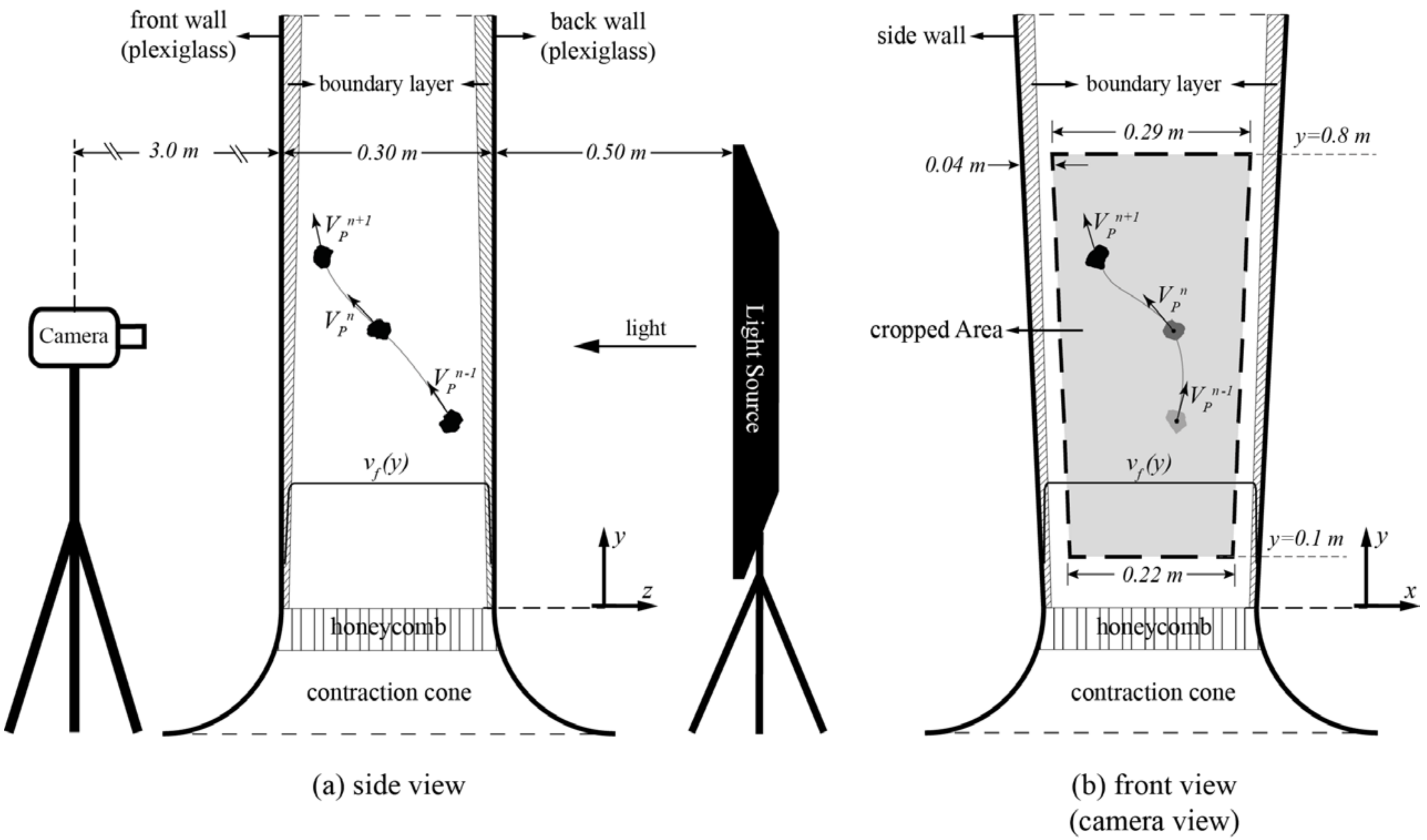


Bagheri et al., Rev. Sci. Instrum. (2013), 84 (5)

Particle secondary motion

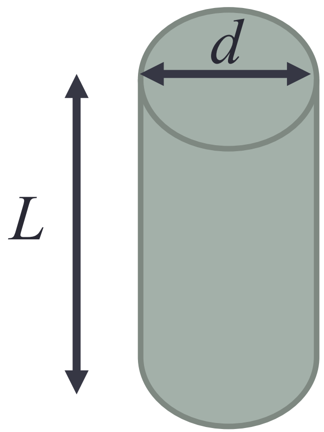


Wind Tunnel setup

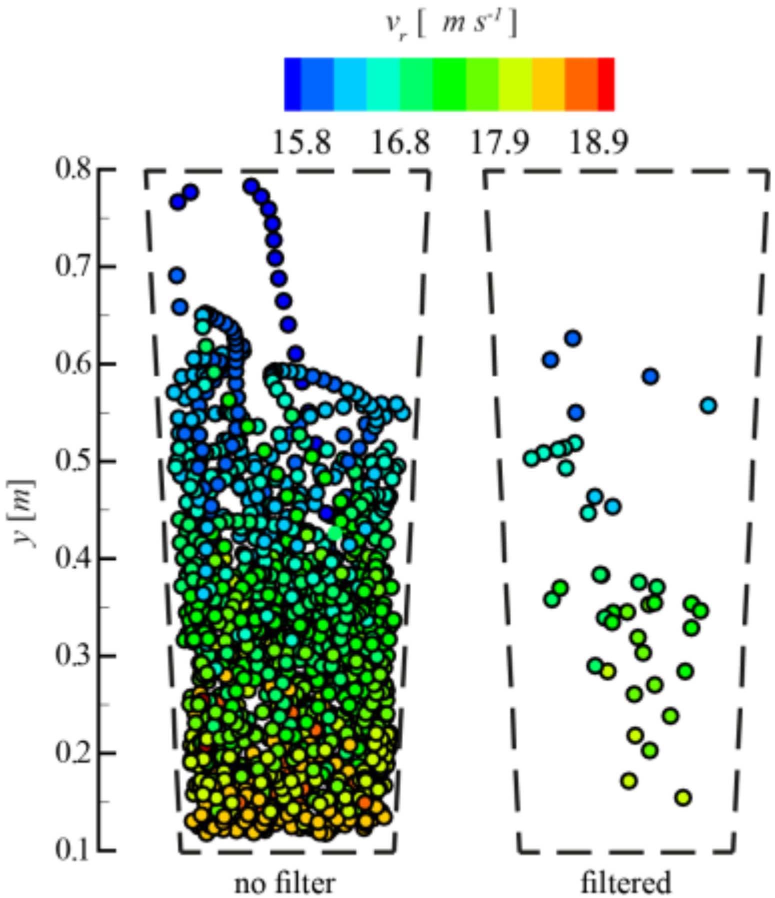


Bagheri et al., Rev. Sci. Instrum. (2013), 84 (5)

Particle tracking code



- $d = 2\ cm$
- $L = 4.7\ cm$
- $m = 9.3\ gr$



(b) C2

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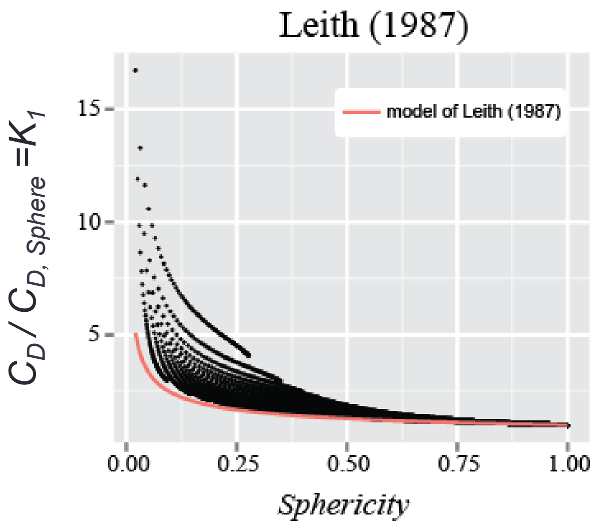
Which shape descriptor correlates with K_1?



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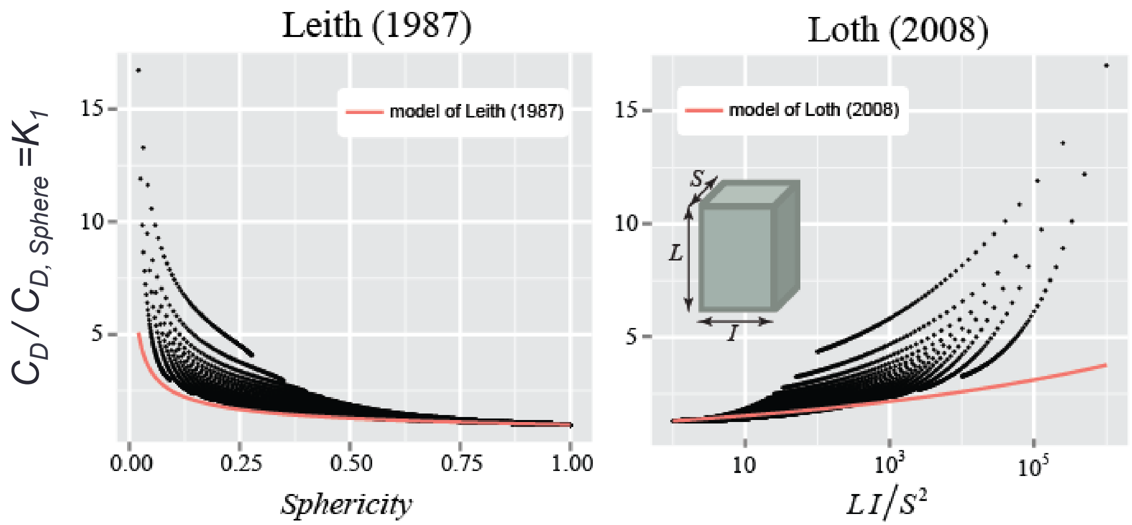
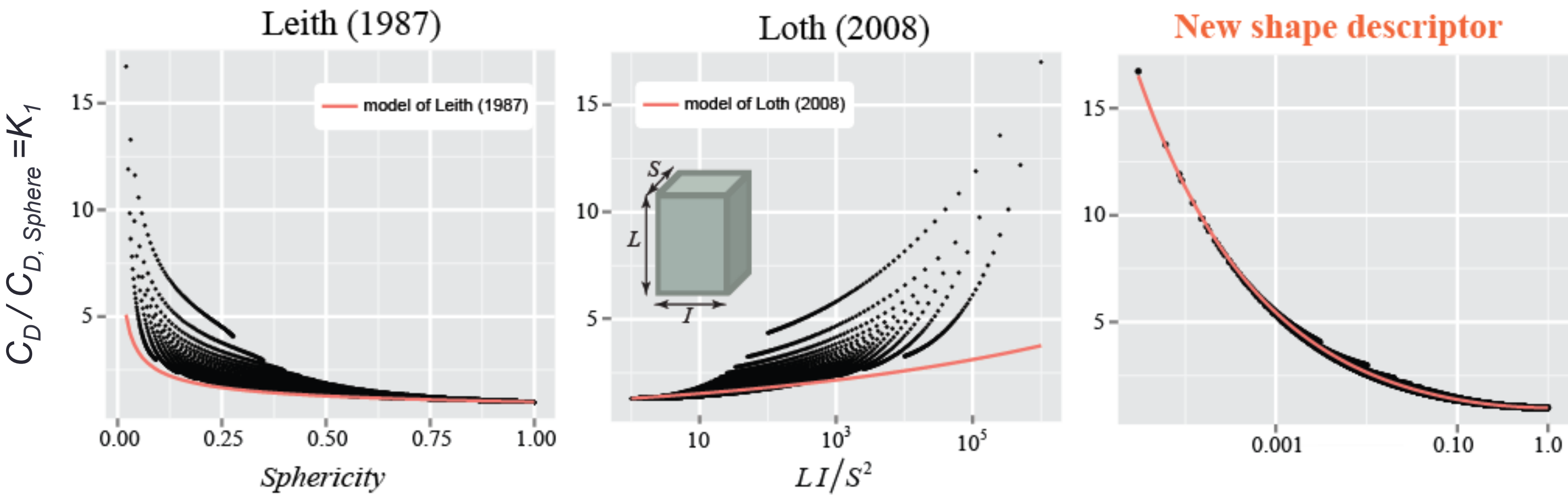
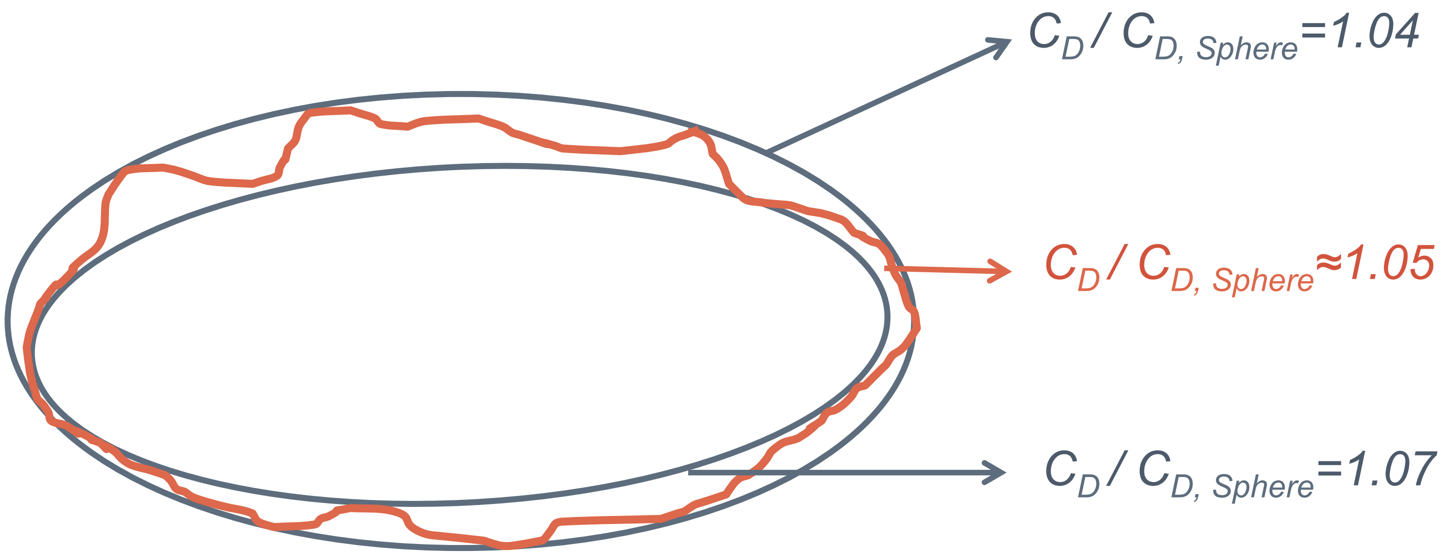


Which shape descriptor correlates better with K_1?

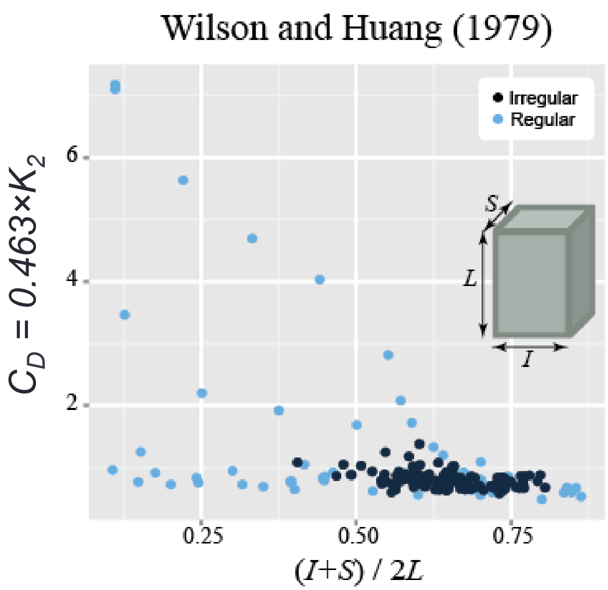


Surface roughness effects at Re<<1

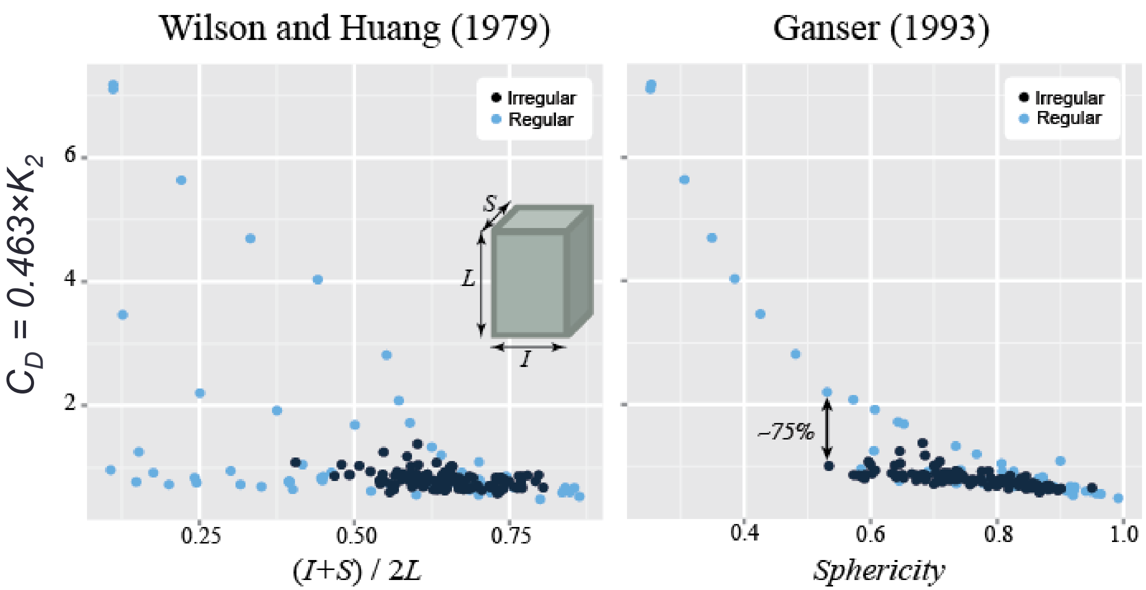
- Hill & Power theorem (1956):



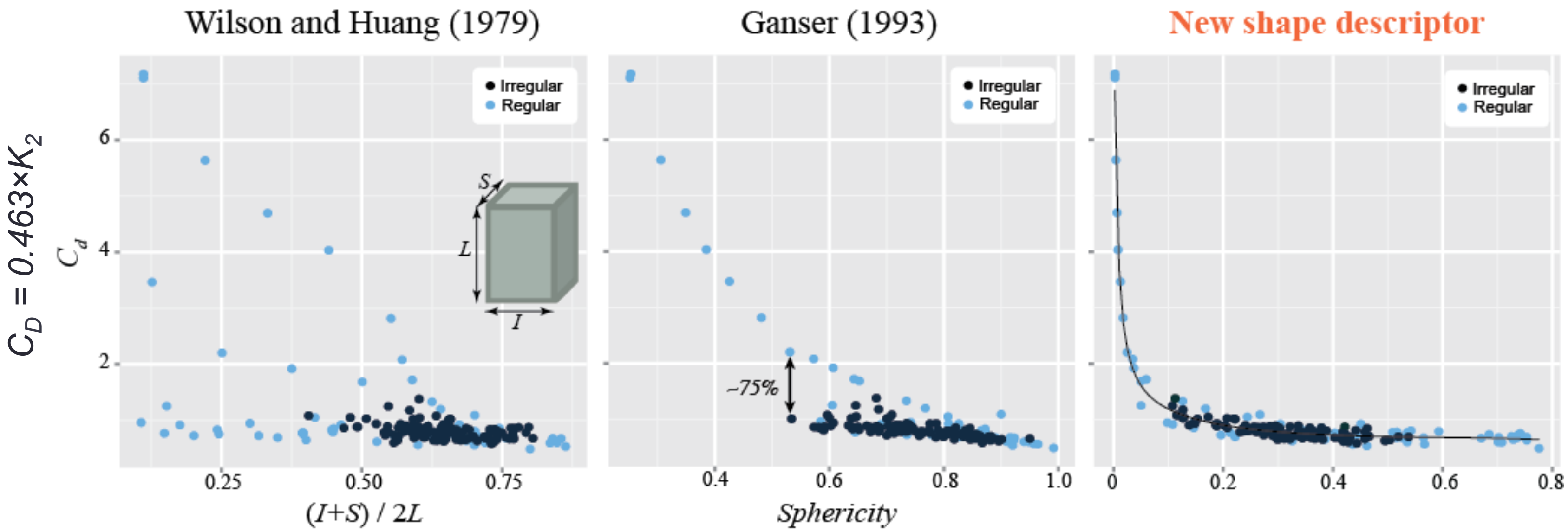
Which shape descriptor correlates with K_2?



Which shape descriptor correlates with K_2?



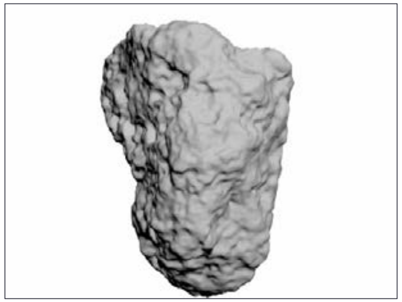
Which shape descriptor correlates better with K_2?



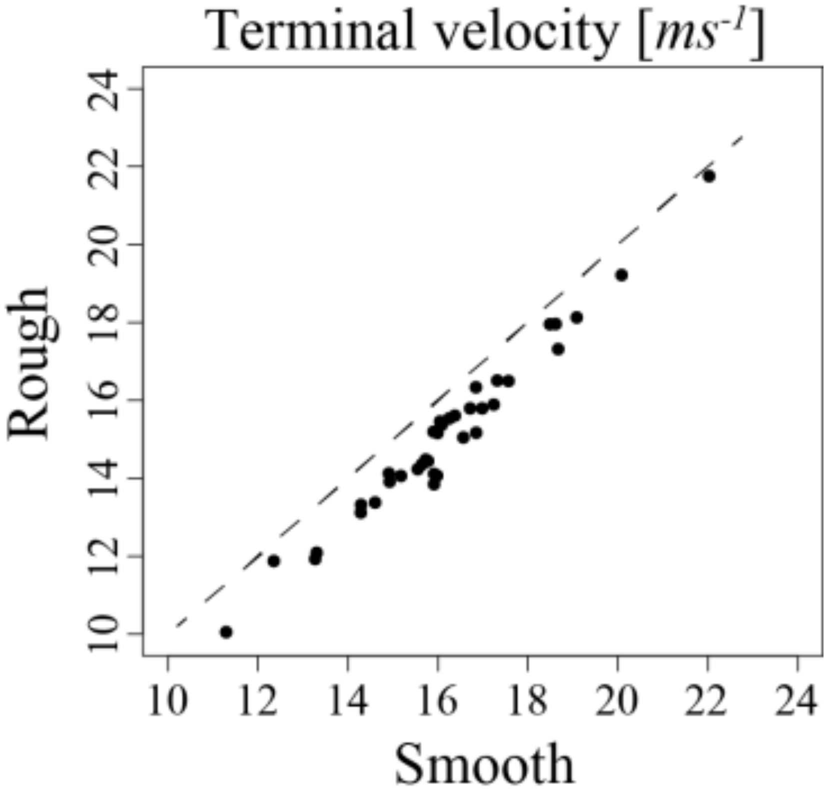
Surface roughness effect at high Re

At least at high Re the effect of surface roughness is almost negligible (< 7 %)

Rough: *Without Parafilm wrap*

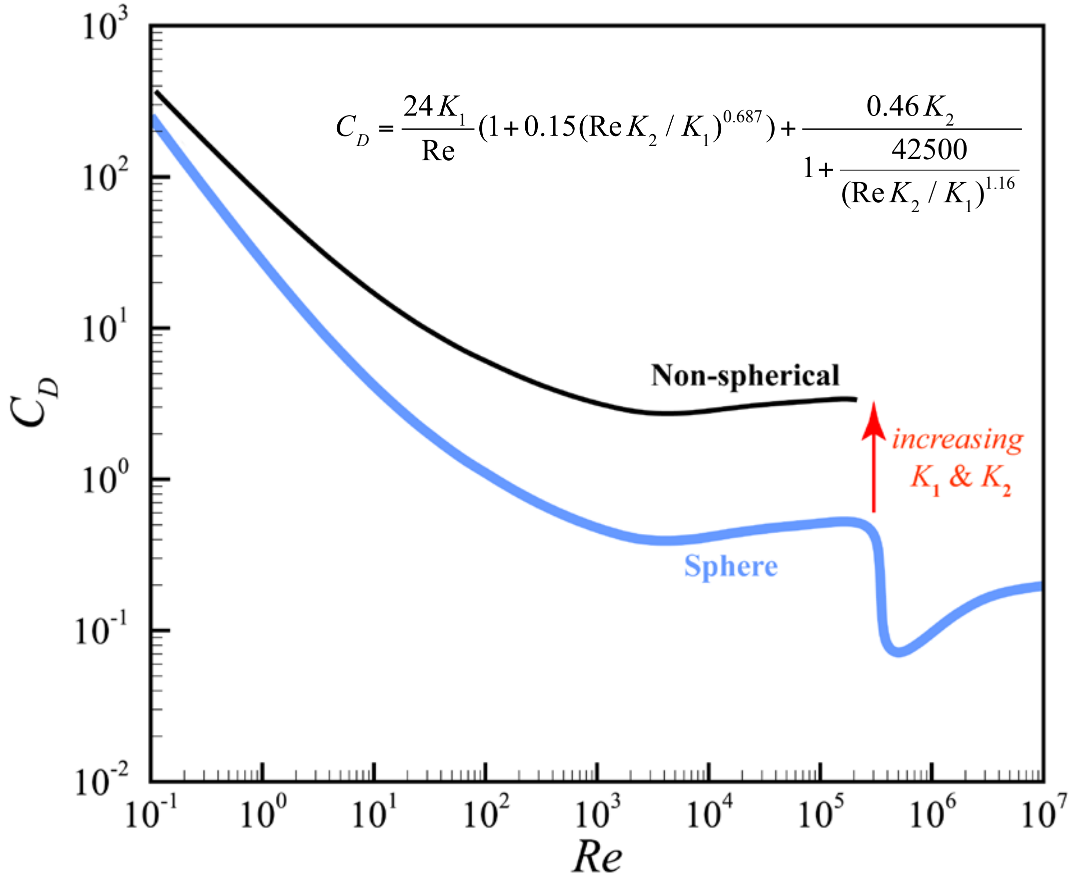


Smooth: *With Parafilm wrap*



New model of C_D

- $K_1 = f\,(\sqrt{S\,I/L}\,)$
- $K_2 = g\,(S^3/I\,L^2)$



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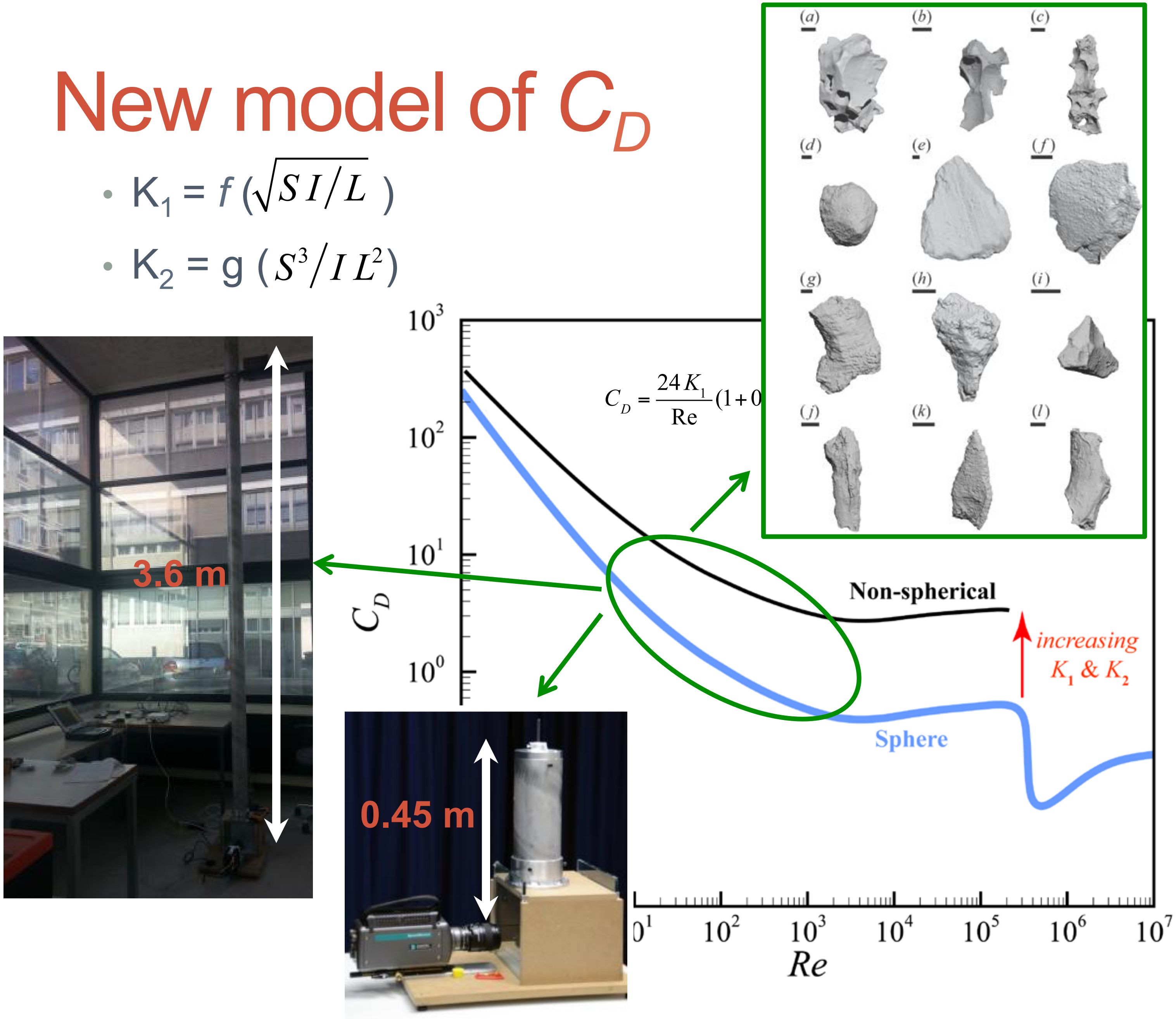
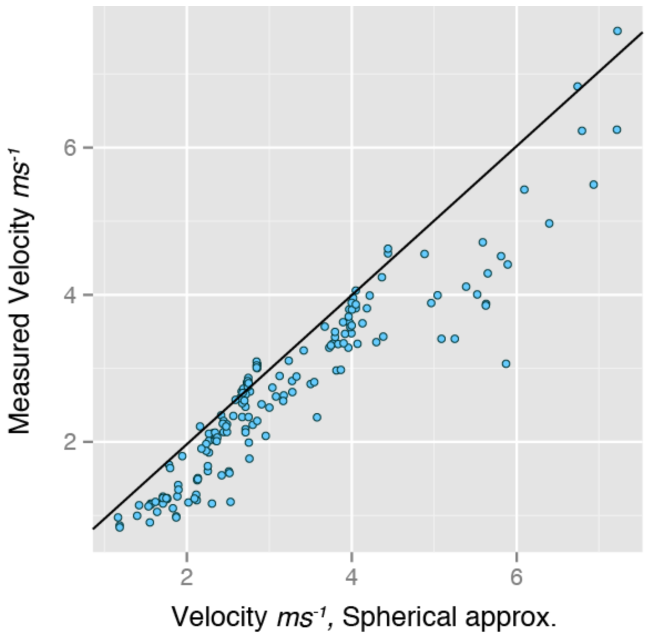


Intermediate Re: estimations vs. measurements



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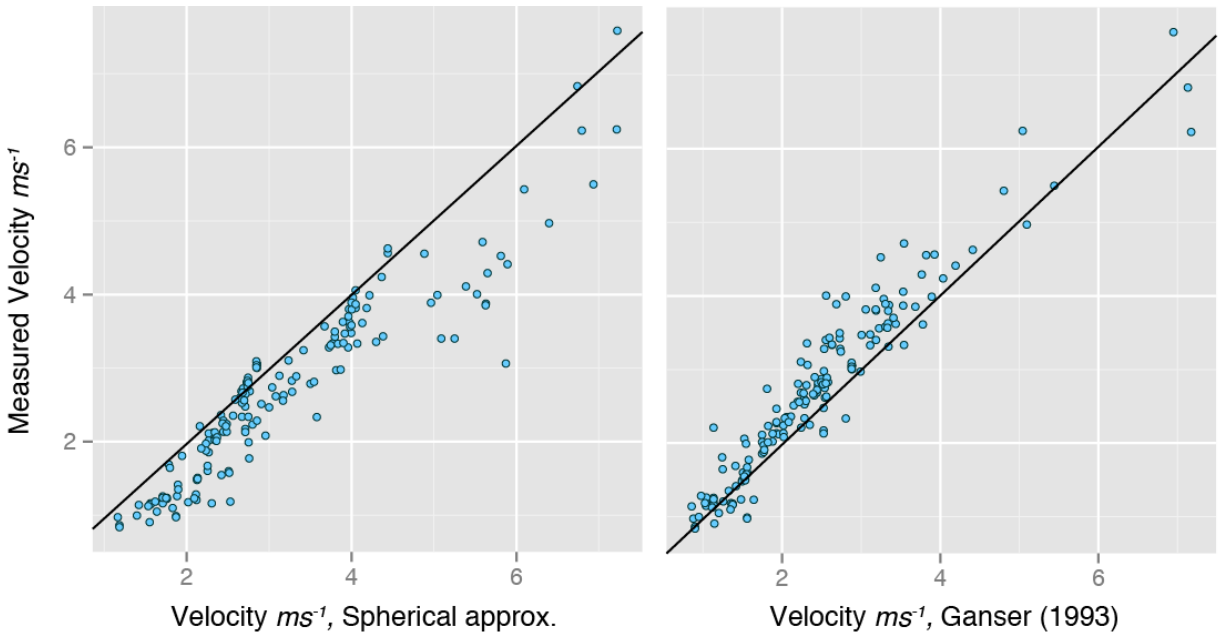

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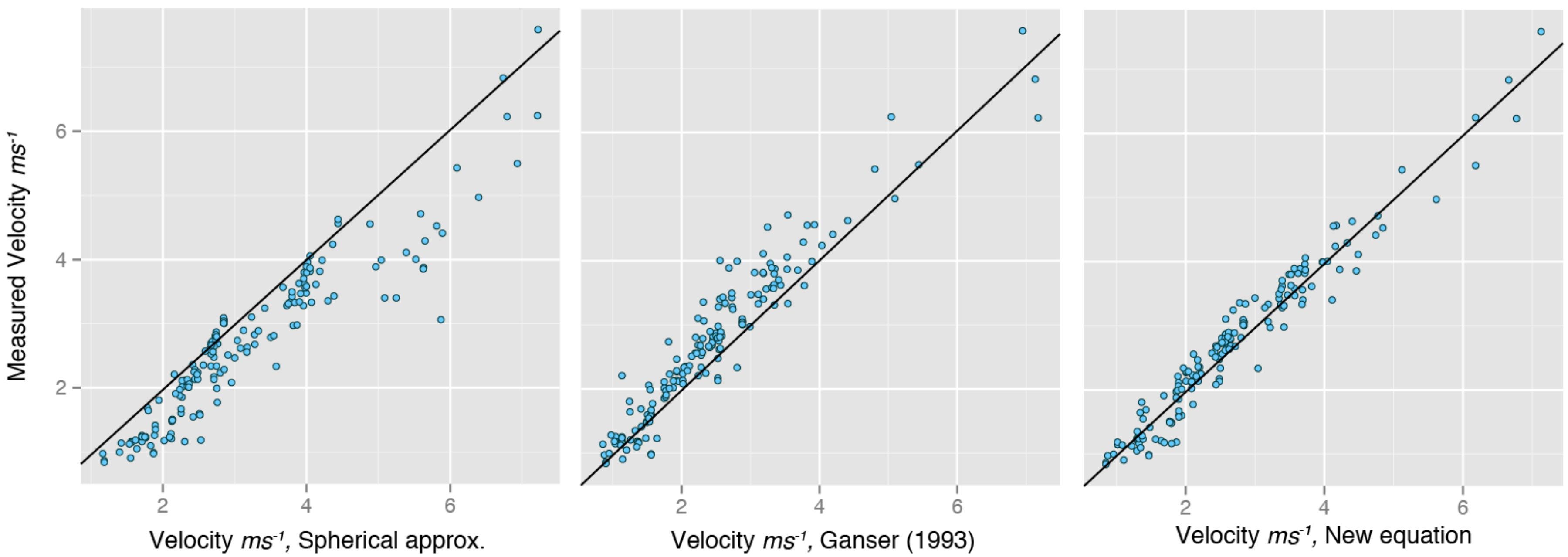

New drag coefficient model

- **First model** of drag coefficient for **freely** moving **non-spherical** particles in **air**
  - Valid in a wide range of Reynolds number ($Re<10^5$)
  - Valid for **spherical**, **regular** and **irregular** particles
  - **Easy-to-measure** shape factors (for low and high Re)
  - **Lowest** value of estimation **error** and **uncertainty**