Multiphase Flow Laboratory
University of Udine

COST Training Schoool (Action FP1005)

Martin Luther Universität, Halle-Wittenberg, May 27-29, 2015

Project supported by COST - European Cooperation in Science and Technology

Lecture 1: Setting the Stage

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MARTIN-LUTHER-UNIVERSITÄT HALLE-WITTENBERG

UNIVERSITÀ DEGLI STUDI DI UDINE

Outline of Lecture 1

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(Some) Applications

INDUSTRIAL APPLICATIONS

- FIBER SUSPENSIONS (PULP & PAPER INDUSTRY)
- PROCESSING OF INDUSTRIAL COLLOIDS
- PNEUMATIC TRANSPORT OF POWDERS (PROCESS INDUSTRY)
- PULVERIZED BIOMASS PARTICLES IN INDUSTRIAL BURNERS
- SPREAD OF INK PARTICLES (PRINTING INDUSTRY)

ENVIRONMENTAL SYSTEMS

- AIRBORNE PARTICLES AND AEROSOLS IN THE ATMOSPHERE
- MICRO-ORGANISMS (E.G. PLANKTON, POLLUTANTS) IN THE OCEAN
- MARINE SNOW

BIOLOGICAL FLOWS

- TRANSPORT OF BLOOD CELLS IN VEINS
- LUNG AEROSOL DYNAMICS

(Some) Applications

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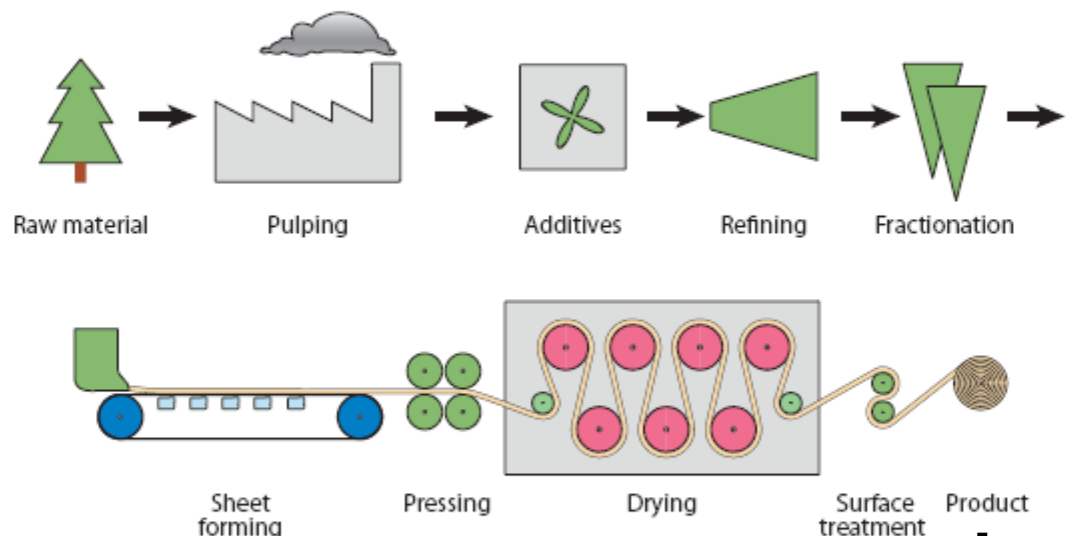
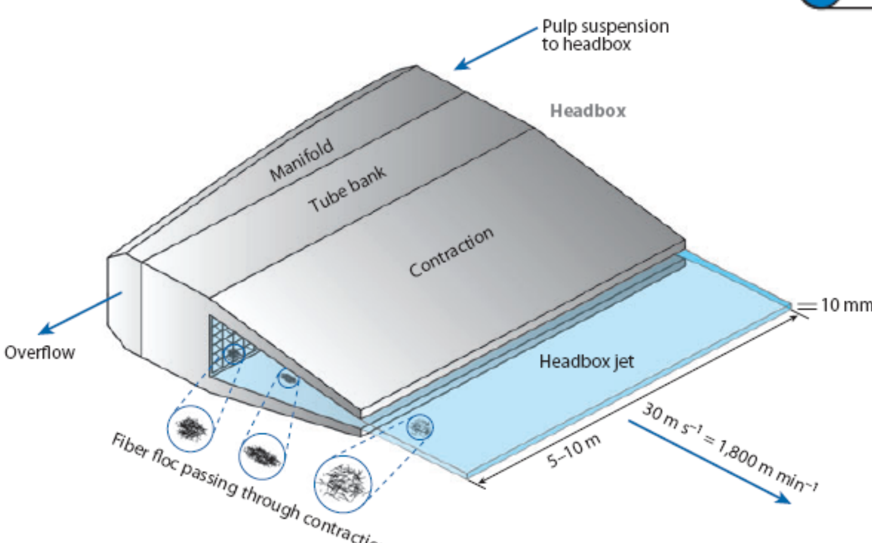
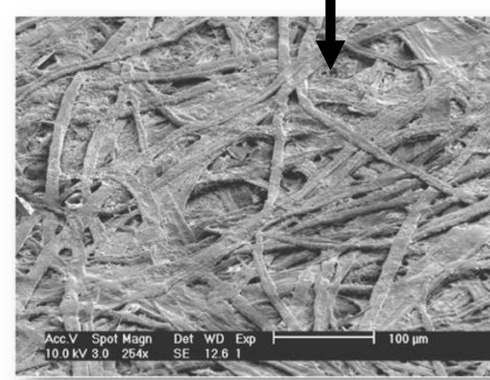
Industrial applications

- Fiber suspensions (Pulp & Paper industry)



Main process steps of paper manufacturing (F. Lundell et al., Annu Rev Fluid Mech (2011)





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(Some) Applications

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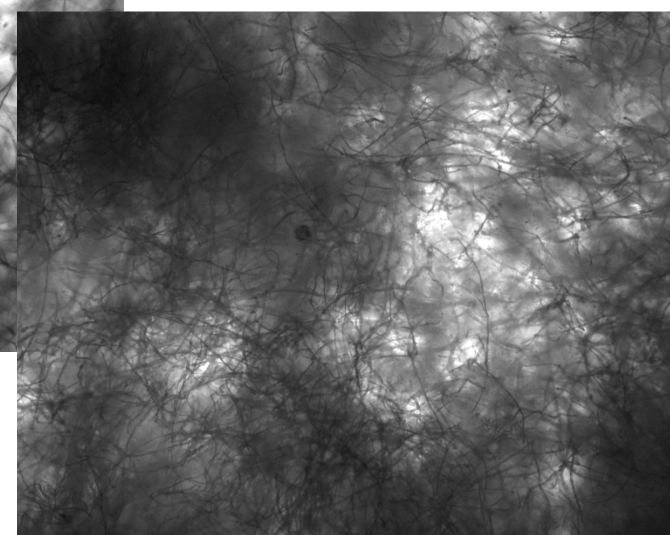
Industrial applications

- fiber suspensions (Pulp & Paper industry)

C=0.02%-w

C=0.1%-w



C=0.5%-w

Suspension of cellulose fibers

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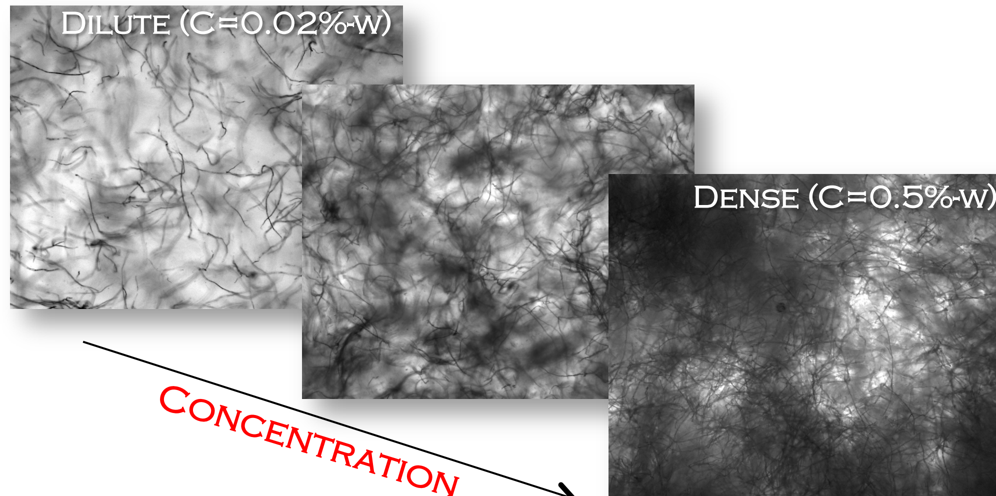
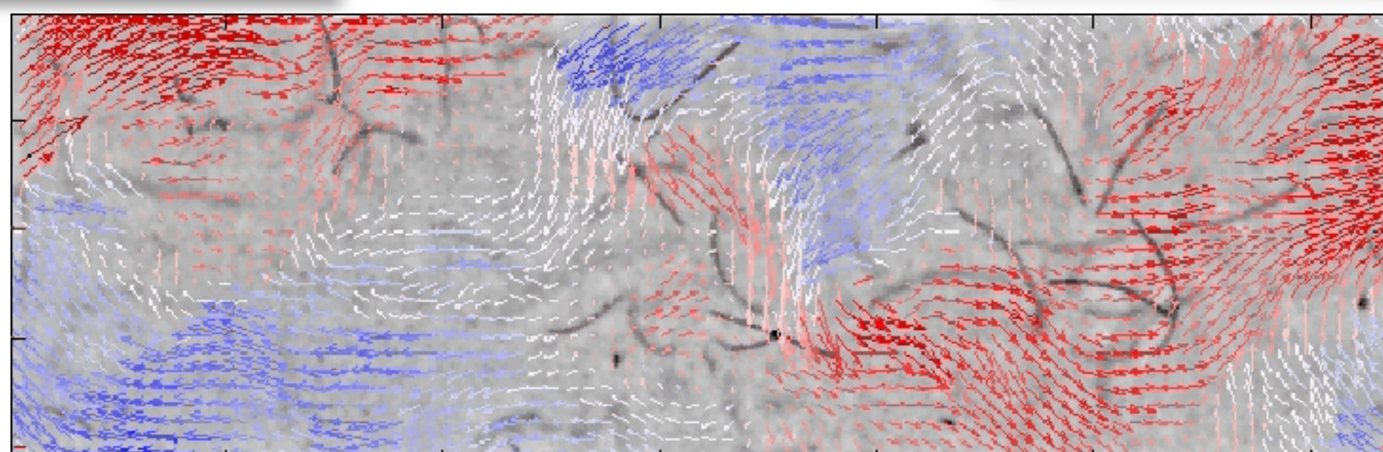
Industrial applications

- fiber suspensions (Pulp & Paper industry)





(Some) Applications

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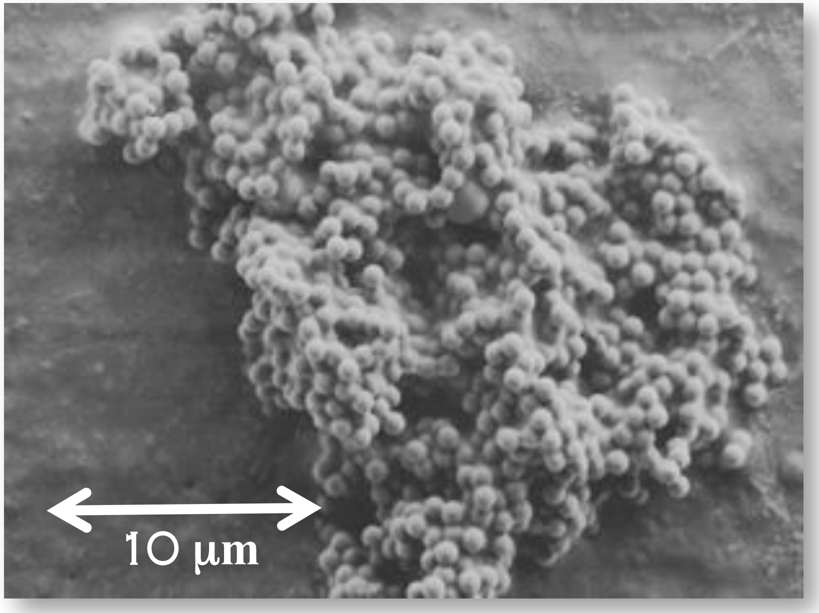
INDUSTRIAL APPLICATIONS

- PROCESSING OF INDUSTRIAL COLLOIDS



PAINTS, ADHESIVES, INKS, LUBRICANTS, COATINGS, COSMETICS, PHARMACEUTICALS AND EVEN ELECTRONIC DISPLAYS

(Some) Applications

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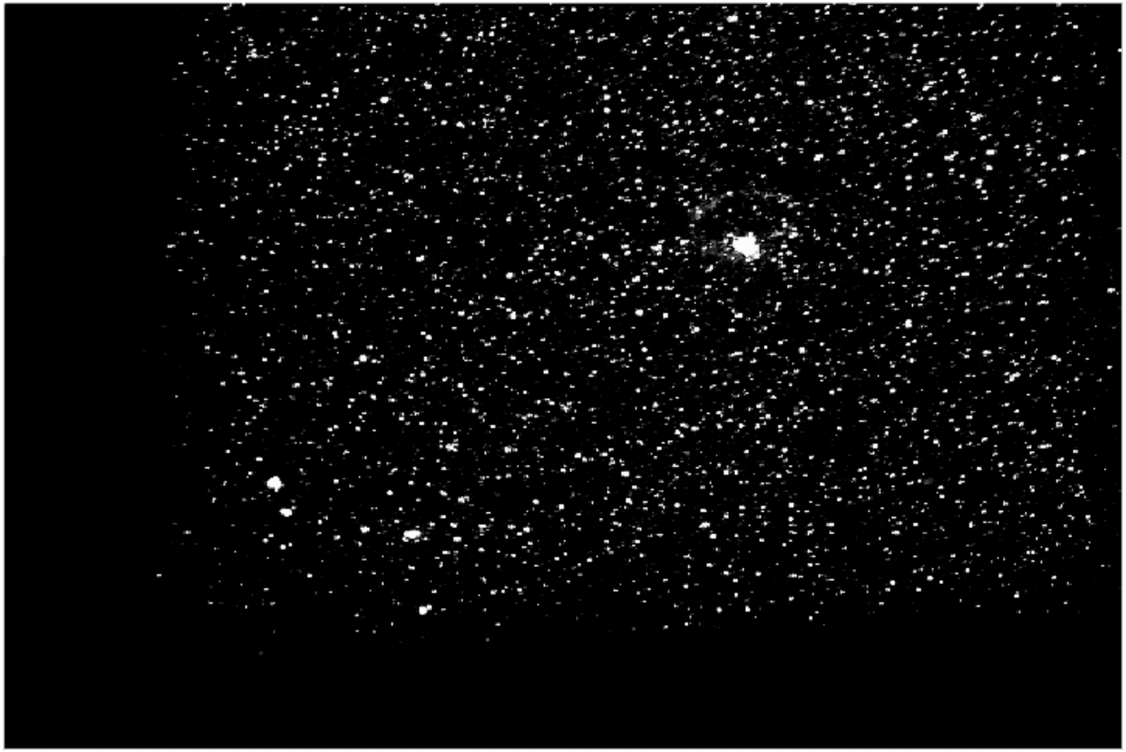
INDUSTRIAL APPLICATIONS

- PROCESSING OF INDUSTRIAL COLLOIDS



PAINTS, ADHESIVES, INKS, LUBRICANTS, COATINGS, COSMETICS, PHARMACEUTICALS AND EVEN ELECTRONIC DISPLAYS

(Some) Applications

cost
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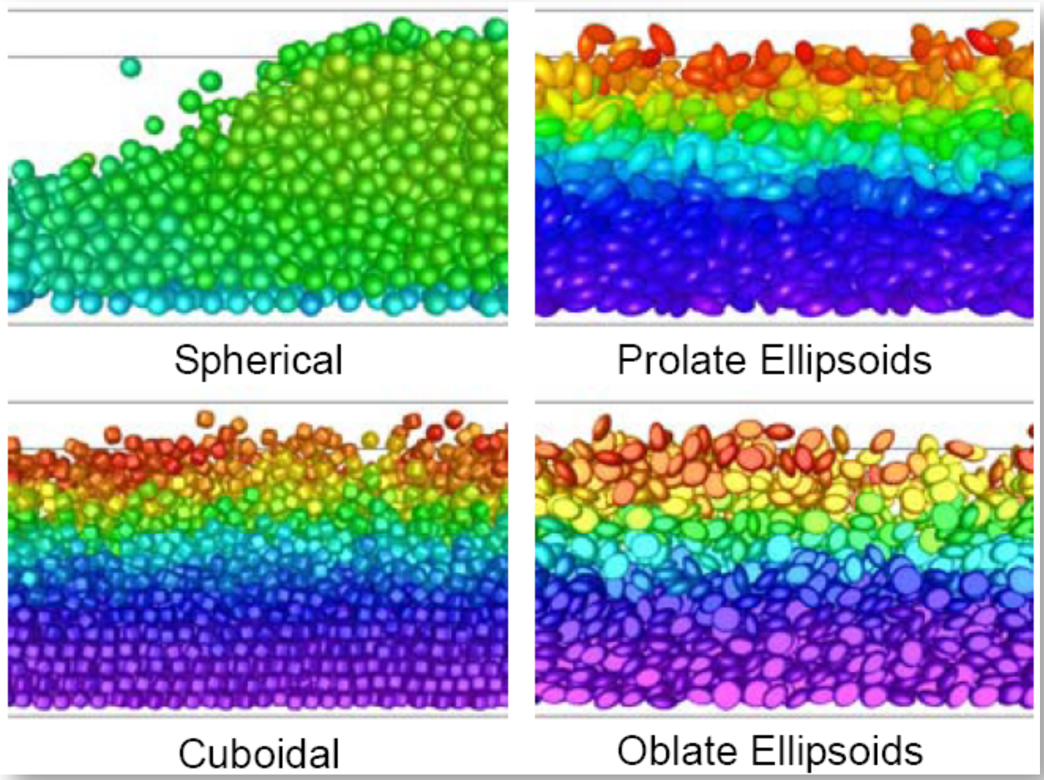
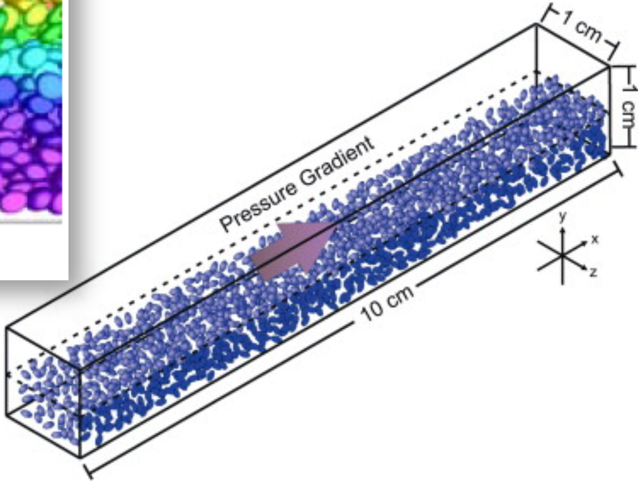
Industrial applications

- pneumatic transport of powders (process industry)





Numerical Simulation (DEM) of non-spherical particles pneumatic conveying in a channel
From: Hilton and Cleary, Chem Eng Sci (2011)

(Some) Applications

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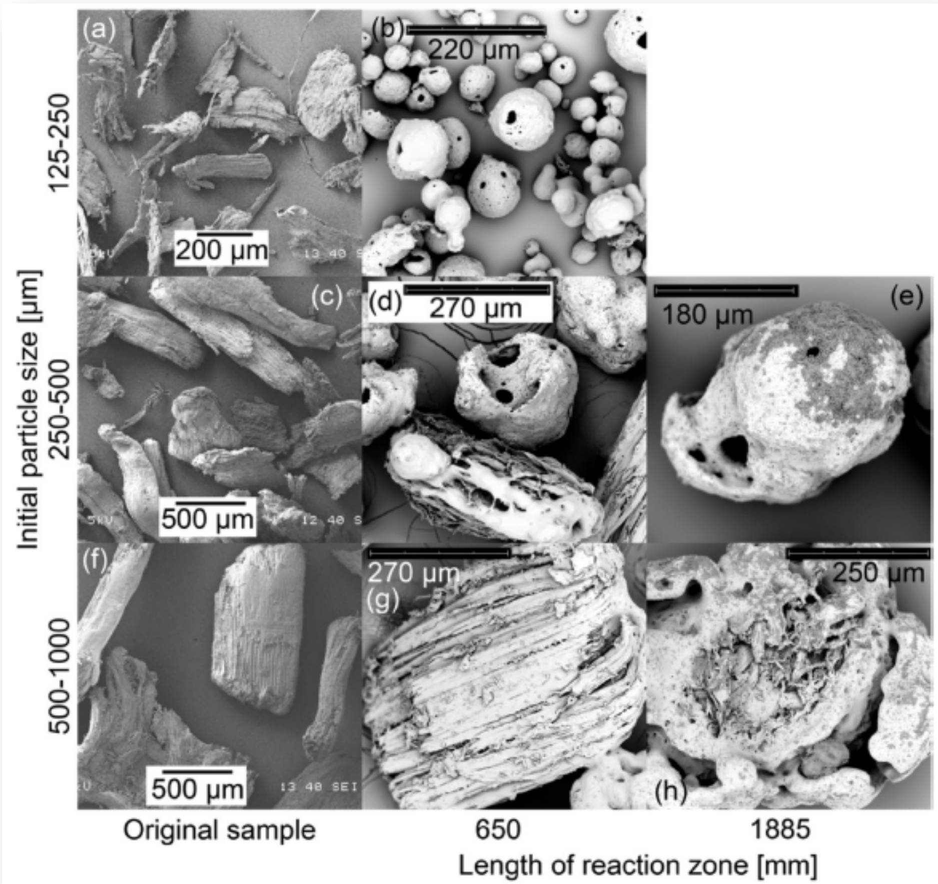
Industrial applications

- Pulverized biomass particles in industrial burners



Biomass and char particles at various reaction conditions
From: Umeki et al.,ind eng chem res (2012)

(Some) Applications

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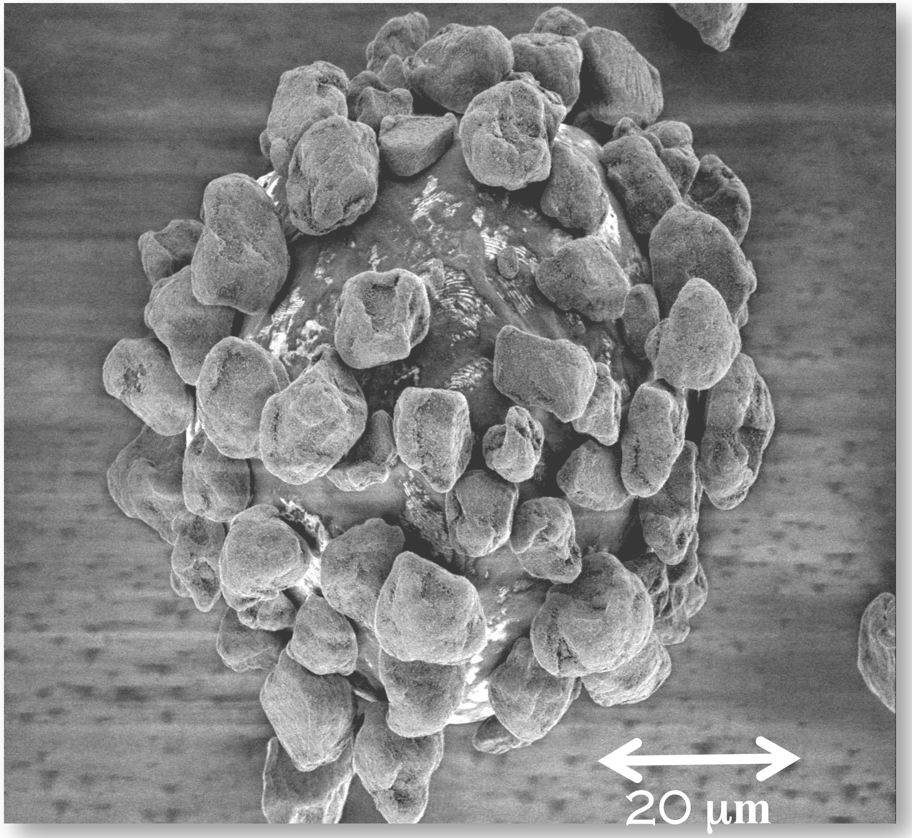
Industrial applications

- spread of ink particles (Printing industry)



Toned carrier bead

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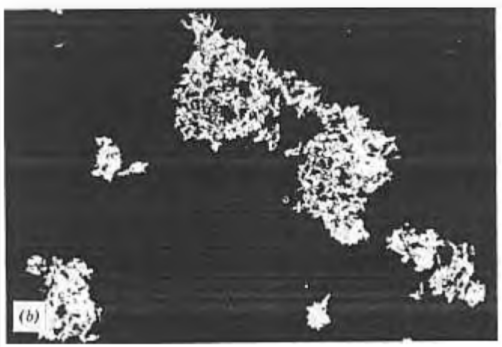
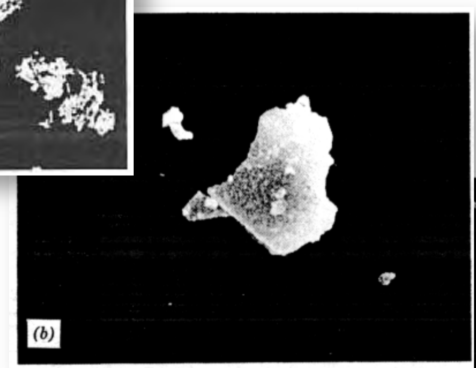
Environmental systems

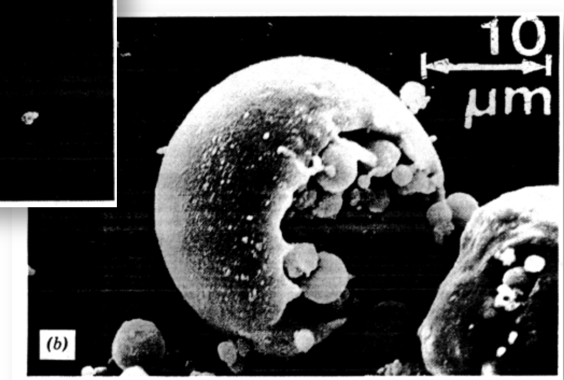
- airborne particles and aerosols in the atmosphere



Iron oxide particles



Granite cutting particle



Fly ash particle from coal burning

Size range: 0.001 mm (molecular cluster) to 100 mm (small raindrop)

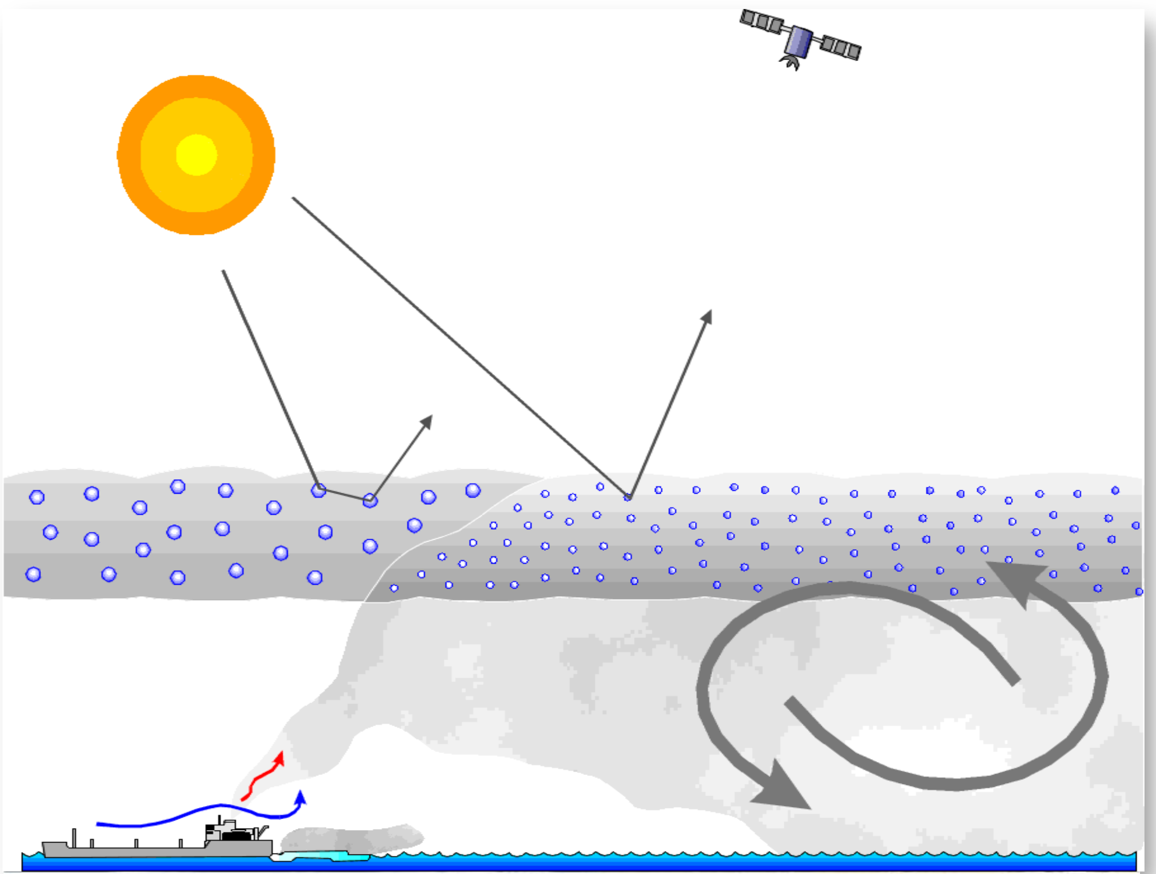
Pictures courtesy of Prof. G. Habib IIT Delhi

(Some) Applications

Environmental systems

- Airborne particles and aerosols in the atmosphere

$N \sim 40\ cm^{-3}$
$W \sim 0.30\ g\ m^{-3}$
$r_e \sim 11.2\ \mu m$



$N \sim 100\ cm^{-3}$
$W \sim 0.75\ g\ m^{-3}$
$r_e \sim 10.5\ \mu m$

Indirect effect of atmospheric aerosols: ship tracks visible in the clouds

(Some) Applications

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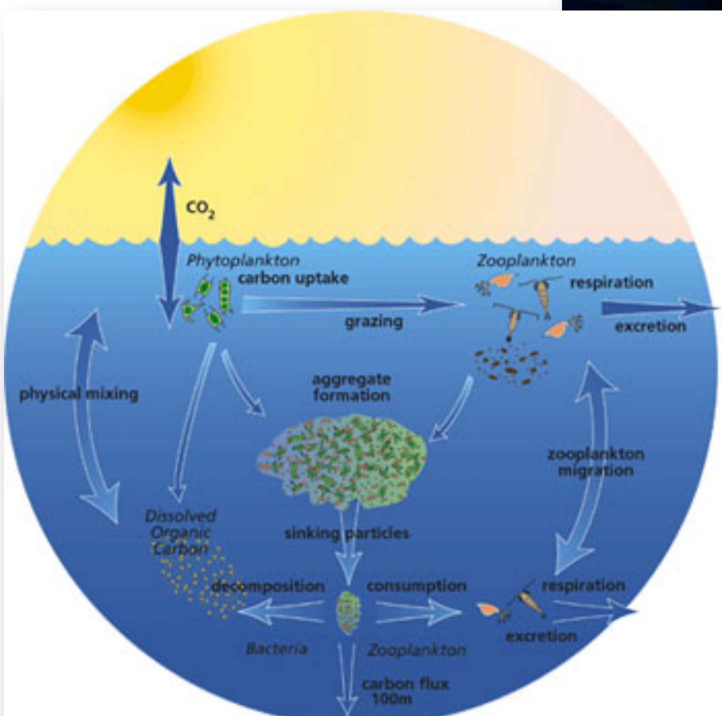
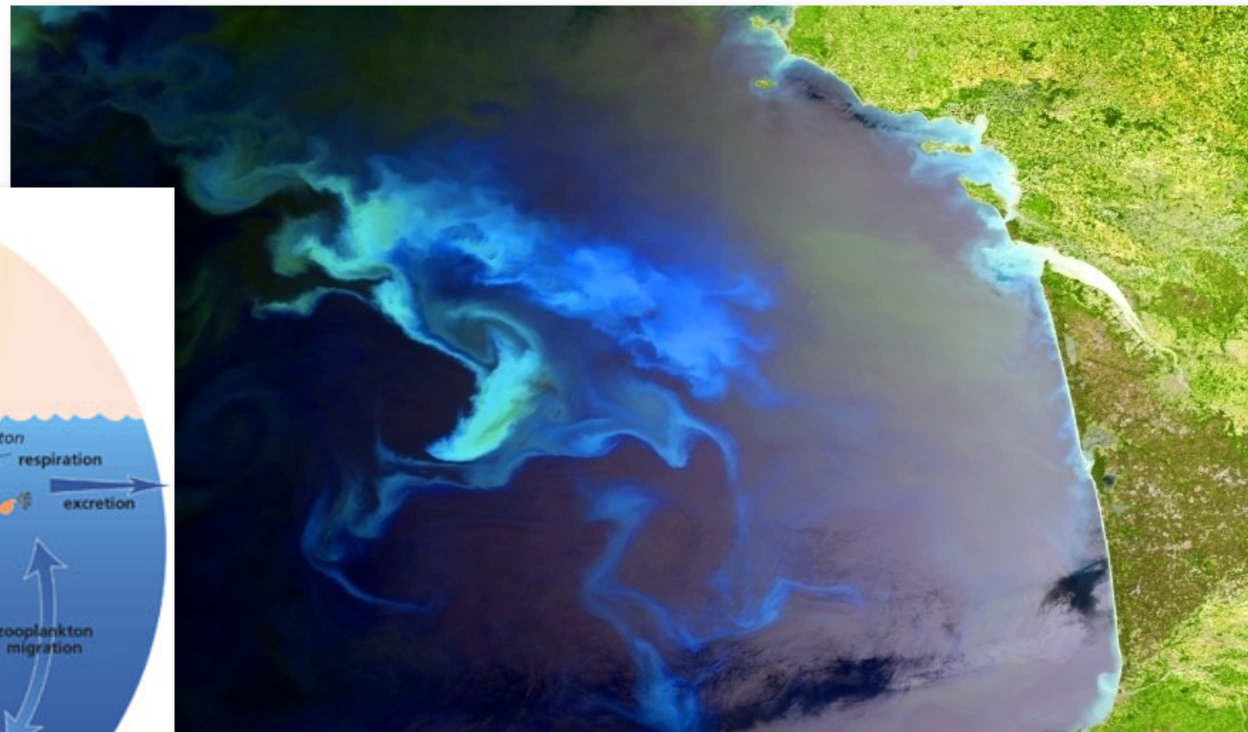
environmental systems

- micro-organisms (e.g. plankton, pollutants) in the ocean





Phytoplankton bloom (bay of biscay, 2004)

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(Some) Applications

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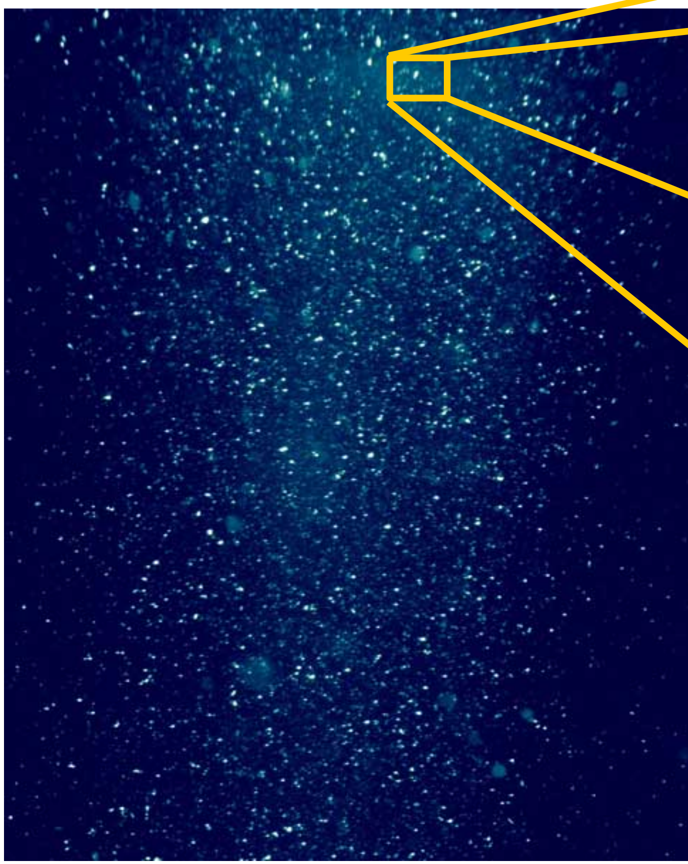
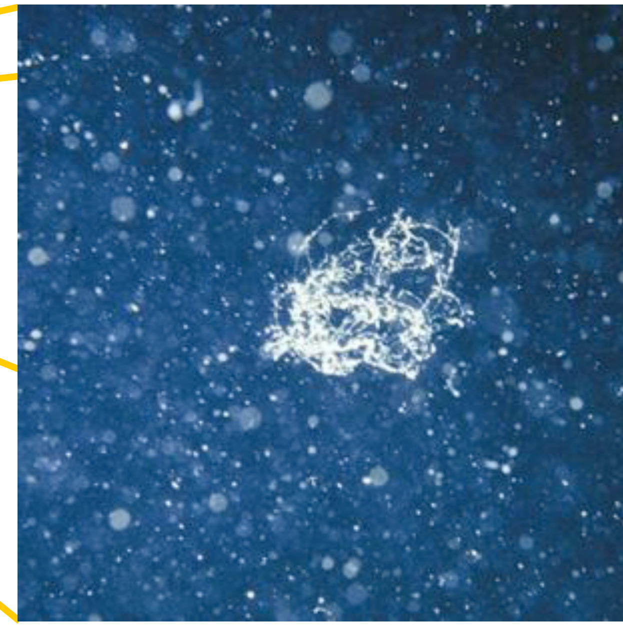
ENVIRONMENTAL SYSTEMS

- MARINE SNOW





Picture: H. P. Grossart, IGB, Leibniz-Institute of Freshwater Ecology and Inland Fisheries

(Some) Applications

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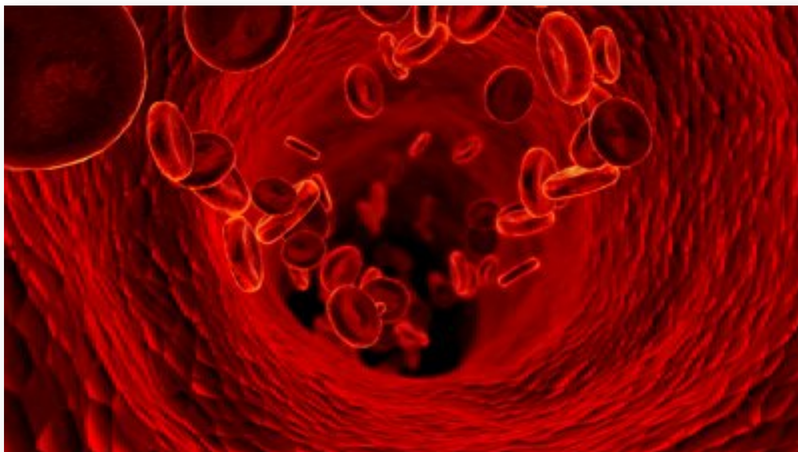
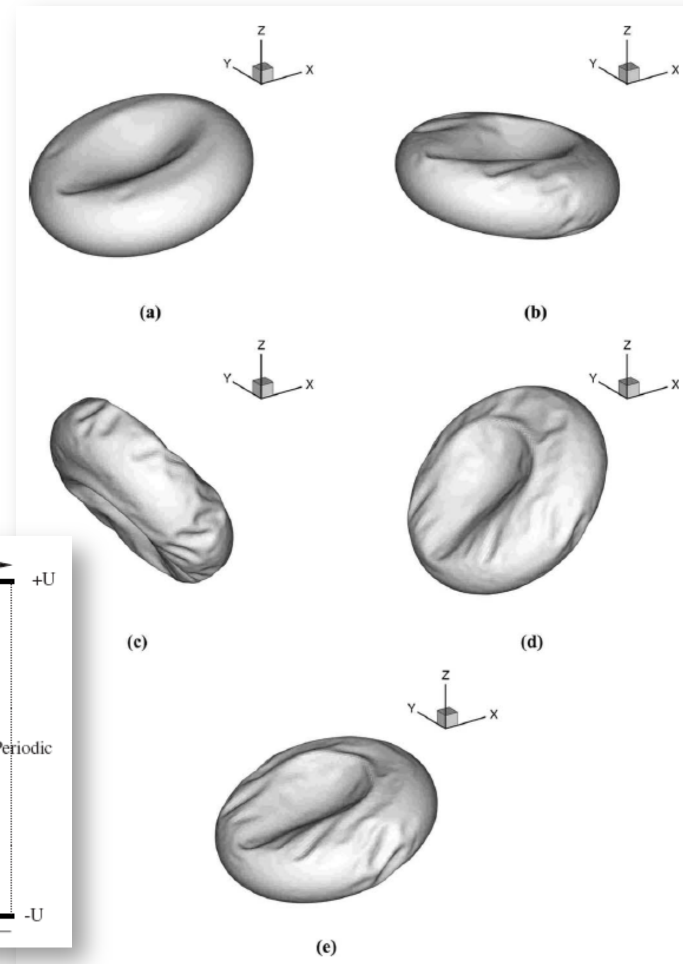
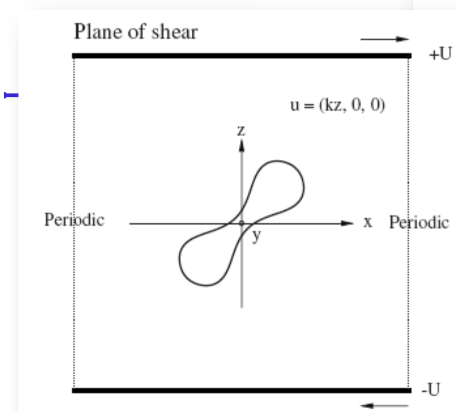
Biological flows

- Transport of blood cells in veins





Example of numerically - simulated (IBM+LBM) blood cell moving in linear shear flow (from: Sui et al., Phys Fluids, 2008)



(Some) Applications

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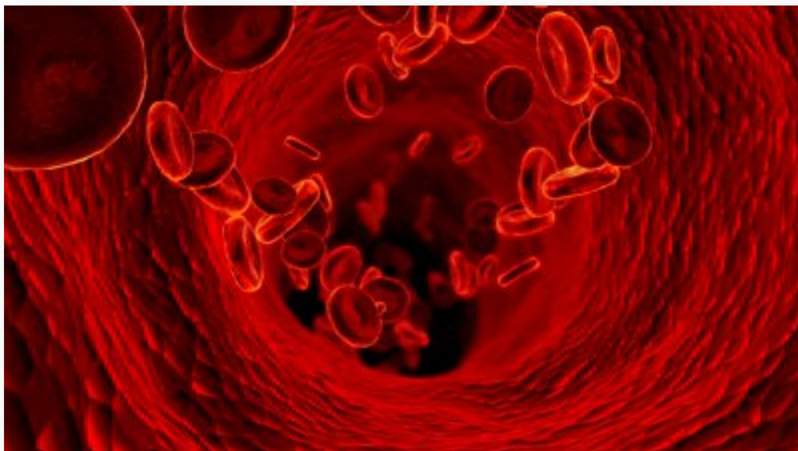
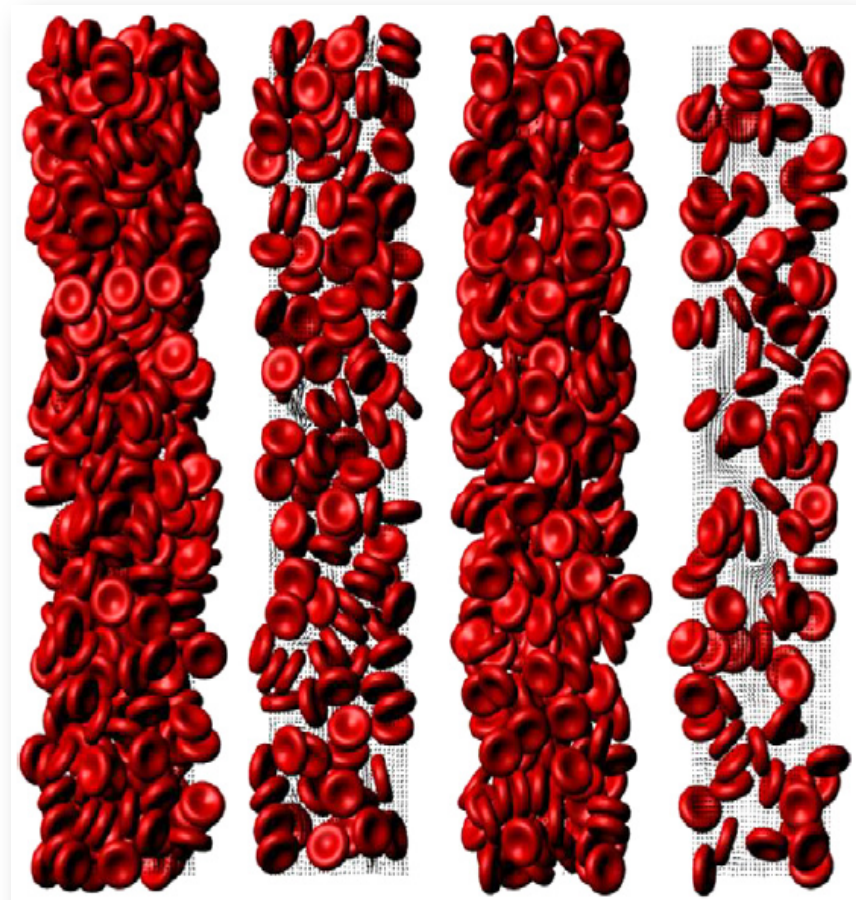
Biological flows

- Transport of blood cells in veins



Example of numerically – simulated (IBM-LBM) dense suspension of blood cells in periodic flow domain (from: Shardt & Derksen, Int J Multiphase Flow, 2012)



(Some) Applications

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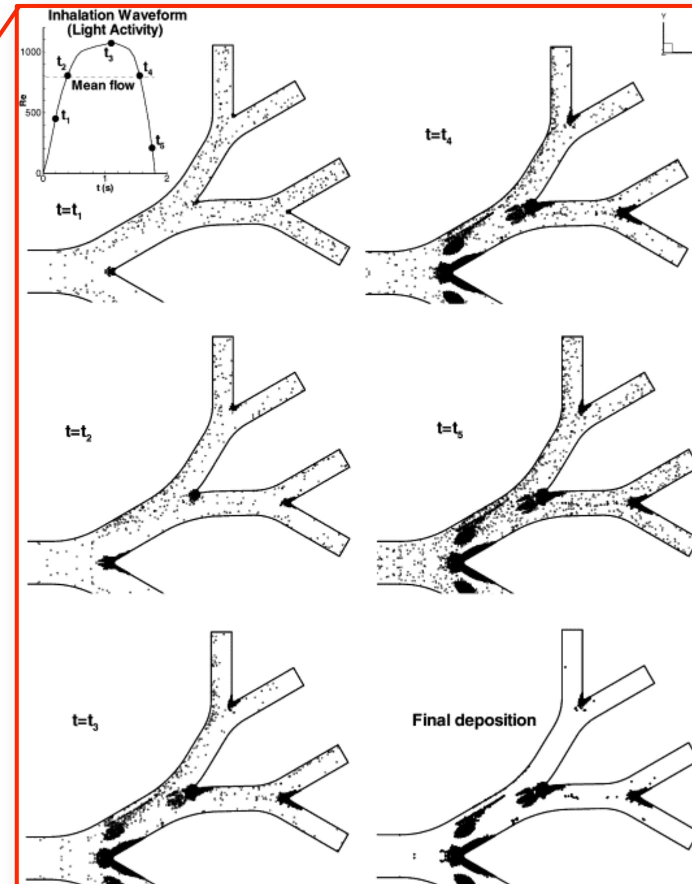
Biological Flows

- Lung aerosol dynamics



Deposition in triple bifurcation lung airway model (Zhang et al., J Aerosol Sci, 2002)

Classification of Non-Spherical Particles*

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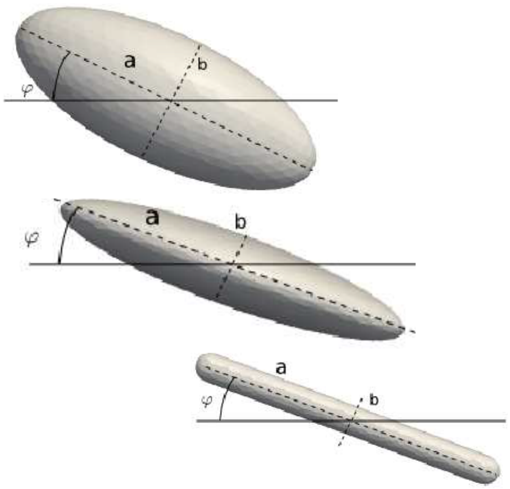

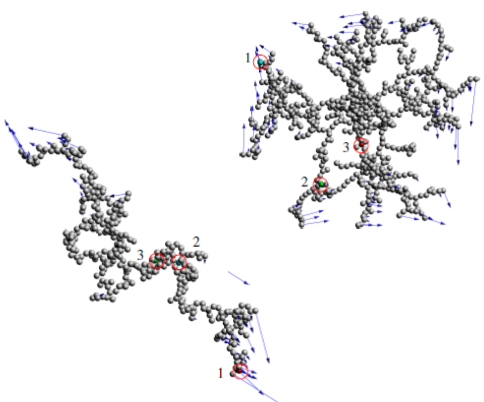

Non-spherical	Spherical

Non-spherical

- ***Regular particles***
  - Cube
  - Disc
  - Cylinder
  - Tetrahedral
  - Ellipsoid
- ***Irregular particles***
  - Defined by product
    - Agricultural products (straw, grain, etc)
    - Blood cells
    - Maple leaf
    - More...
  - Defined by production method
    - Grinding
    - Chipping
    - Spray Drying
    - More...
  - Complex shapes
    - Snow flakes
    - Black liquor droplets
    - Agglomerates
    - More...

Spherical

- ***Perfectly smooth spheres***
- ***Roughened spheres***
  - ex. golf balls

* From Mandø et al. Proc. 6th Int. Conference on Multiphase Flows (ICMF2007)

Classification of Non-Spherical Particles

Note: challenges with irregular non-spherical particles

- Model all relevant forces acting on particles:
  - Correlations for aerodynamic coefficients currently based on statistical distributions
  - No measure available for shear-induced and rotation-induced lift
- Model wall-collision:
  - need to 'convert' particles into equivalent spheres
  - Need to obtain statistical measures of restitution and friction coefficients
- Heavily dependent on availability of accurate experimental measurements or particle-level direct simulations

How to Define Size and Shape of Non-Spherical Particles?

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- **Common diameter definitions ***

Aerodynamic/drag diameter	Diameter of a sphere of unity density with the same terminal velocity as the particle
Stokes diameter	Diameter of a sphere of same density and the same terminal velocity as the particle
Projected area diameter	Diameter of a circle having the same area as the projection of the particle
Ferets diameter	The mean value of the distance between pairs of parallel tangents to the projected outline of the particle
Martins diameter	The mean chord length of the projected outline of the particle
Area equivalent diameter	Diameter of a sphere having the same surface area as the particle
Volume equivalent diameter	Diameter of a sphere having the same volume as the particle
Sieve/mesh diameter	The width of the minimum square aperture through which the particle will pass
Laser diffraction diameter	Diameter is calculated according to the Mie or Fraunhofer diffraction theory

$$\boxed{d_{eq} = \sqrt[3]{\frac{6V_p}{\pi}}}$$

* From Mandø & Rosendhal, Powder Technology 202 (2010) 1-13

How to Define Size and Shape of Non-Spherical Particles?

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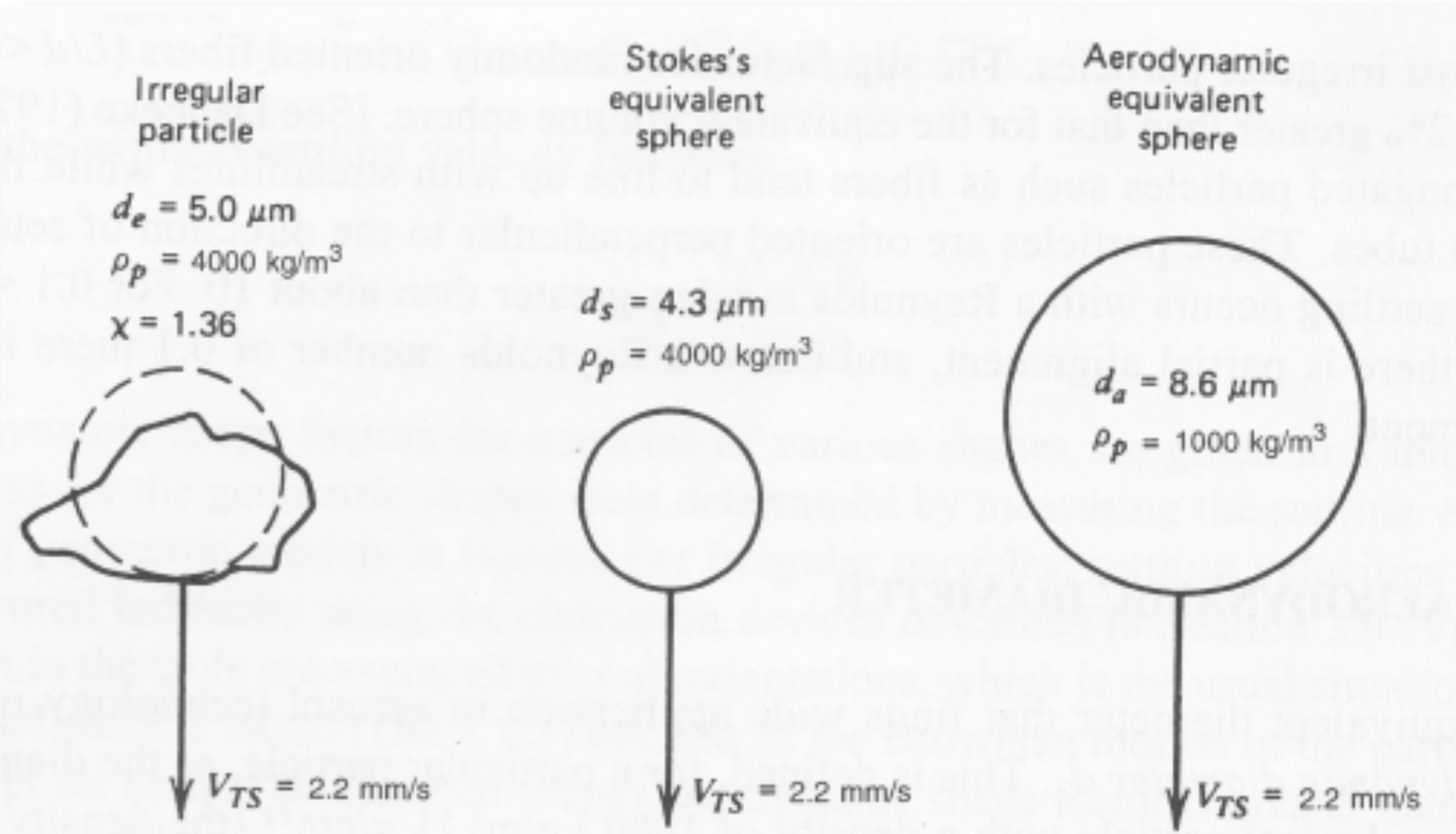

The aerodynamic diameter is always larger than the Stokes's equivalent diameter

How to Define Size and Shape of Non-Spherical Particles?

- Common shape factors
  - Volumetric shape factor
  - Corey shape factor
  - Roundness
  - Sphericity

$$\psi = \frac{S_{sph}}{S_p} \approx \sqrt[3]{\frac{V_p}{V_{sph}}} \approx \sqrt[3]{\frac{L \cdot I \cdot S}{L^3}}$$

How to Define Size and Shape of Non-Spherical Particles?

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- Common shape factors
  - Volumetric shape factor
  - Corey shape factor
  - Roundness
  - Sphericity

$$\boxed{\psi = \frac{S_{sph}}{S_p} \approx \sqrt[3]{\frac{V_p}{V_{sph}}} \approx \sqrt[3]{\frac{L \cdot I \cdot S}{L^3}}}$$

In many engineering handbooks, drag is estimated using correlations for spherical particles and corrected for non-spherical particles based on sphericity

Good shape factors should correlate well with the particle's terminal velocity

Problem: a cylinder and a disc with the same sphericity have different terminal velocity!

How to Define Size and Shape of Non-Spherical Particles?

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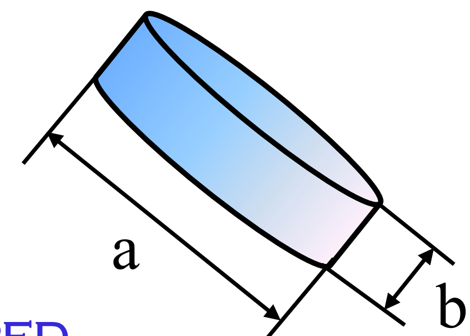
Consider for instance a cylindrical particle:

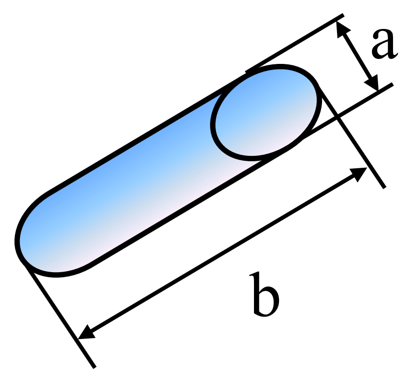
$$\boxed{\psi = \frac{S_{sph}}{S_p} = \frac{2\left(\frac{3}{2}\lambda\right)^{\frac{2}{3}}}{1+2\lambda}}$$

- Reminder: crosswise sphericity!

$$\boxed{\psi(\lambda \approx 0.42) = 0.8} \qquad \boxed{\psi(\lambda \approx 2.67) = 0.8}$$



$$\boxed{\lambda = \frac{b}{a}}$$



Disk-shaped particle!

Same sphericity!*

Rod-like particle!

How to Define Size and Shape of Non-Spherical Particles?

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Why do I bother?

Because in the literature:

$$C_D = \frac{\mathbf{F}_\mathrm{D}}{\frac{1}{2}\rho \mathbf{u}^2_{\mathrm{rel}} A_\mathrm{p}} = f(\mathrm{Re}_p, \psi)$$

DRAG COEFFICIENT

SHAPE EFFECTS

OR

$$C_D = f(\mathrm{Re}_p, \lambda)$$

WHERE:

$$\mathrm{Re}_p = \frac{u_{rel} d_\mathrm{p}}{\nu}$$

PARTICLE REYNOLDS NUMBER

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Drag Coefficient for Non-Spherical Particles

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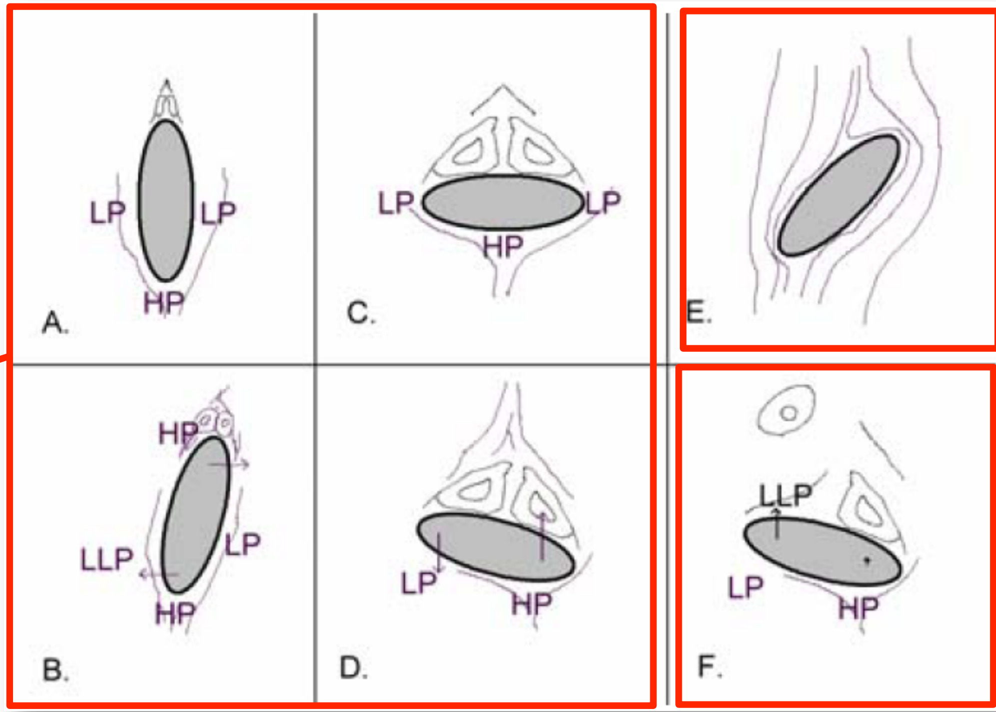
$$Re_p = \frac{u_{rel} d_p}{\nu}$$



Intermediate regime $(0.1 < Re_p < 100)$

Stokes regime $(Re_p < 0.1)$

Newton regime $(Re_p > 100)$

Stokes regime: exact limiting and approximate solutions for the drag on spheroids exist at creeping flow conditions

Newton regime: "empirical" correlations from exp. (Wen & Yu) or sim. (e.g. Loth 2008, Sommerfeld 2009, van Wachem 2012)

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Drag Coefficient for Non-Spherical Particles

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Let's keep it simple: C_D for spheroids in creeping flow

$$\boxed{C_D\left(\lambda, \mathrm{Re}_p \to 0\right) = C_D\left(\mathrm{Re}_p \to 0\right) \cdot f_\lambda}$$

$$\boxed{f_\lambda = \frac{F_D\left(\lambda, \mathrm{Re}_p \to 0\right)}{3\pi d_p \mu_f u_{rel}}}$$

SHAPE	$f_{\lambda\parallel}$	$f_{\lambda\perp}$
OBLATE EXACT ($\lambda<1$)	$\dfrac{(4/3)\lambda^{-1/3}(1-\lambda^2)}{\lambda + \dfrac{(1-2\lambda^2)\cos^{-1}\lambda}{\sqrt{1-\lambda^2}}}$	$\dfrac{(8/3)\lambda^{-1/3}(\lambda^2-1)}{\lambda - \dfrac{(3-2\lambda^2)\cos^{-1}\lambda}{\sqrt{1-\lambda^2}}}$
PROLATE EXACT ($\lambda>1$)	$\dfrac{(4/3)\lambda^{-1/3}(1-\lambda^2)}{\lambda - \dfrac{(2\lambda^2-1)\ln\left(\lambda+\sqrt{\lambda^2-1}\right)}{\sqrt{\lambda^2-1}}}$	$\dfrac{(8/3)\lambda^{-1/3}(\lambda^2-1)}{\lambda + \dfrac{(2\lambda^2-3)\ln\left(\lambda+\sqrt{\lambda^2-1}\right)}{\sqrt{\lambda^2-1}}}$

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Drag Coefficient for Non-Spherical Particles

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From an engineering point of view:

$$\boxed{C_D = f(\mathrm{Re}_p, \mathrm{shape})}$$

could be acceptable (engineers like it easy...)

but a complete description of the drag coeff. for a non-spherical particle would require:

$$\boxed{C_D = f(\mathrm{Re}_p, \mathrm{shape}, \mathrm{orientation})}$$

This requires:

- an expression taking into account all possible inclination angles for a given shape and Re_p
- modelling particle translation, but also rotation (see lecture 2 on Wednesday morning)

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Lessons Learned

L1. Non-spherical particles are ubiquitous in industry and nature

L2. Particles with regular shape are mathematically treatable and exact or approximate solutions are available for particular flow conditions

L3. Shape factors are especially suited for particles with irregular shape

L4. Non-spherical particles require a multi-parameter description

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R7. Sui y, Chew yt, Roy p, Cheng yp, Low ht, Phys Fluids, vol 20 (2008), pp 112106

R8. Umeki K, Kirtania K, Chen L, Bhattacharya S, Ind Eng Chem Res vol 51 (2012), pp 13973-13979

R9. Zhang Z, Kleinstreuer C, Kim CS, J Aerosol Sci, vol 33 (2002) pp 257-281

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Thank You
For Your Kind Attention!

Any questions?