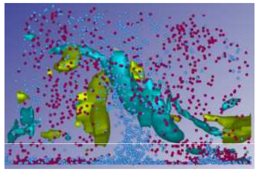


Doctoral Course in:

Modelling Turbulent Dispersed Flows

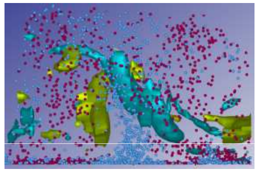
Particles, Vortices, Coherent Structures and Turbulence: Physics, computations and a little literary review

Alfredo Soldati [§*]

[§] Dipartimento di Energetica e Macchine &
Centro Interdipartimentale di Fluidodinamica e Idraulica, Università di Udine

[*]Dept. Fluid Mechanics, International Center for Mechanical Sciences, Udine

Lausanne, 7 May 2008



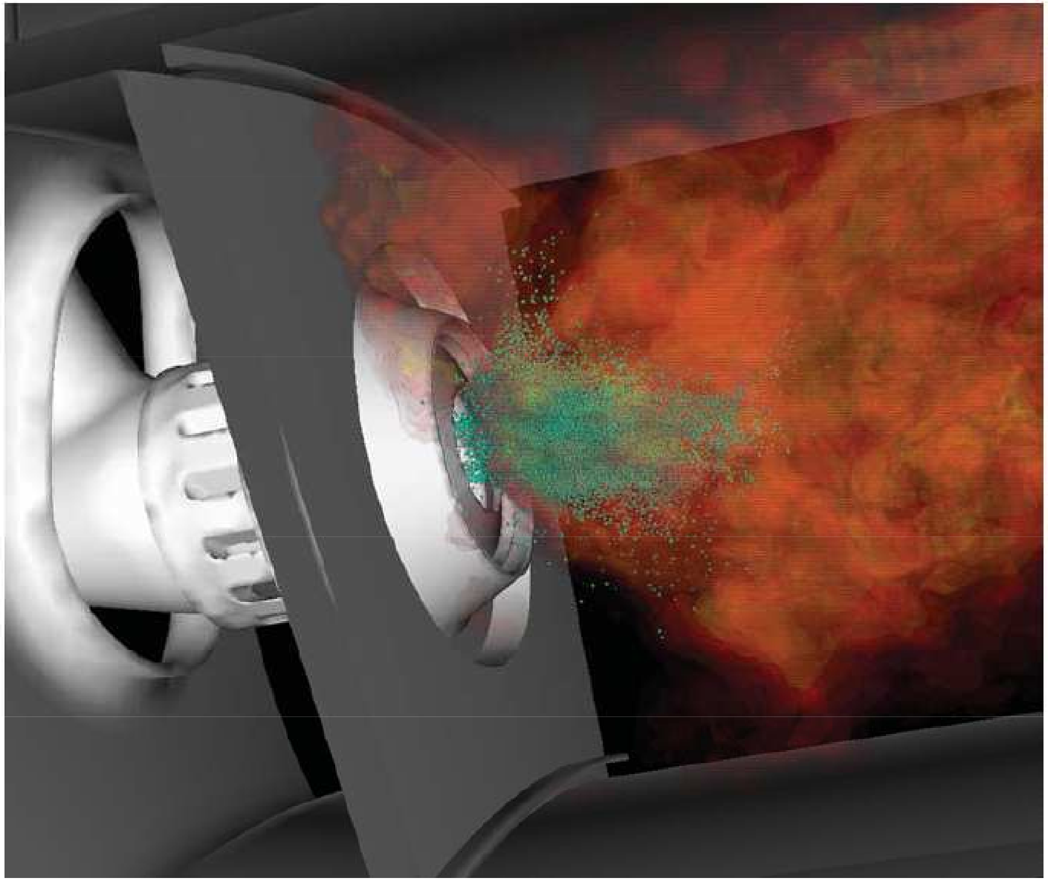
A complicated scientific application…

Our motivation is turbulent dispersed and reactive flow modelling

In this picture…
A sophisticate recent simulation
Of a dispersion of droplets burning
Into a Pratt & Whitney gas Turbine
Combustor.

Modelling Problems:

1. **Turbulence**
2. **Droplets and turbulence**
3. **Droplet evaporation and reaction**
4. **Droplet droplet interaction..**
5. **…**

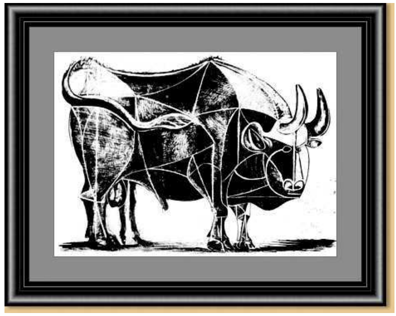


Large-Eddy Simulation of a modern Pratt & Whitney gas turbine combustor (Mahesh et al. 2005, Moin & Apte 2005).

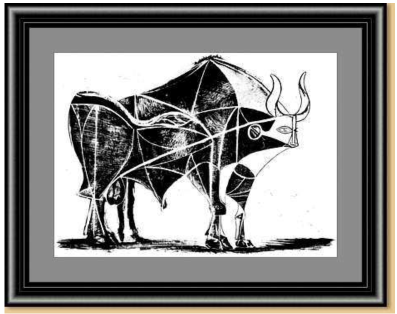
Bull (Plate I. - December 5 1945)

Bull (Plate II. - December 12 1945)

Bull (Plate III. - December 18 1945)



Bull (Plate IV. - December 22 1945)

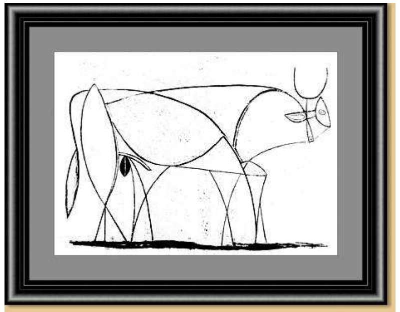


Bull (Plate V. - December 24 1945)

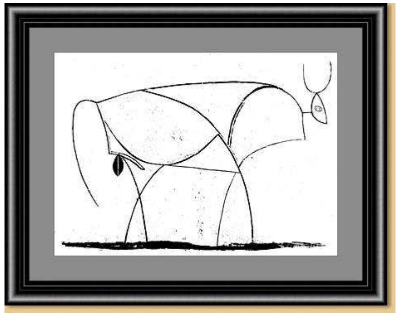
Bull (Plate VI. - December 26 1945)

Bull (Plate VII. - December 28 1945)

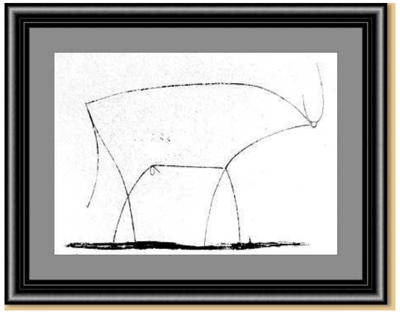
Bull (Plate VIII. - January 2 1946)



Bull (Plate IX. - January 5 1946)



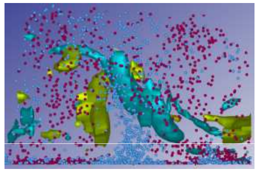
Bull (Plate X. – January 10 1946)



Bull (Plate XI. - January 17 1946)

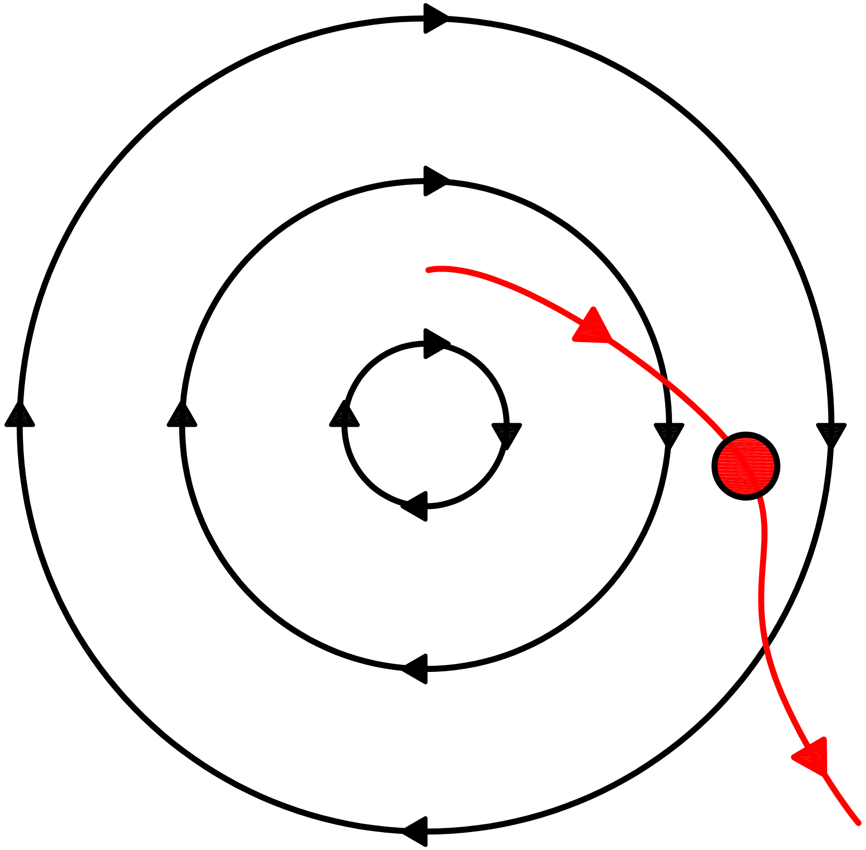
He has ended up where he should have started! He had gone in successive stages through all the other bulls. When you look at that line you canno imagine how much work it involved. He had in mind to retrieve the bull's constituent parts, his dream bull - bred of pure lines - an elemental, disembodied, quintessential bullishness

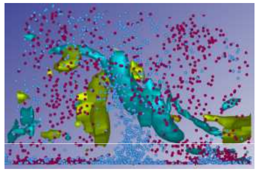
Picasso



The simplest problem…

- *We focus on the problem of the one single particle in a fixed vortex*





… A little Literature search on the influence of inertia on the Behavior of a floating body immersed in a vortical fluid

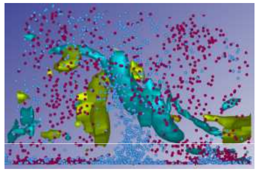
ilors
ner w
ms in

Homer let Circe tell the sailor experinece to Odysseus….

… A famous ‘local’ vortex. 2….
An important difference between elongated bodies and spheres

Edgar Allan Poe, in his Descent

ment



… Essentially, we learn that inertia controls particle dynamics
This is expressed via the particle relaxation time scale

The dynamics of a particle is controlled by the single parameter τ_p (in the simplest dynamic model)

$$\frac{d\, m_p \overline{v}_p}{dt} = \frac{1}{2} C_D^{*} \pi \frac{D_p^2}{4} \left(\overline{u}_f - \overline{v}_p\right) \left|\overline{u}_f - \overline{v}_p\right|$$

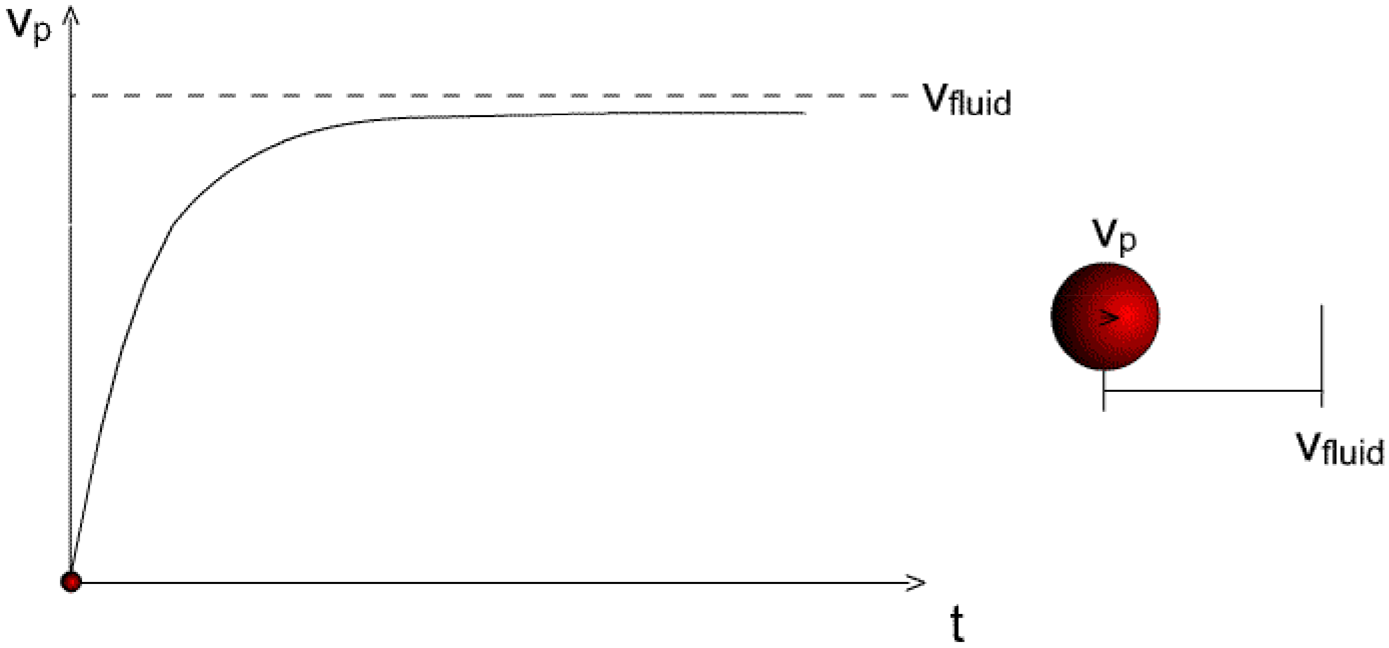
which reduces to: $\dfrac{d\overline{v}_p}{dt} = \dfrac{\overline{u}_f - \overline{v}_p}{\tau_p}$

τ_p = particle charact. Time scale $= \rho_p \dfrac{D_p^2}{18\mu}$

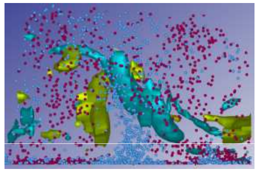
---

*purely creeping flow (Stokes flow)

… *Essentially, we learn that inertia controls particle dynamics*
This is expressed via the particle relaxation time scale



.. The particle relaxation time scales with the time
It takes to accelerate a particle to the ambient fluid velocity

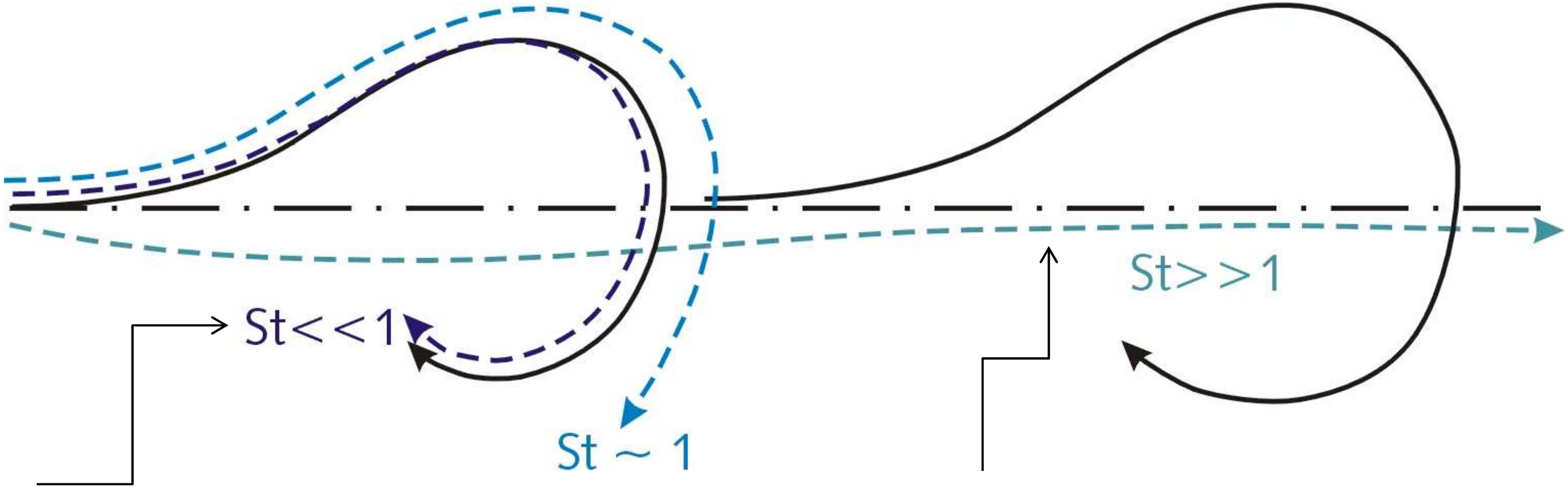


The characteristic particle time scale has a meaning when compared with a relevant Flow Time scale

Particle Relaxation Time, $\tau_p = d_p^2 \rho_p/18$

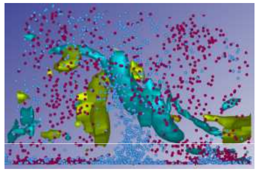
Flow Time Scale, τ_f^{μ}

Particle Stokes number, St: τ_p/τ_f



Viscosity Dominated Motion

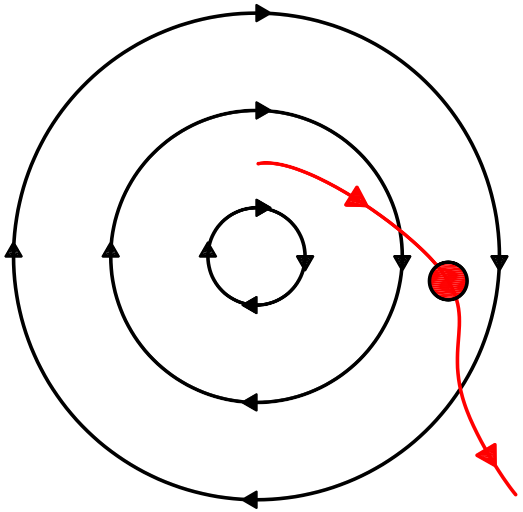
Inertia Dominated Motion



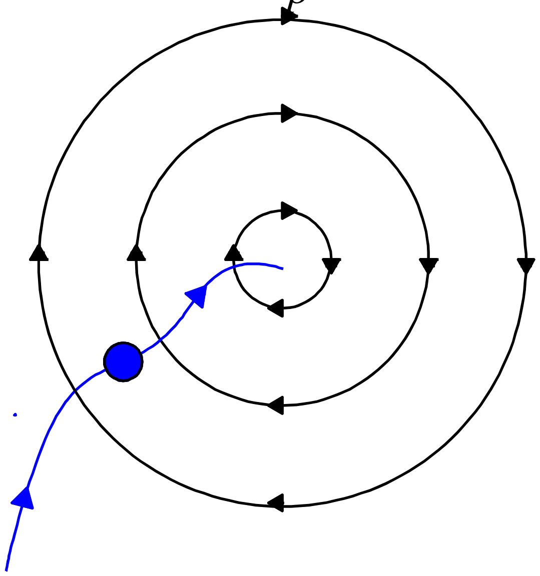
And now, we can get more complicate…

We start with two-D vortices and poitwise spheres….

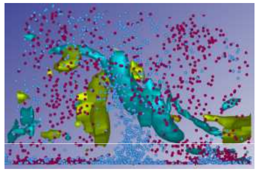
- **Particle (Aerosol):** $\rho_p >> \rho_F$



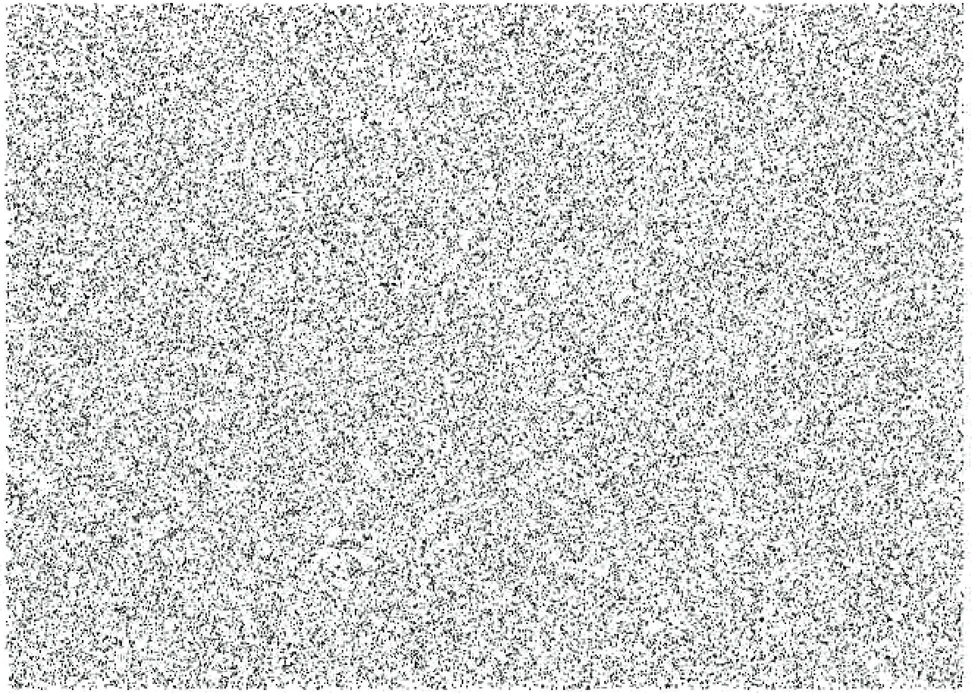
- **Bubble:** $\rho_p << \rho_F$



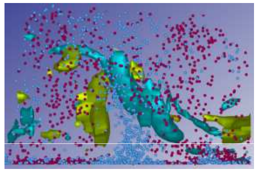
- **Particles are expelled from the vortices via the slingshot effect**
- **Bubbles are driven inward, due to the lesser inertia**



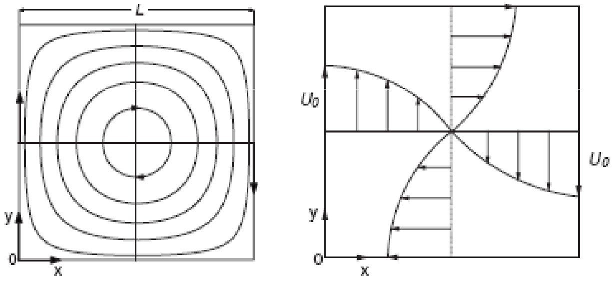
… So, in a more pictorial view, if there are no vortices we can picture particle settling under gravity as…



Particles settle at the velocity determined by the equilibrium between Drag (Stokes) and Gravity: $v_s = d_p\ 2g(\rho_p\text{-}\rho_f)/(18\ \mu)$

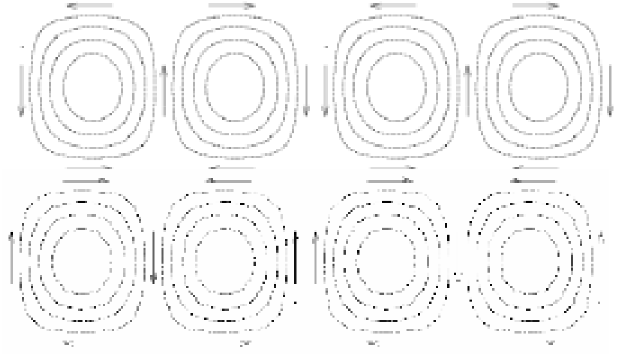


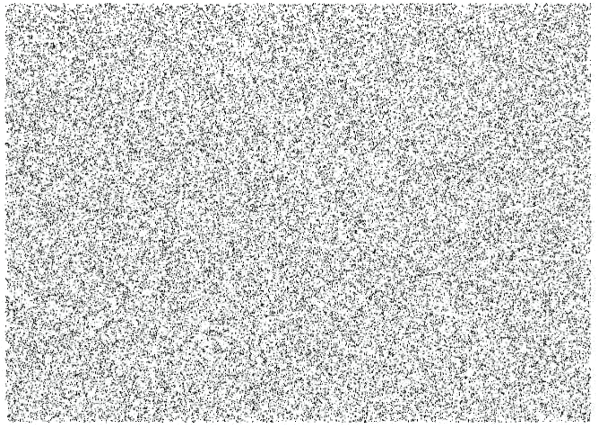
.. *What if we add vortices? The problem of light/heavy particle settling under gravity becomes non-trivial (Maxey 1987) …preferential segregation*

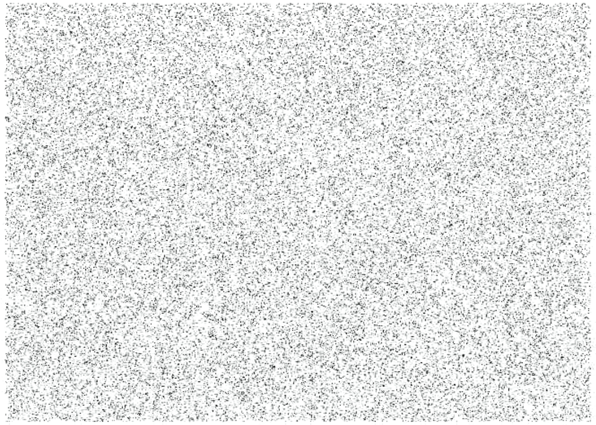


(a) (b)

FIG. 1. (a) Streamlines and (b) velocity profiles for the periodic cellular flow field. The arrows show direction of the flow.



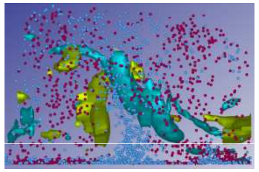




Heavy Particles

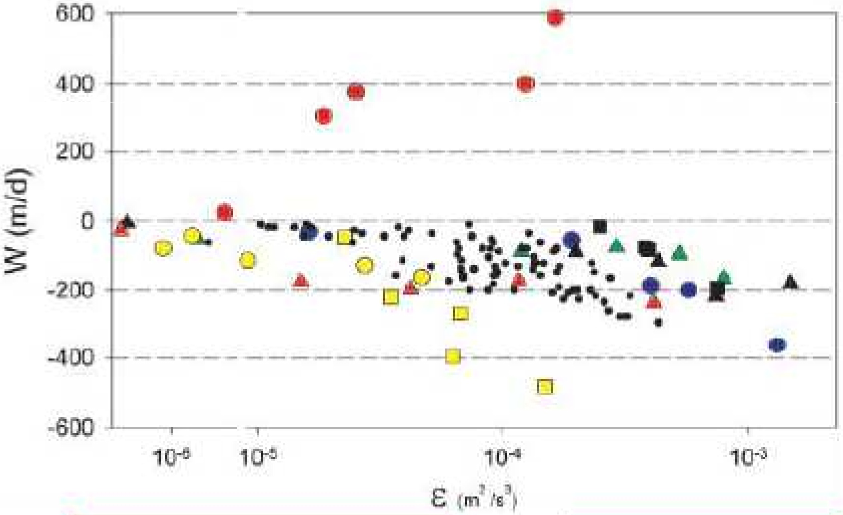
Light Bubbles

Heavy particles are propelled out of the vortices while settling down. Light bubbles are propelled inward while rising up. Globally, there is a general influence on the effective settling velocity (Maxey, Phys Fluids 1983)



…with this in mind, the following experiments become inexplicable…

Turbulence increases the average settling velocity of phytoplankton cells

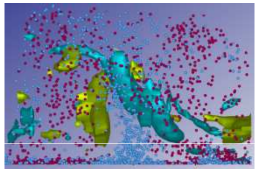


$$\langle v_y \rangle > v^{Stokes}$$

$$\rho \approx \rho^{water}$$

A species of *phytoplankton* (●, *Artemia Salina Eggs*) rise with:

At a recent conference this paper was brought to the attention of an audience largely Inexperienced of Biocomplexity problems….How can be a particle heavy enough to take the Vortex uplift and still light enough to rise?



…but this because there is more than just gravity, drag and inertia…there are the non-stationary effects and others…

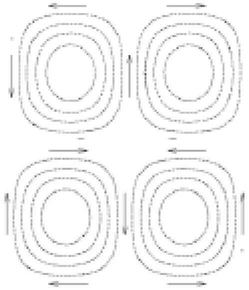
- many forces dominate particle motion: *added mass*, *lift*, Basset…

$$m_p \frac{d\vec{v}_p}{dt} = (m_p - m_F)\vec{g} + m_F \frac{D\vec{u}}{Dt} - \frac{1}{2} m_F \frac{d}{dt}(\vec{v}_p - \vec{u}) - 6\pi a\mu(\vec{v}_p - \vec{u}) - 6\pi a^2 \mu \int_0^t \frac{d(\vec{v}_p - \vec{u})/d\tau}{\sqrt{\pi\nu(t-\tau)}} d\tau$$

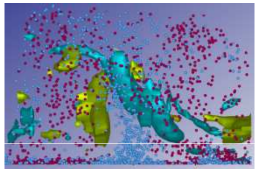
Maxey and Riley, 1983

Object is to study the behavior of particle only slightly lighter than the surrounding fluid in a Taylor-Green Cellular Flow.

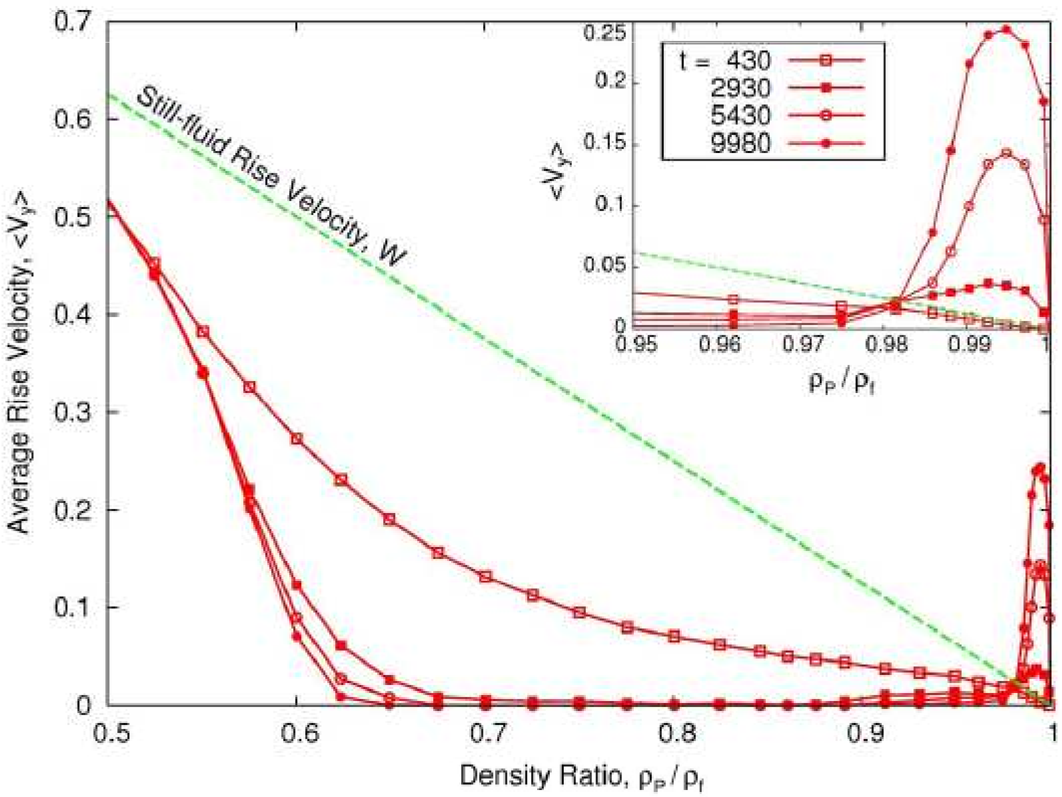
- We will reproduce the numerical model of Maxey PoF (1987);
- Particle/fluid density: ρ_p/ρ_f [0.5:1.0]
- Forces Acting: Inertia; Gravity; Buoyancy; Added Mass



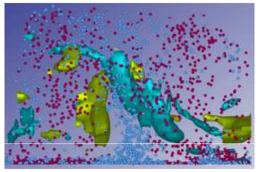
Albeit an unsatisfactory model, this equation is probably the most accurate Representation of the forces acting an a particles moving in a fluid under no restrictive Assumption beside being poitwise (!!!)



…just addinf the added mass effect the rise velocity of plankto can change dramatically….



Mean rise velocity, <Vy>, of light particles in (Taylor-Green) vortex flow versus particle-to-fluid density ratio, ρ_p/ρ_f (Marchioli et al., Phisics of Fluids, 2007)



… intermezzo…but please, remain seated

First half:

The problem of particle dispersion in vortical flows is Definitely non-trivial…there is still room for simple models

Second Half:

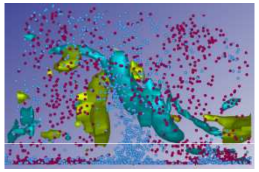
And what can we do with complicate models?

We want to solve for turbulence…how accurately?

Pollution in the Caspian sea (from B.G.)

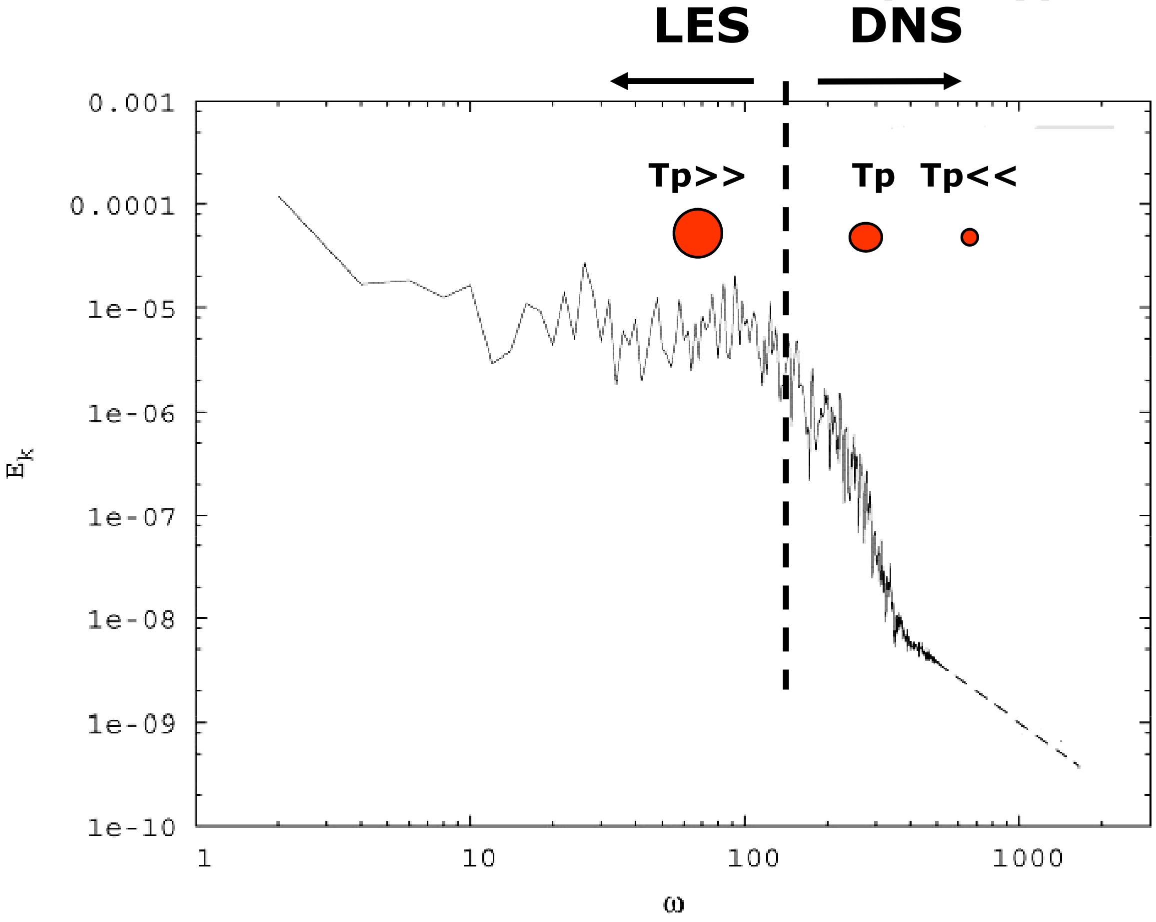
Non Filtered

Filtered



but, in (albeit dilute) multiphase Turbulent flow, which are the relevant scales we should solve for particle motion?

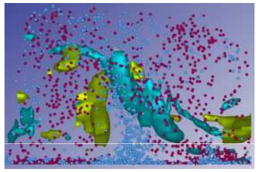
This is a generic turbulence spectrum (Energy Associated with frequency)



Any filter will prevent particles from being exposed to small scales which can modify their local behavior, segregation,

Inaccurate particle dispersion will bring errors into subsequent particle motion and fluid

The scatter in the data is too large, even for Engineers! And these data Are actually used for modelling practice



So, how can we solve all these scales? We do not want to filter Out any relevant scale of motion! …

Reynolds Averaged Techniques

(Fluent, StarCD, CFX, etc.)

- **Need extensive empirical data for constants**
- **Geometry specific**
- **Underlying assumption of isotropy (sometimes)**

$<u'_i\, u'_j>$

$<u'_i\, T'>$

Large-Eddy Simulations (LES) (Commercial Research, etc.)

- **Resolve the large eddies**
- **Average over small scales**
- **Simple universal models (may be)**

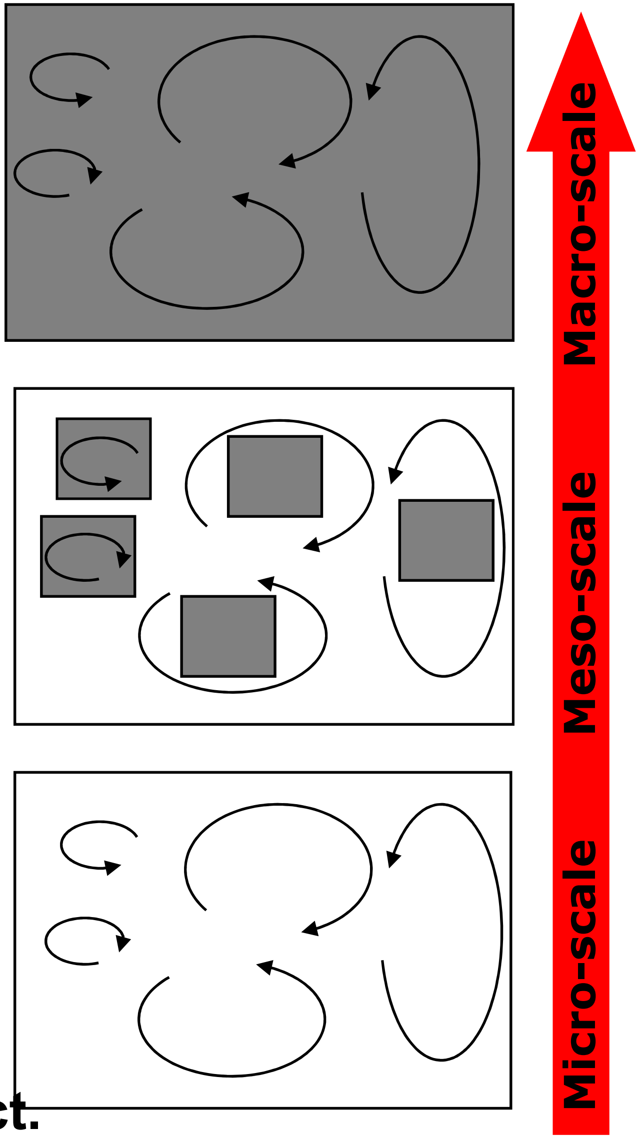
$\overline{u'_i\, u'_j}$

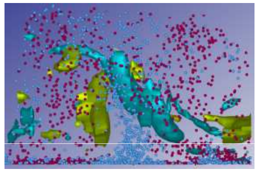
$\overline{u'_i\, T'}$

Direct Numerical Simulation (DNS)

- **Valid for resolution finer than smaller eddies**
- **Applicabile to low Reynolds number turbulent flows (-> due to limited computational power)**

Operative def. DNS: No need of subgrid Models to predict smaller scales motion/effect.





The downside of Direct Numericsal Simulation
Numerical Issues: Spatial Resolution

- Influenced by numerical method used (spectral methods are better)

- Differentiation error and errors due to nonlinearity of governing equations also affect

- Reynolds number is most important. DNS is restricted (by cost considerations) to low Re flows.

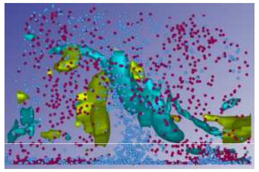
$$N_{DNS} = (0.088\,\mathrm{Re}_h)^{9/4}$$

- => Re of 10^6 requires 133 billion grid points!!

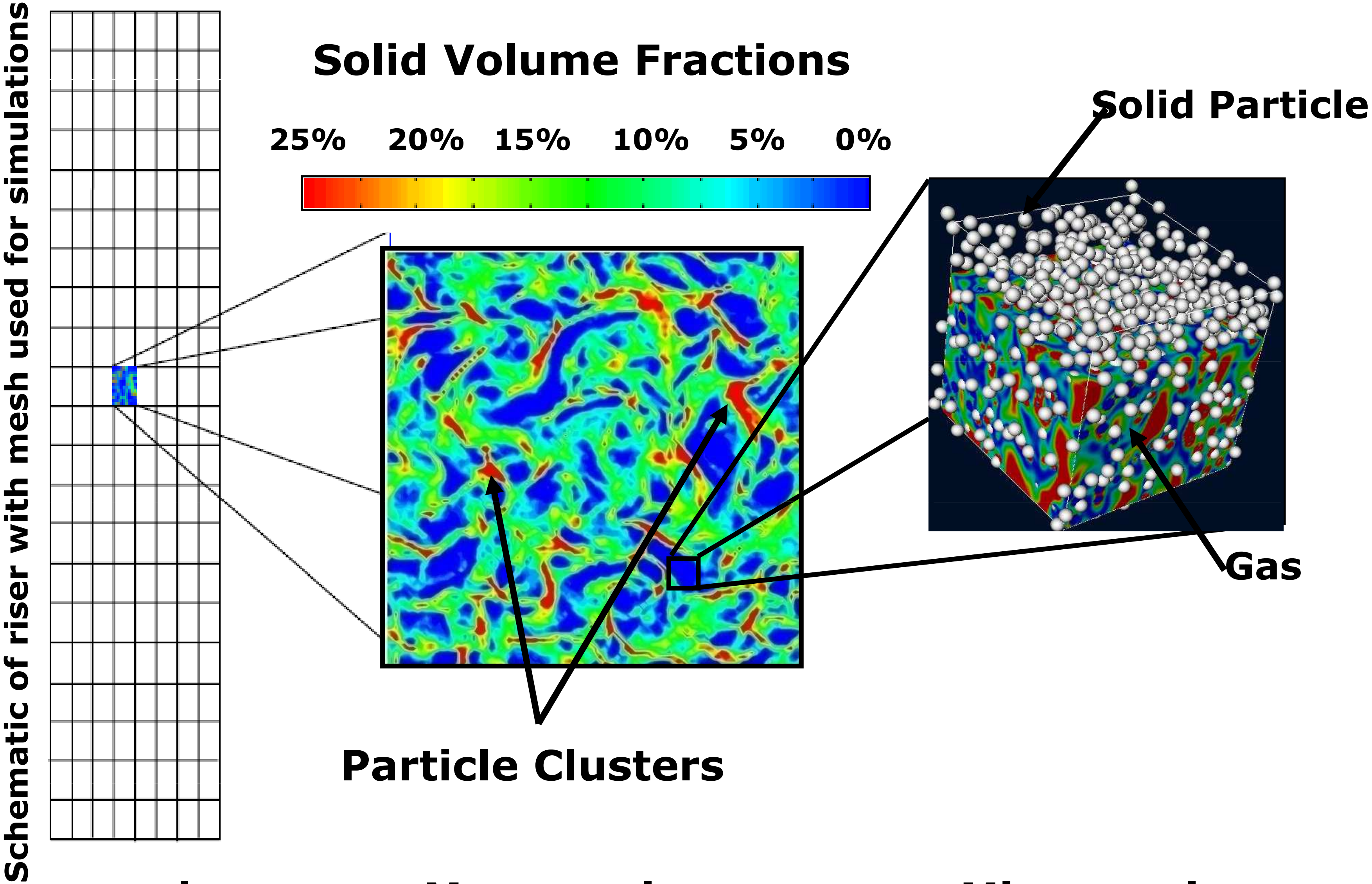
- But, since the higher Re the smaller (and faster) the vortices, the cost is proportional to $\mathrm{Re}^{(11/4)}$

- Optimal Re depends upon application. Re of DNS need not actually match real-life Re to be useful

Part I



Our approach is the following: we solve smaller problems in the belief that they 'Control' the macroscale behavior



Schematic of riser with mesh used for simulations

Solid Volume Fractions

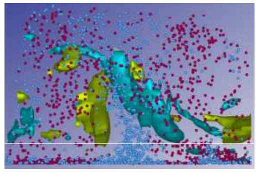
25% 20% 15% 10% 5% 0%

Solid Particle

Gas

Particle Clusters

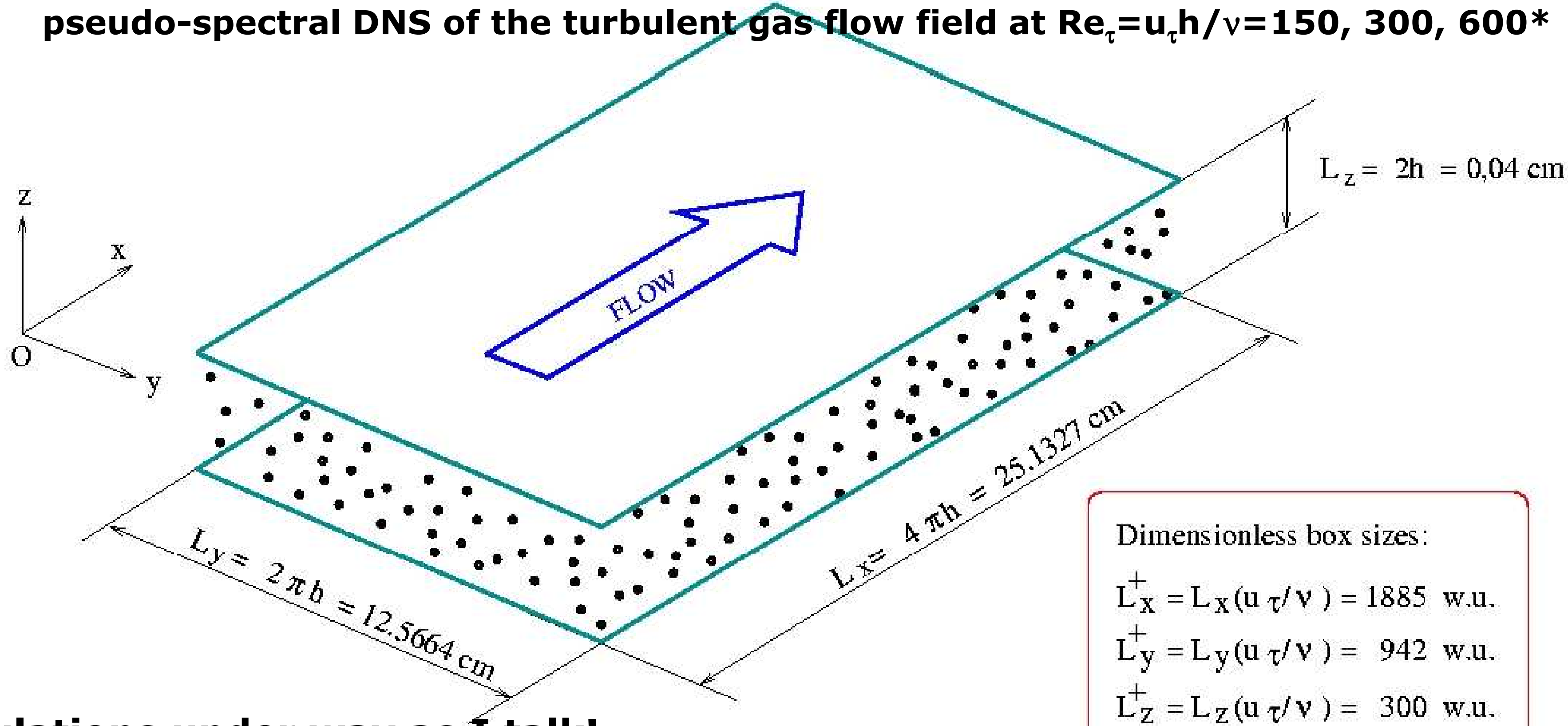
Macro-scale (cm-m) Meso-scale (mm – cm) Micro-scale (μm)



...What we do in our lab is Direct Numerical Simulation to Understand the Physics and develop simpler models for engineering practice

We focus on this problem

pseudo-spectral DNS of the turbulent gas flow field at $Re_\tau = u_\tau h/\nu = 150, 300, 600$*



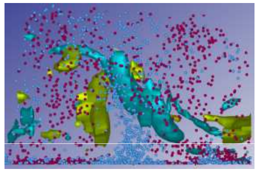
Dimensionless box sizes:

$L_x^+ = L_x(u_\tau/\nu) = 1885$ w.u.

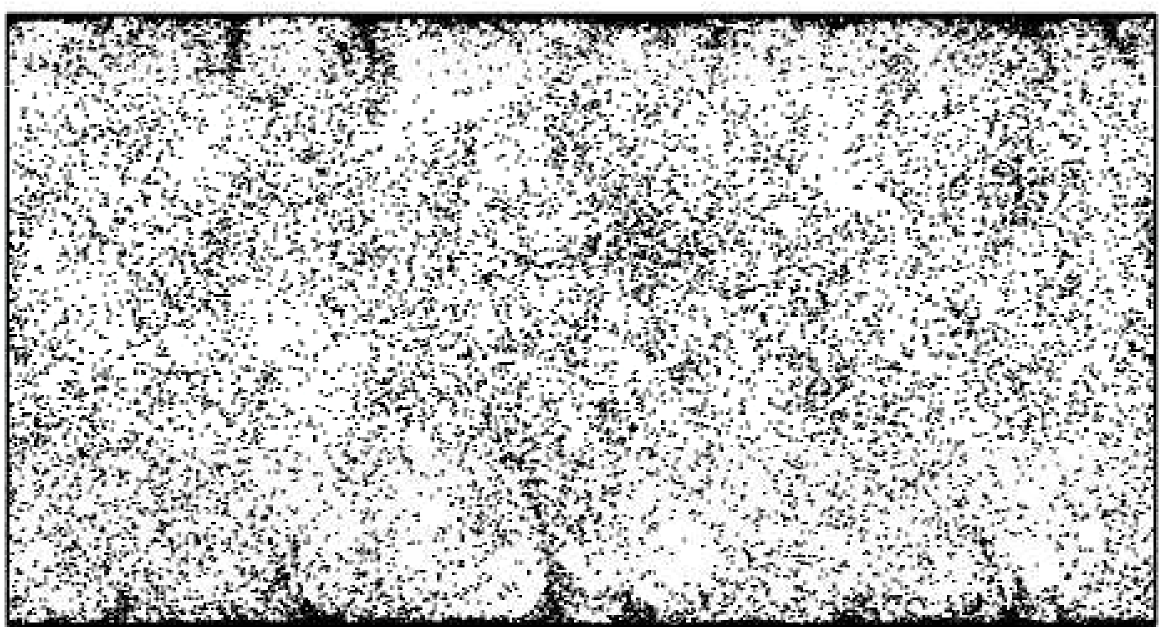
$L_y^+ = L_y(u_\tau/\nu) = 942$ w.u.

$L_z^+ = L_z(u_\tau/\nu) = 300$ w.u.

Calculations under way as I talk!



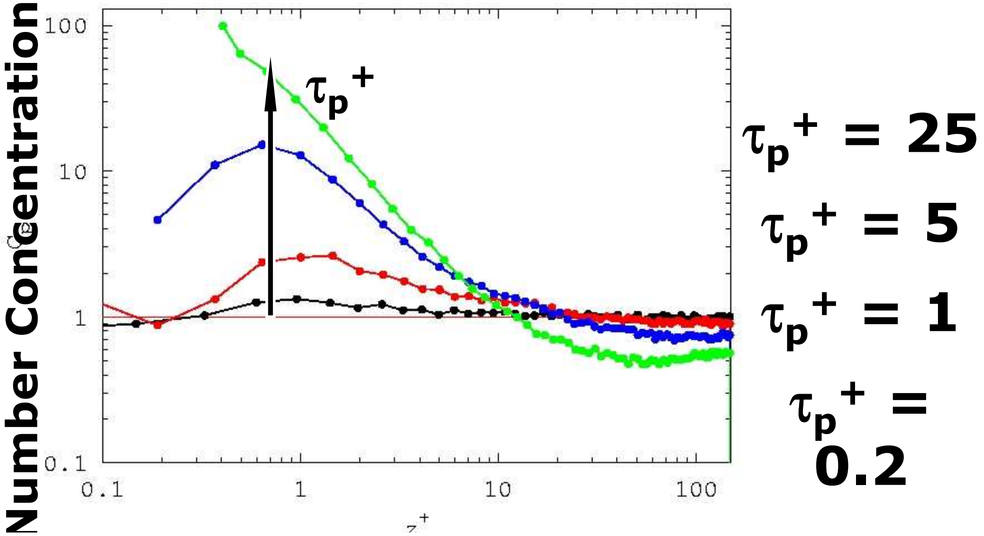
This is the typical result of our computational experiments!

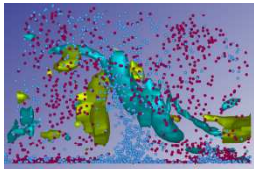


Observation –

In Bounded flows particles accumulate at the wall at different rates depending on their inertia (forces:drag and inertia)

Accumulation at the wall is turbulence induced and non uniform. Phenomenon will persist from a qualitative viewpoint until gravity will dominate (large particles)





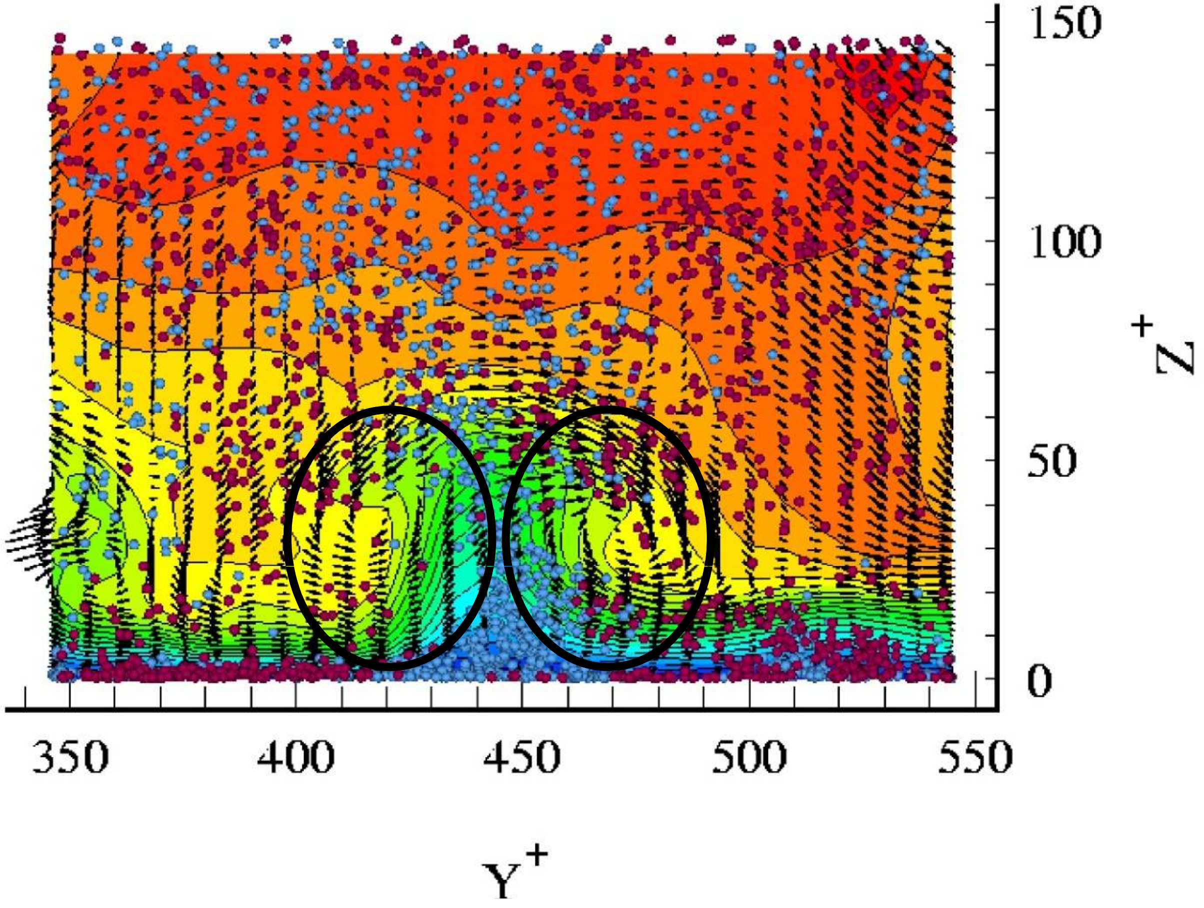
Rule of Thumb for Maximum Segregation/Deposition:
Matching between particles and wall flow scales

Red: high
Streamwise vel.

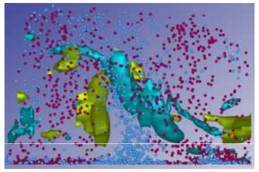
Blue: low
Streamwise vel.

Purple Particles:
to the wall

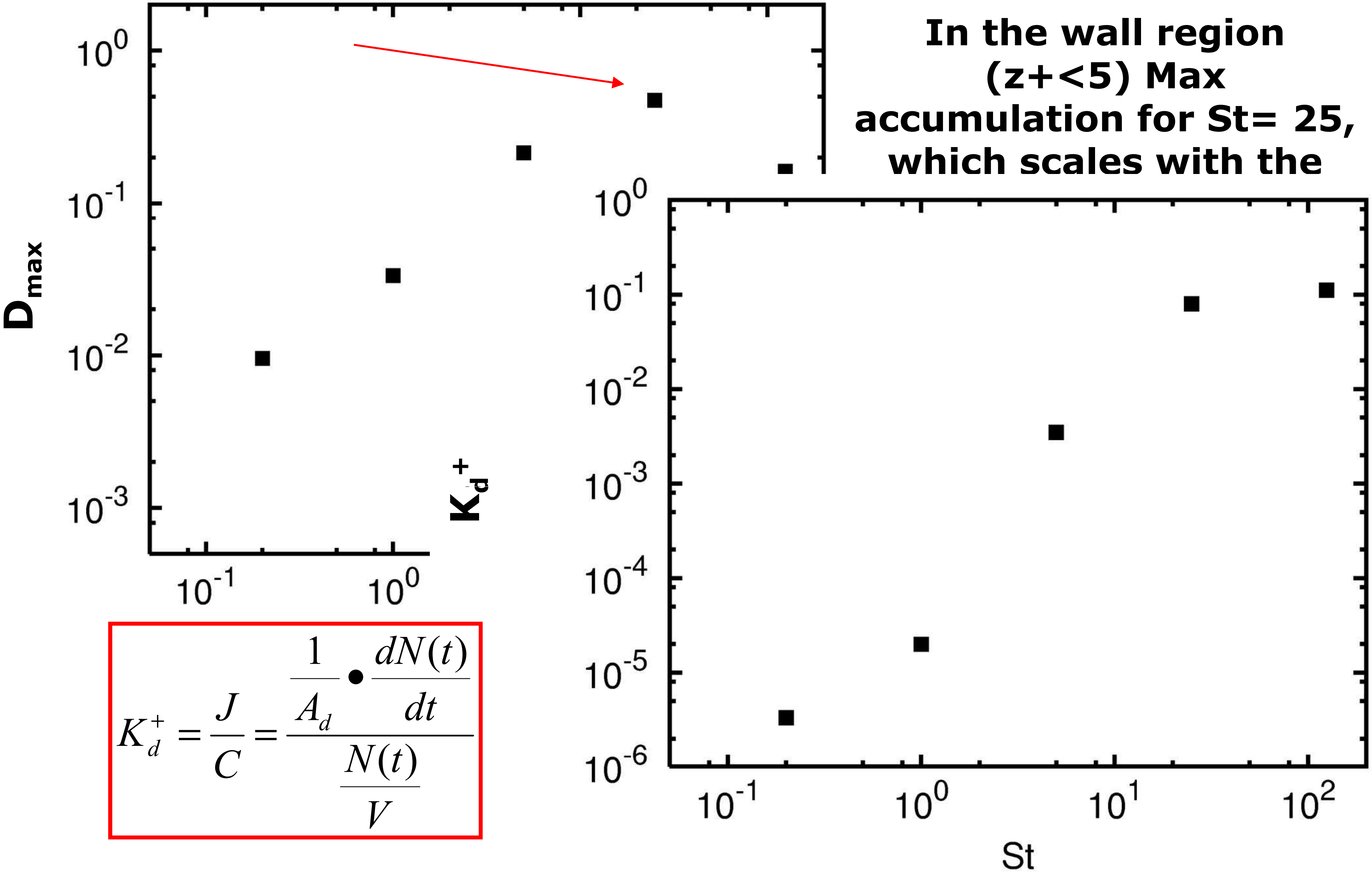
Blue Particles:
off the wall



In the context of industrial modelling of turbulent dispersed flows:
… is an accurate quantification of this effect currently available? (practical issue)
… will Large Eddy Simulation be able to capture this effect? (modelling issue)

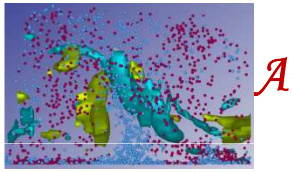


Deposition happens in two stages:
First: Accumulation near the wall
Second: deposition at the wall

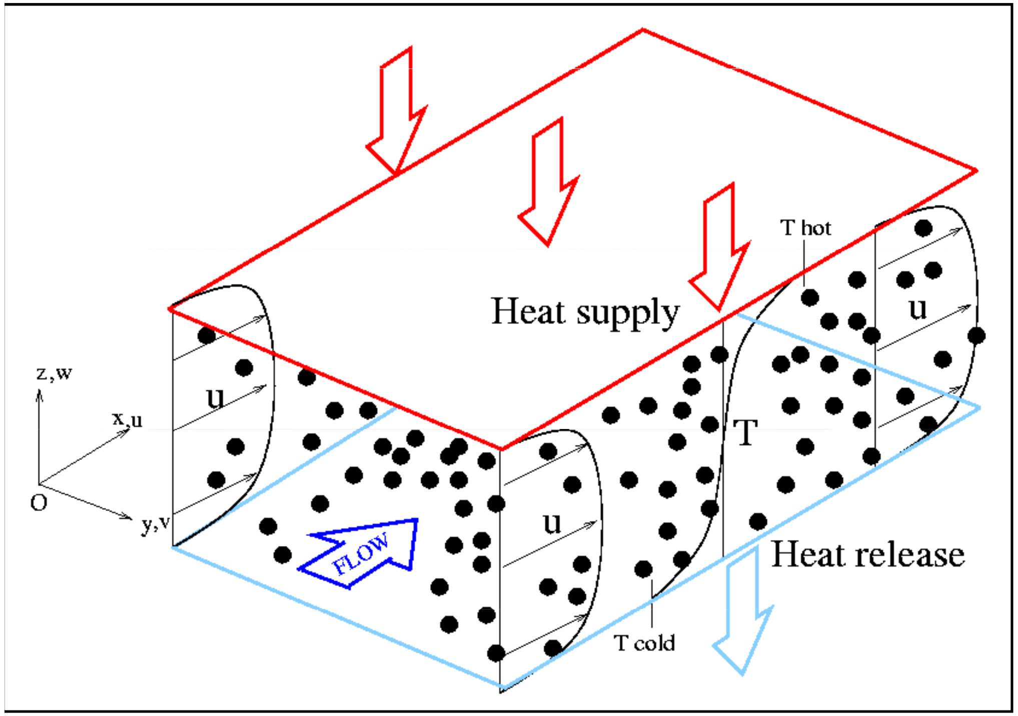


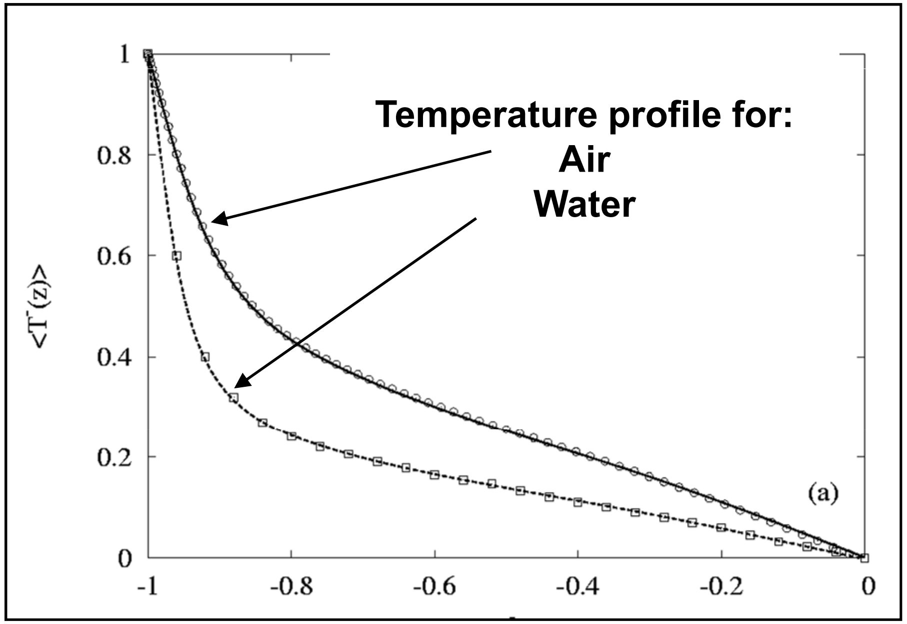
In the wall region (z+<5) Max accumulation for St= 25, which scales with the

$$K_d^+ = \frac{J}{C} = \frac{\frac{1}{A_d} \bullet \frac{dN(t)}{dt}}{\frac{N(t)}{V}}$$



And now a fancy application: we added many micro and nano particles to a Turbulent fluid in between differentially heated walls (Paper in the special issue)





Temperature profile for:
Air
Water

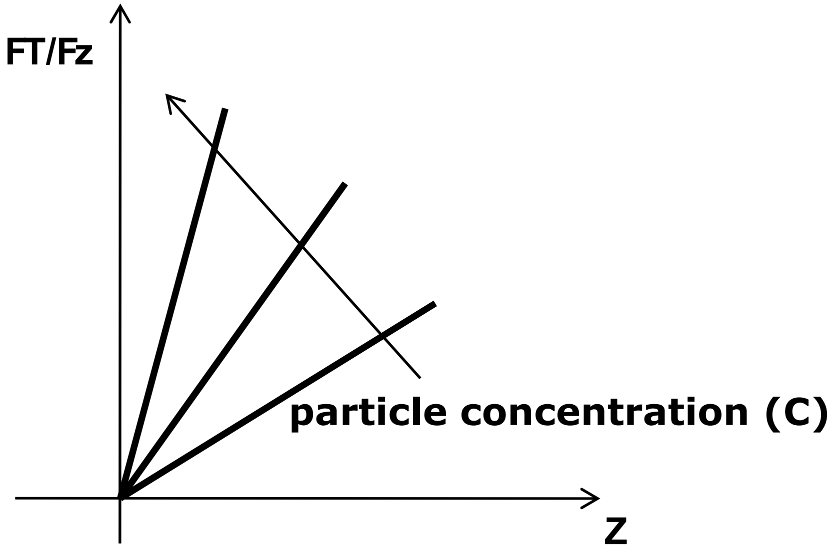
Removable heat flux (flux at the wall)

$$q_w = k \left.\frac{\partial T}{\partial z}\right|_w$$

and k is low for water and air

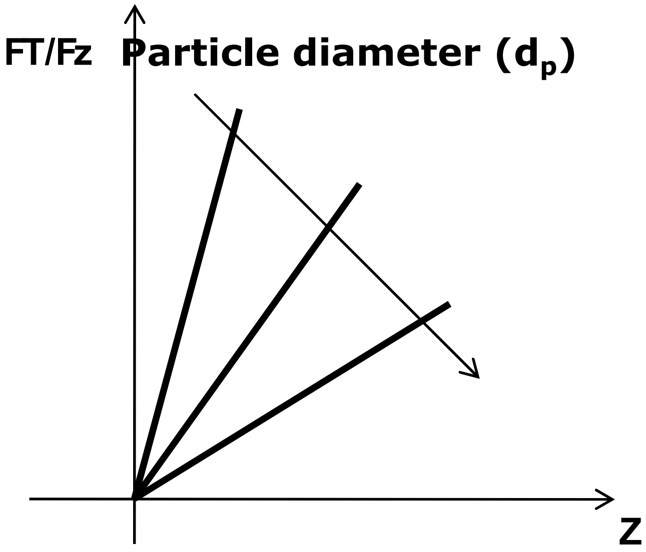
if we can use only water and we want to increase turbulent heat transfer...

Influence of particles on carrier fluid Temperature field



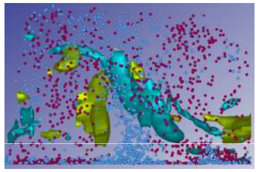
Particle diameter (d_p) = cost

↗Concentration → ↗Wall Heat flux

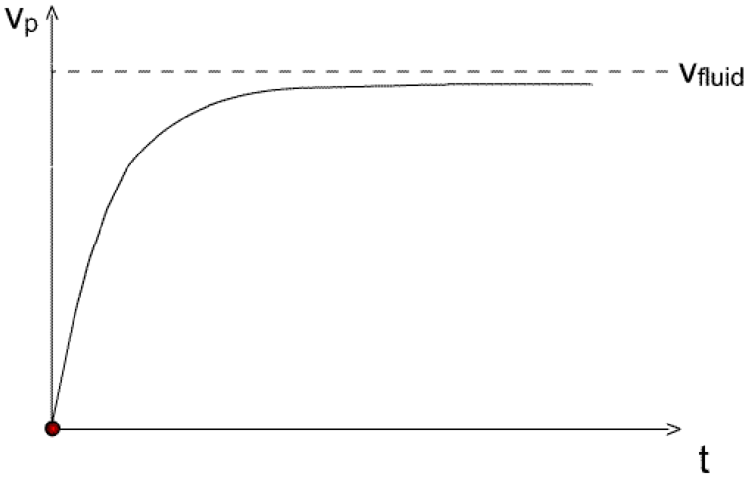


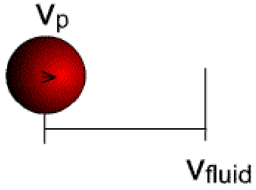
Particle concentration (C) = cost

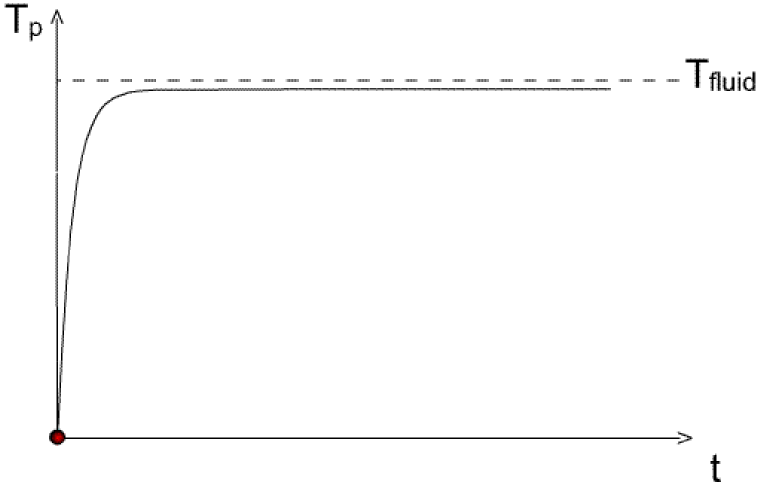
↘Particle diameter → ↗Wall Heat flux

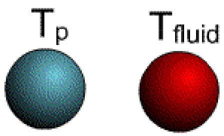


… The trick here is to use particles with small inertia but large thermal inertia

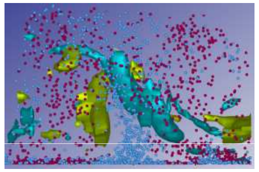








.. So particles should behave like fluid but should carry the heat a longer time…
Exactlky the opposite of what is shown



... and what did we obtain insofar?
...heavy computations but not much quantitative satisfaction

Mass Conservation

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad i = 1,2,3 \quad j = 1,2,3$$

Mom. Conservation (Navier-Stokes)

$$\frac{\partial u_i}{\partial t} = -\frac{\partial u_i u_j}{\partial x_j} + \delta_{i1} + \frac{1}{Re}\frac{\partial^2 u_i}{\partial x_j \partial x_j} - \frac{\partial p}{\partial x_i}$$

Heat Transport

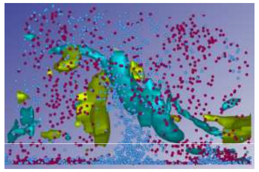
$$\frac{\partial T}{\partial t} = -\frac{\partial T u_j}{\partial x_j} + \frac{1}{Re \cdot Pr}\frac{\partial^2 T}{\partial x_j \partial x_j}$$

Momentum Cons. For each particle

$$\bullet\ m_p \frac{d\bar{v}_p}{dt} = \sum_i \tilde{\bar{f}}_i \simeq f(\tau_p^i, \bar{v}_p^*)$$

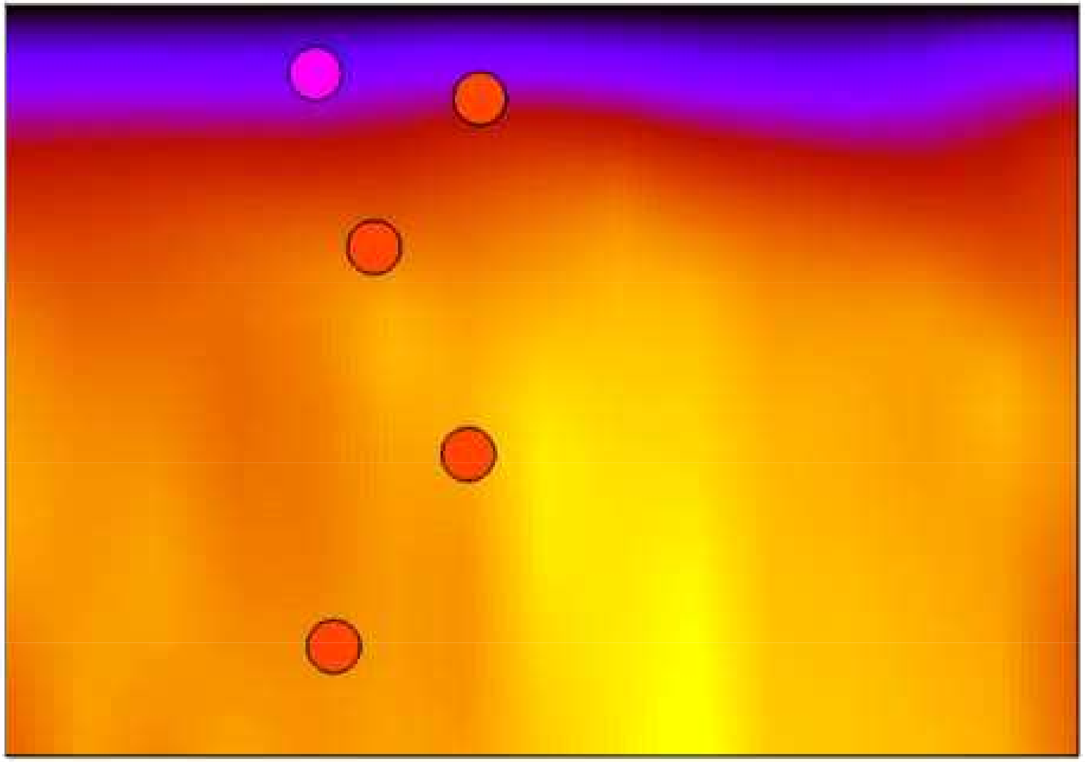
Energy Cons. For each particle

$$\bullet\ m_p c_p \frac{d\vartheta}{dt} = h_p \pi d_p^2 (\tilde{\vartheta} - \vartheta_p) \simeq f(\tau_p^\vartheta, \vartheta_p^*)$$

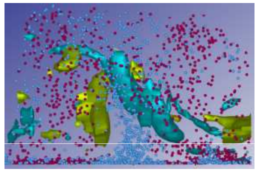


...and what have we obtained insofar?
a collection of qualitative results...

COLD WALL

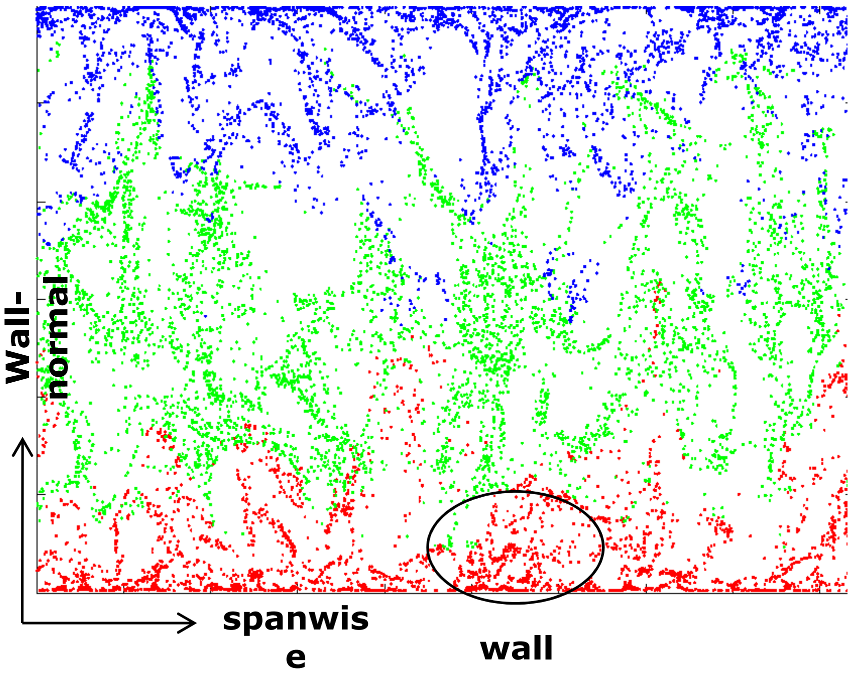


BACKGROUND:
From Yellow (highest) to black (lowest) temperature.

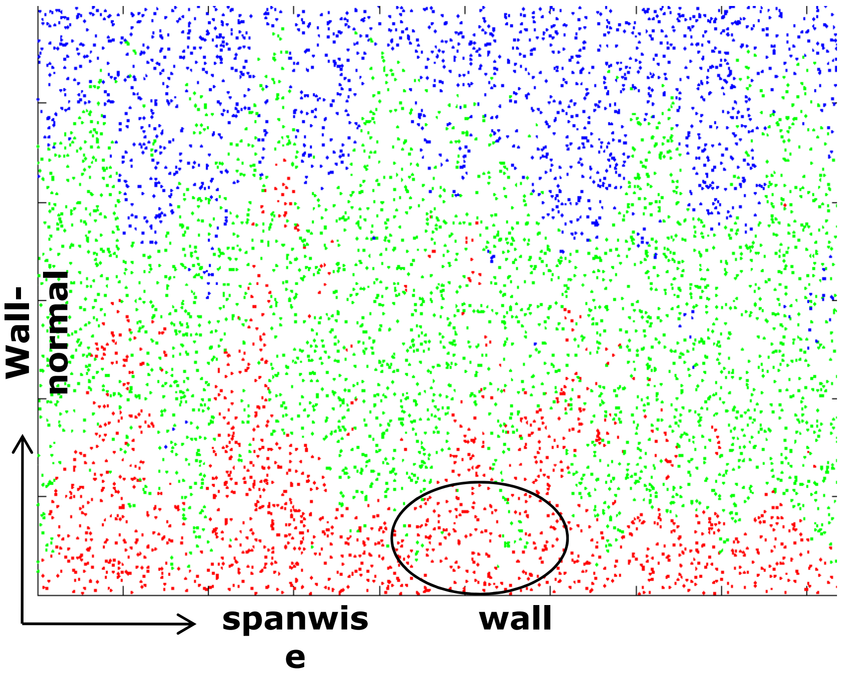


...but in this case we have to avoid preferential distribution.
Size matters, the smaller the better!

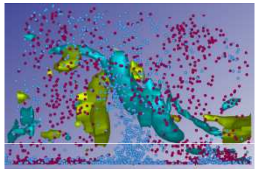
Solids (Gold in this case) have thermal conductivity orders of magnitude higher than water, but their size matters...



8 micron particles segregate



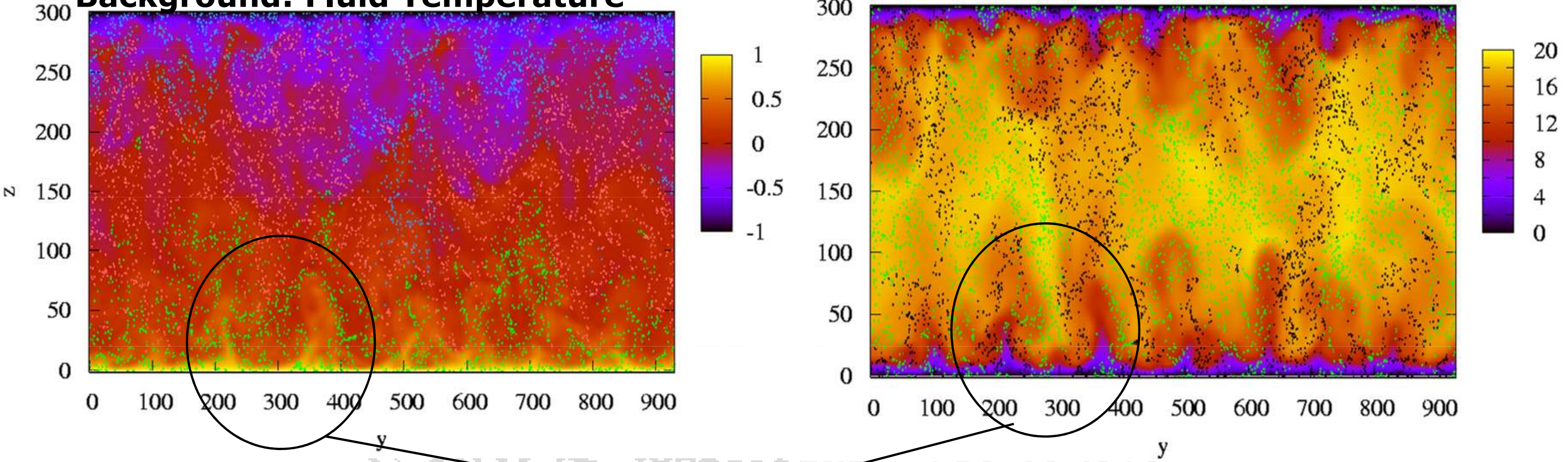
4 micron particles are already uniformly distributed



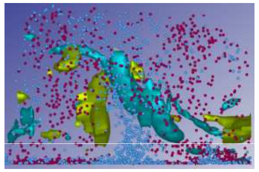
Preliminary Computations: DNS + Lagrangian Particle Tracking and 2 way coupling approach

Green Particles: High Temperature
Purple Particles: Mean Temperature
Blue Particles: Low Temperature
Background: Fluid Temperature

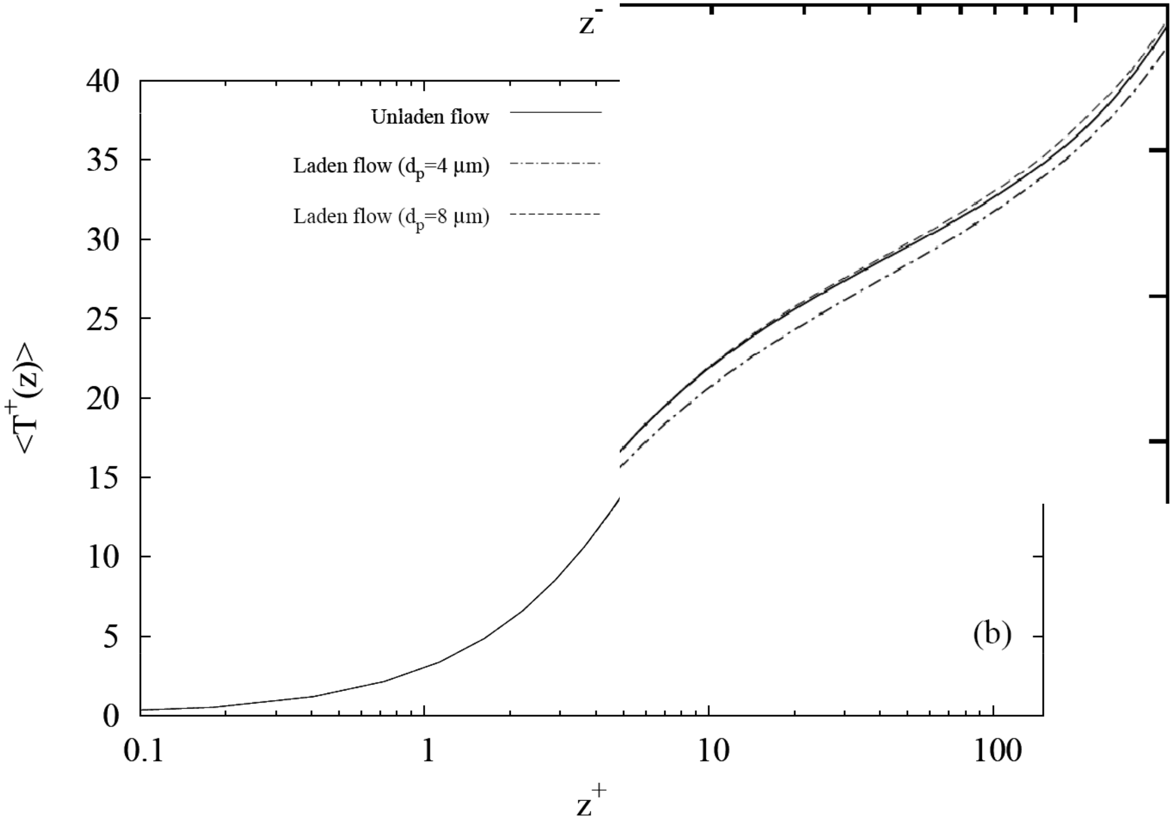
Green Particles: w’<0
Black Particles: w’>0
Background: Fluid Streamwise Velocity



Turbulence structures advect Temperature and drive Particles



... and what did we obtain insofar?
...heavy computations but not much quantitative satisfaction



Hi resolution DNS for water flow (Re*=300; Pr>1)

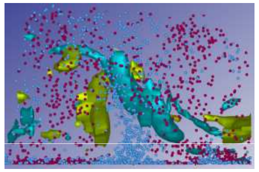
Mass fraction (at least $\Phi_m=10^{-2}$) → 10^9 n.particles

Small time step size (low inertia particles)

Data storage: 10 -100 TBytes disk space

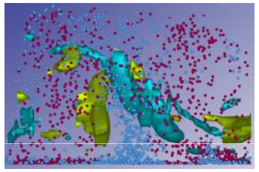
RAM memory: 50 Gbytes

Computational time: 1,000,000 CPU hours



… and finally

… The seminar is over



… and the course 1/2

Doctoral Course:

Modelling of Turbulent Dispersed Flows (28 hrs)

Lecturer:

Professor Alfredo Soldati, University of Udine, Italy (http://158.110.32.35/alfredo.html)

Seminars by Dr. Abdel Dehbi, Paul Scherrer Institute, CH… ???

Motivation:

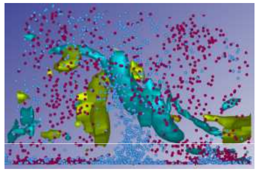
Turbulent dispersed particle flows play a part in several technological areas.
Since the individual particle motion can involve the transport and exchange of mass, momentum and heat with the carrier fluid, insights into detailed physics of this motion and how it influences and is influenced by its surroundings can lead to significant technological advancements.

Object:

cover the current methodologies for predicting turbulent dispersed flows. Specific attention will be devoted to the fundamental modelling aspects and to the physical phenomena involved.
In particular, i) Fluid particle interactions including particle exchanges of momentum, heat and mass with the fluid. ii) Turbulence structure and the several simulation methodologies including assumptions and modelling. iii) Some issues related to the computational aspects will be discussed.

Extra Activities:

To focus on the described issues, small hands-on-computer projects and seminars on specific applications and issues will be given.
The course will be addressed to PhD students in Engineering and Applied Sciences.



… and the course 2/2

Location: The course will be held in room ??? with the following schedule:

1. Wednesday May 7: 14 pm to 18 pm
   Introductory seminar. Fundamentals on Stokes flow around a sphere.
2. Wednesday May 14: 14 pm to 18 pm
   Forces acting on a sphere. Steady and transient forces
3. Wednesday May 21: 14 pm to 18 pm
   Heat and Mass transfer from a sphere.
4. Wednesday May 28: 14 pm to 18 pm
   Special topic on PDF approaches: Dr Abdel Dehbi, PSI.
5. Wednesday June 4: 14 pm to 18 pm
   NOT COVERED (JRT Course).
6. Wednesday June 11: 14 pm to 18 pm
   Particle dispersion in synthetic turbulence. Project description
7. Wednesday June 18: 14 pm to 18 pm
   Particle Turbulence Interactions. Are particles a compressible flow?
8. Wednesday June: 25 14 pm to 18 pm
   Project Discussion.
9. Wednesday July: 2 14 pm to 18 pm
   To be confirmed. Final Remarks