Turbulence modulation in particle-laden flow

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Multiscale Modeling and Simulation (Twente)
Anisotropic Turbulence (Eindhoven)

Jastrzebia Gora, September 2008

Modulation of turbulence

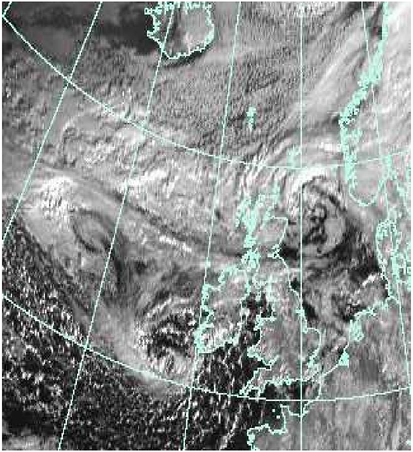
Particles added to Navier-Stokes turbulence alter microscopic and macroscopic flow properties

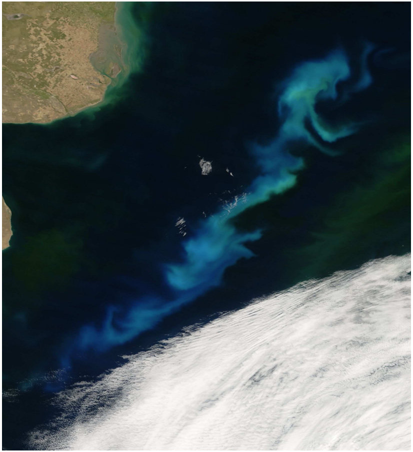
Also: e.g., due to rotation, stratification, combustion, ...

Muddy waters

Bend in Iruay river:

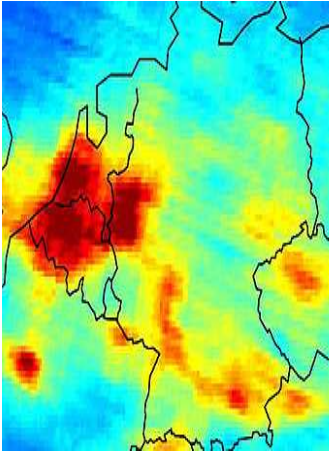
Environmental dispersion processes





European weather and Argentinian plankton bloom
Additional processes, e.g., phase transitions, active 'swimming'

Dutch challenges



- Analysis of water motion, sediment transport and morphologic variability – long-term new coast?
- Spreading of pollutants - air-quality monitoring (NO_2)

Computational approach

Euler-Lagrange setting

- continuous liquid or gas phase
- discrete particulate phase (particles, droplets, aerosol, ...)

Integrate capability to simulate

(a) turbulence (directly or after smoothing)

(b) coupled, interacting point-particle system

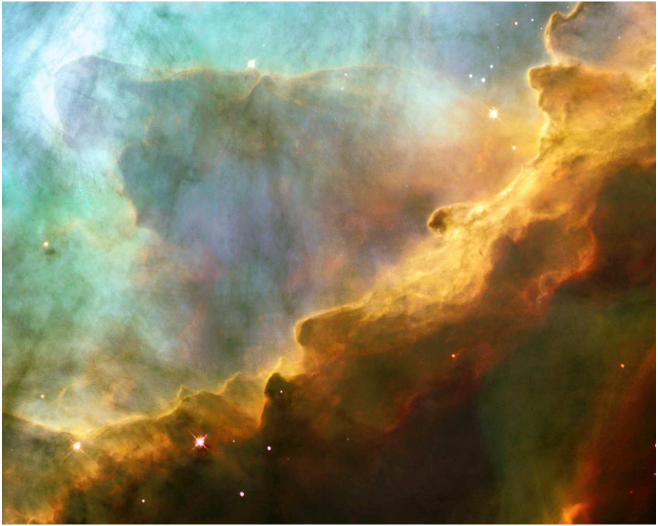
Focus: development of methods and ‘canonical’ applications

Outline

1. Turbulence and LES
2. Particle-laden turbulent flow
3. Concluding remarks

Outline

DNS and LES in one picture



Filtering Navier-Stokes equations

$$\partial_j u_j = 0 \quad ; \quad \partial_t u_i + \partial_j(u_i u_j) + \partial_i p - \frac{1}{Re}\partial_{jj} u_i = 0$$

Convolution-Filtering: filter-kernel G

$$\overline{u}_i = L(u_i) = \int G(x-\xi)u(\xi)\,d\xi \quad ; \quad L(1) = 1$$

Large-eddy equations:

$$\partial_j \overline{u}_j = 0$$

$$\partial_t \overline{u}_i + \partial_j(\overline{u}_i \overline{u}_j) + \partial_i \overline{p} - \frac{1}{Re}\partial_{jj}\overline{u}_i = -\partial_j(\overline{u_i u_j} - \overline{u}_i \overline{u}_j)$$

Sub-filter stress tensor

$$\tau_{ij} = \overline{u_i u_j} - \overline{u}_i \overline{u}_j$$

Some explicit subgrid models

Popular models:

- Dissipation: Eddy-viscosity models, e.g., Smagorinsky

$$\tau_{ij} \to -\nu_t S_{ij} = -(C_S \Delta)^2 |S| S_{ij} \quad ; \quad \text{effect } \frac{1}{Re} \to \left(\frac{1}{Re} + \nu_t \right)$$

- Similarity: Inertial range, e.g., Bardina

$$\tau_{ij} \to [L, \Pi_{ij}](\overline{\mathbf{u}}) = \overline{\overline{u}_i \overline{u}_j} - \overline{\overline{u}}_i \overline{\overline{u}}_j$$

- Mixed models ?

$$m_{ij} = \mathit{Bardina} + C_d \mathit{Smagorinsky}$$

C_d via dynamic Germano-Lilly procedure

Convective modifications: Leray regularization

Alter convective fluxes:

$$\partial_t u_i + \overline{u}_j \partial_j u_i + \partial_i p - \frac{1}{Re} \Delta u_i = 0$$

LES template:

$$\partial_t \overline{u}_i + \partial_j (\overline{u}_j \overline{u}_i) + \partial_i \overline{p} - \frac{1}{Re} \Delta \overline{u}_i = -\partial_j \left(m_{ij}^L \right)$$

Implied Leray model

$$m_{ij}^L = L\left(\overline{u}_j L^{-1}(\overline{u}_i) \right) - \overline{u}_j \overline{u}_i = \overline{\overline{u}_j u_i} - \overline{u}_j \overline{u}_i$$

Requires approximate filter inversion

Regularization requires filter-inversion

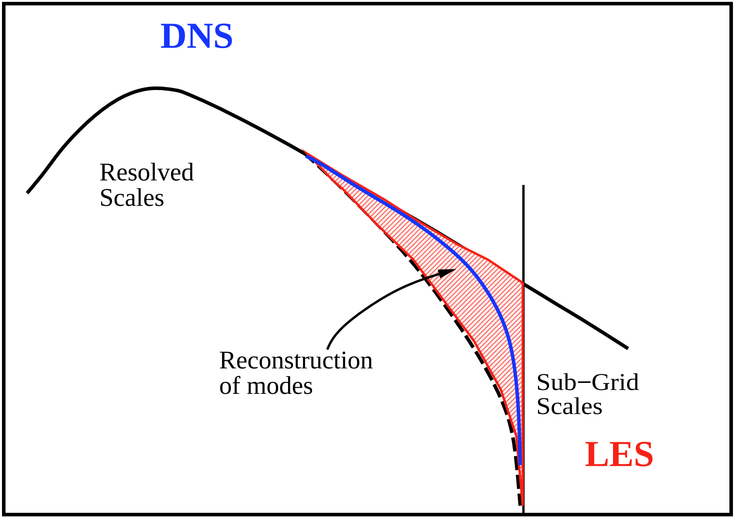
Geometric series: repeated filtering

$$L^{-1} = (I - (I - L))^{-1} \rightarrow \sum_{n=0}^{N} (I - L)^n$$

For example:

$$\begin{aligned}
N = 0: \quad u &= \quad L_0^{-1}(\overline{u}) = \overline{u} \\
N = 1: \quad u &= \quad L_1^{-1}(\overline{u}) = \overline{u} + (I - L)\overline{u} = 2\overline{u} - \overline{\overline{u}} \\
N = 2: \quad u &= \quad L_2^{-1}(\overline{u}) = \overline{u} + (I - L)\overline{u} + (I - L)(I - L)\overline{u} \\
&= \quad 3\overline{u} - 3\overline{\overline{u}} + \overline{\overline{\overline{u}}}
\end{aligned}$$

Inversion and Energy distribution over Scales

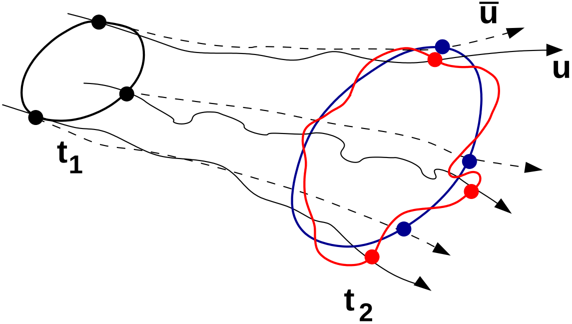


NS-α regularization

Kelvin's circulation theorem

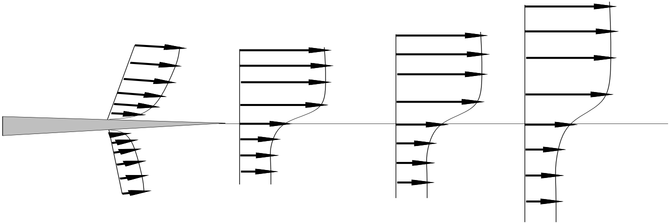
$$\frac{d}{dt}\left(\oint_{\Gamma(\mathbf{u})} u_j \, dx_j\right) - \frac{1}{Re}\oint_{\Gamma(\mathbf{u})} \partial_{kk} u_j \, dx_j = 0 \quad \Rightarrow \quad NS - eqs$$

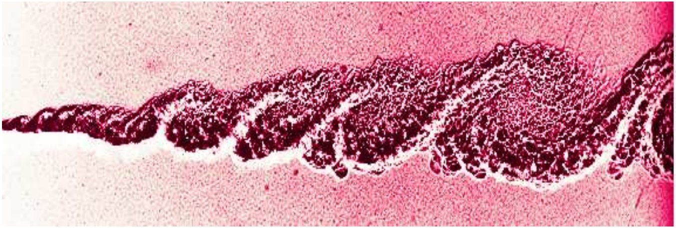
Filtered Kelvin theorem extends Leray



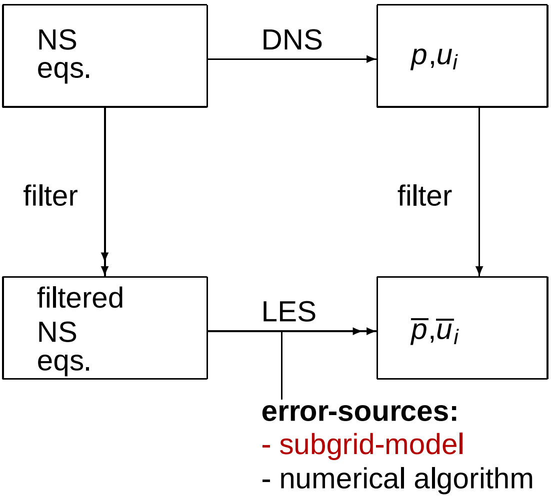
Obtain NS-α model by $\Gamma(\mathbf{u}) \rightarrow \Gamma(\overline{\mathbf{u}})$: Euler-Poincaré

Mixing layer: testing ground for LES

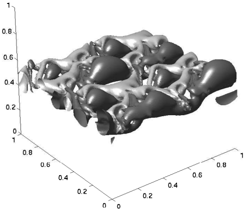




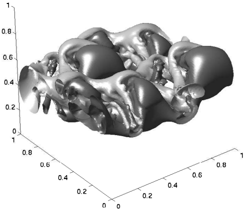
A posteriori LES testing



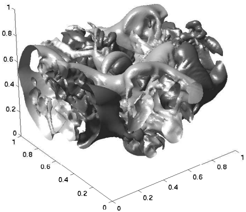
Mixing: spatial and temporal model



$t = 20$

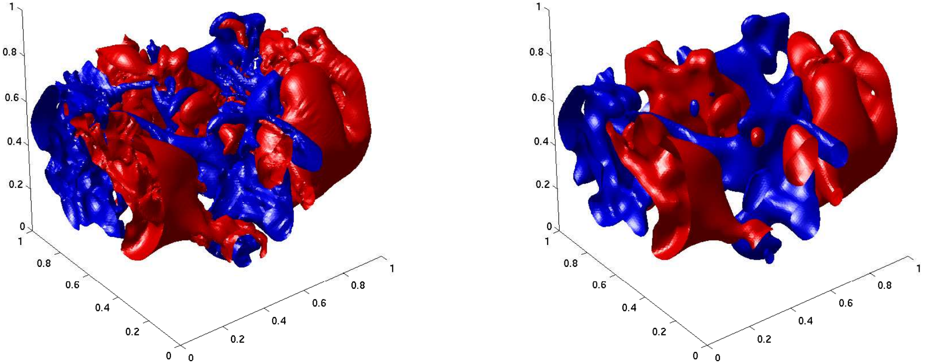


$t = 40$



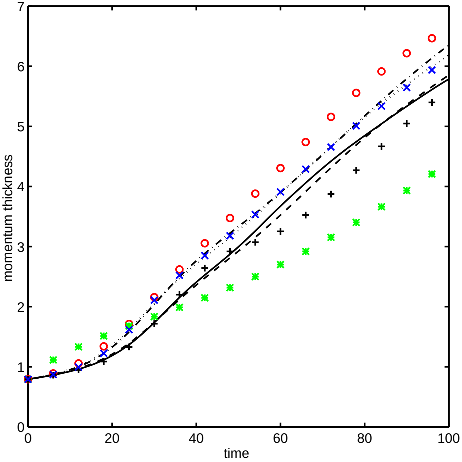
$t = 80$

Temporal at different $t \approx$ Spatial at different x



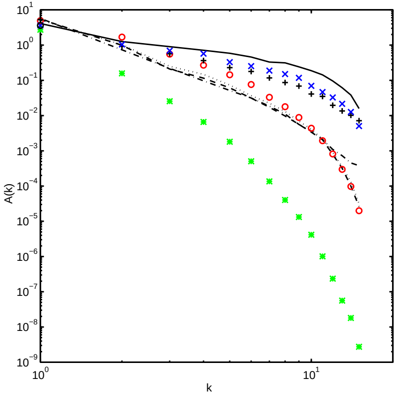
1
0.8
0.6
0.4
0.2
0
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1
0.8
0.6
0.4
0.2
0
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1

Mean flow - momentum thickness



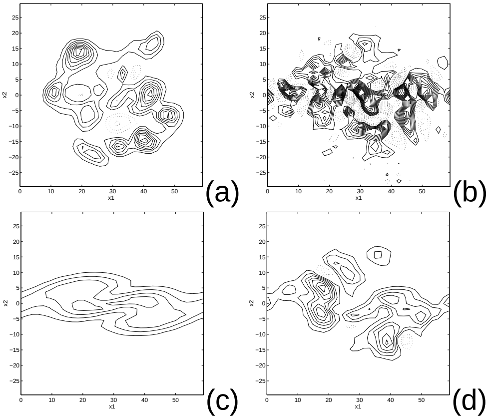
- Smagorinsky too dissipative
- Bardina, dynamic models preferred

Closer look: Streamwise energy spectrum



- Dissipation: Smagorinsky too much, Bardina not enough
- dynamic models quite acceptable
- but: ‘middle range’ wavenumbers much too low

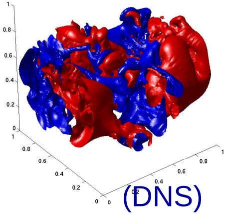
Instantaneous snapshots of spanwise vorticity



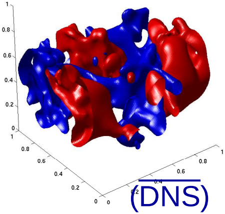
- a: $\overline{\text{DNS}}$, b: Bardina, c: Smagorinsky, d: dynamic

  Accuracy limited: regularization models better?

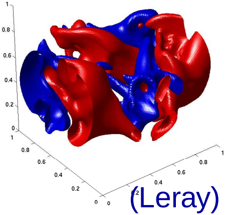
Leray and NS-α predictions: $Re = 50$, $\Delta = \ell/16$



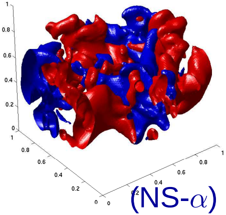
(DNS)



($\overline{\text{DNS}}$)



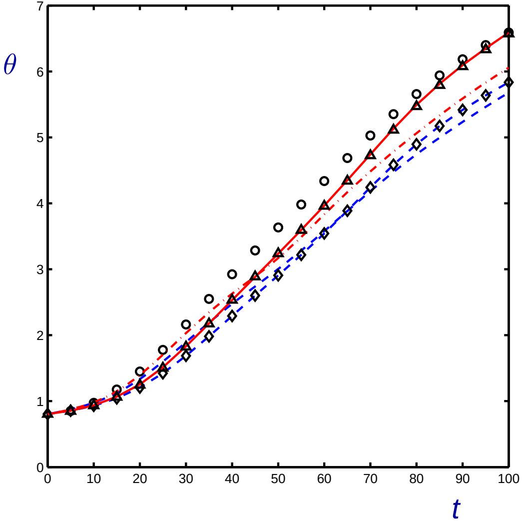
(Leray)



(NS-α)

Snapshot u_2: red (blue) corresponds to up/down

Momentum thickness θ as $\Delta = \ell/16$



Filtered DNS ($\circ$)

Leray-model

32^3: **dash-dotted**

64^3: **solid**

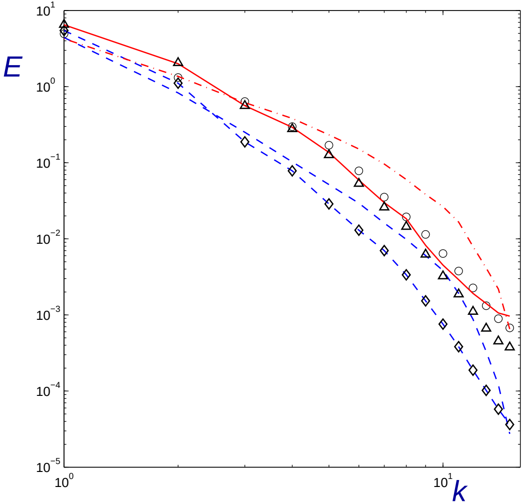
96^3: $\triangle$

dynamic model

32^3: **dashed**

64^3: **dashed with** $\diamond$

Streamwise kinetic energy E as $\Delta = \ell/16$



Filtered DNS ($\circ$)

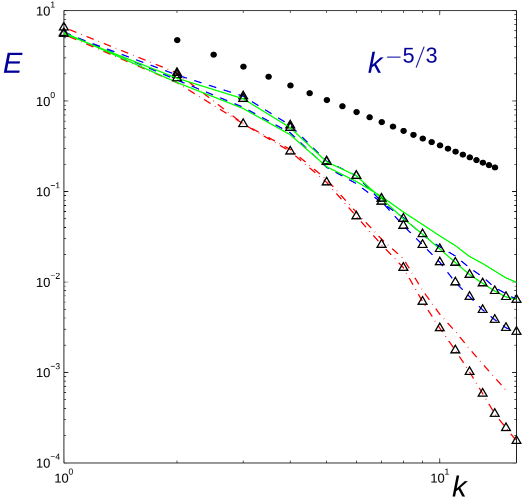
Leray-model

- 32^3: **dash-dotted**
- 64^3: **solid**
- 96^3: $\triangle$

dynamic model

- 32^3: **dashed**
- 64^3: **dashed with** $\diamond$

Robustness at arbitrary Reynolds number



$Re = 50$

64^3: **dash-dotted**

96^3: **dash-dotted,** $\triangle$

$Re = 500$

64^3: **dashed**

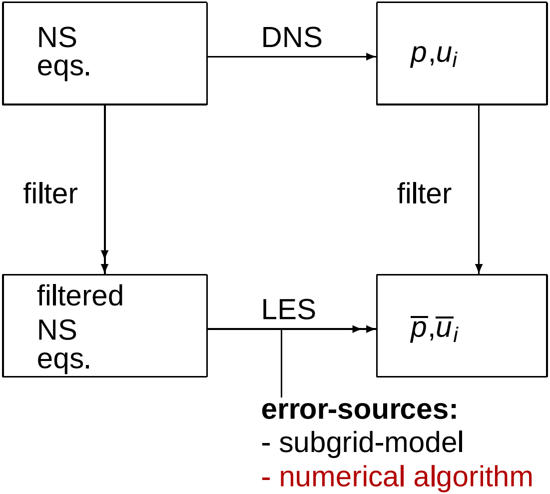
96^3: **dashed,** $\triangle$

$Re = 5000$

64^3: **solid**

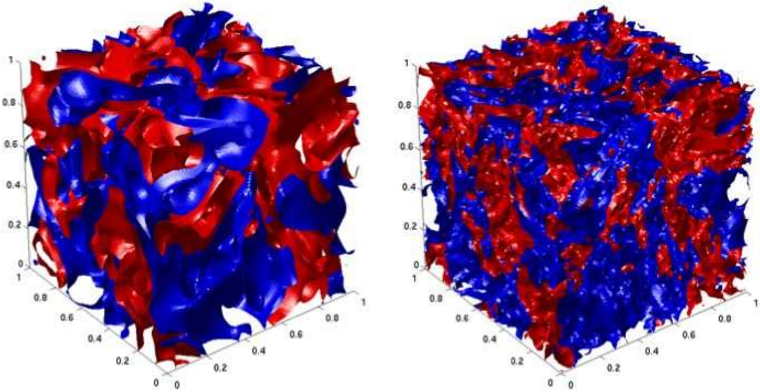
96^3: **solid,** $\triangle$

A posteriori LES testing

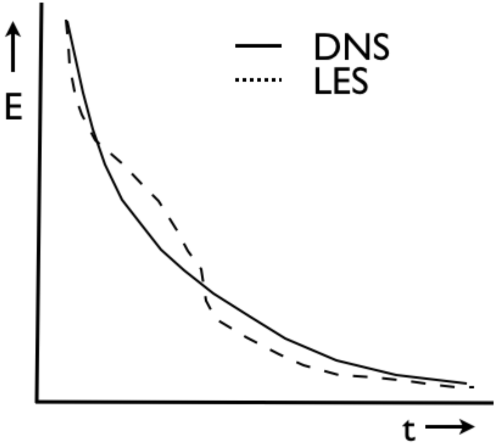


Smagorinsky fluid

Homogeneous decaying turbulence at $Re_\lambda = 50,\ 100$

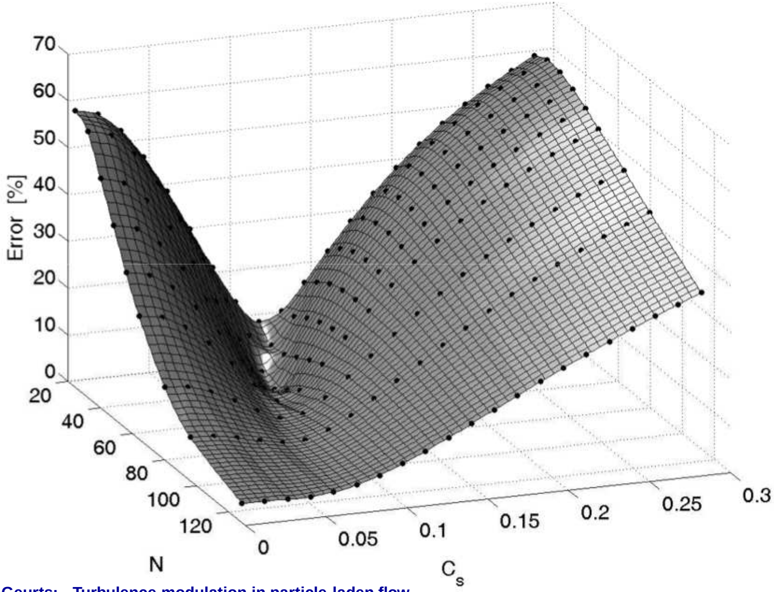


Decay of kinetic energy



Compare decay - quantify error

Total error-landscape: DNS-LES



Outline

1. Turbulence and LES
2. **Particle-laden turbulent flow**
3. Concluding remarks

Process-engineering: Cracking of oil

Catalyst = dispersed particles

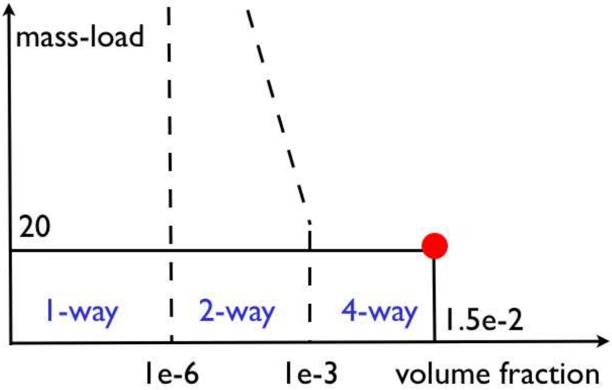
Safety?
Environment?
Chemical efficiency?

Are collisions important?
Do clusters form?
Operational Stability?

Computational approach: Euler-Lagrange

1-2-4 way coupling - Elghobashi

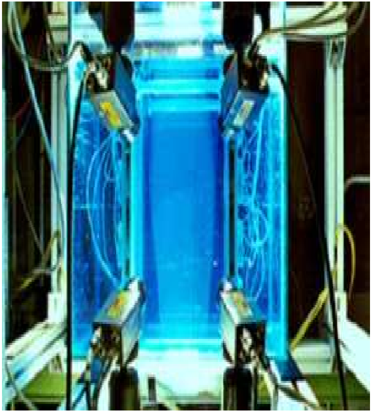
Volume fraction: $\Psi = Nv_p/\Omega$: Mass-load: $m = \Psi\rho_p/\rho_{fluid}$



Mass-load and volume fraction determine interaction regime

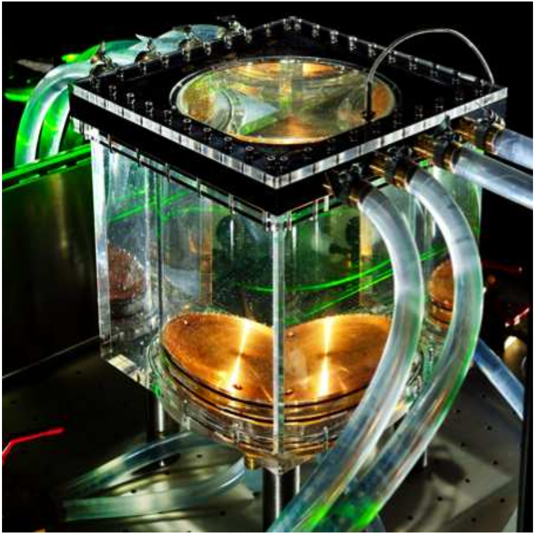
1-way

Test particles - PIV/PTV technique



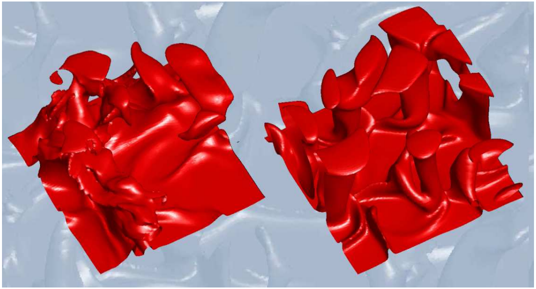
Small, light particles follow the flow precisely - no modulation
Recent developments: also measure temperature, ...
instrumented tracers (‘smart particles’)

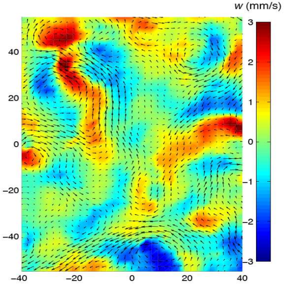
Application: RRB



Collaboration TU/e: Rudie Kunnen, Herman Clercx

Rotating Rayleigh-Bénard problem

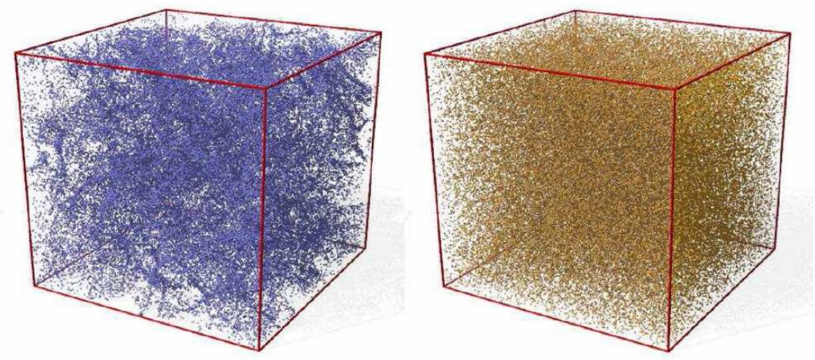




- Temperature: buoyancy dominated ($Ta = 0$ - left) and rotation dominated ($Ta > Ra$)
- Stereo PIV measurement of (u, v, w) in horizontal plane

Inertial effect - preferential clustering

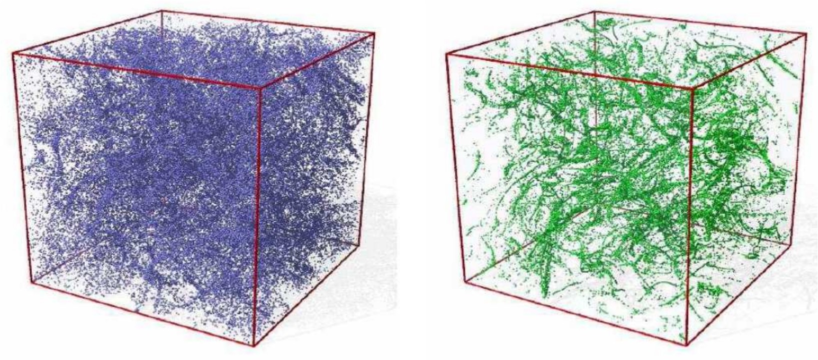
Motion of heavy particles in HIT



Heavy particles (left) display preferential clustering compared to test-particles (right)

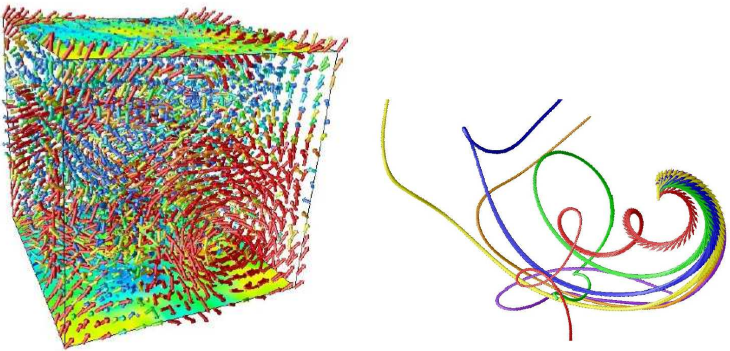
Inertial effect - preferential clustering

Motion of heavy and light particles in HIT



Heavy particles (left) are ‘ejected’ from high vorticity regions while bubbles (right) are staying close to pressure minima

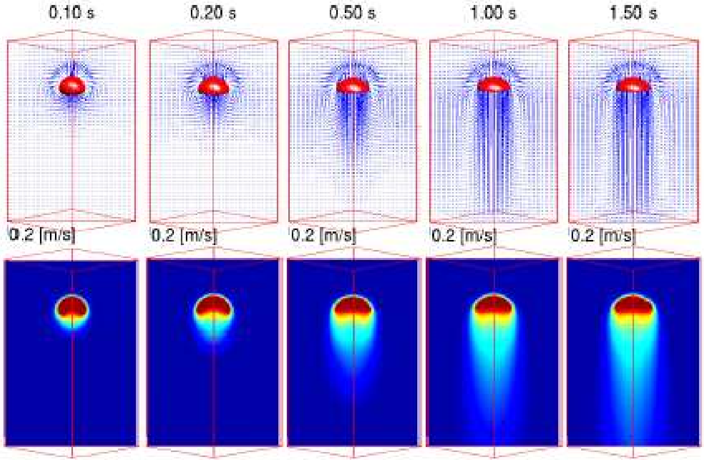
Heavy and light particles



Inertial particles respond differently to the same flow

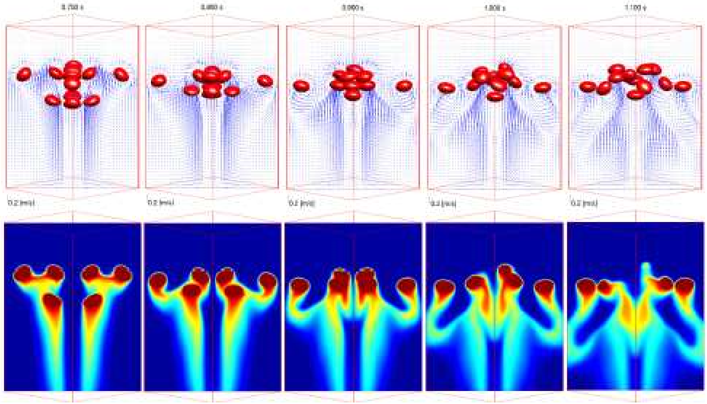
2-way

2-way coupling



Significant non-local flow modification

Spatially extended hydrodynamic interactions



VOF approach - interface tracking

In case many particles: interacting point-particle models

4-way

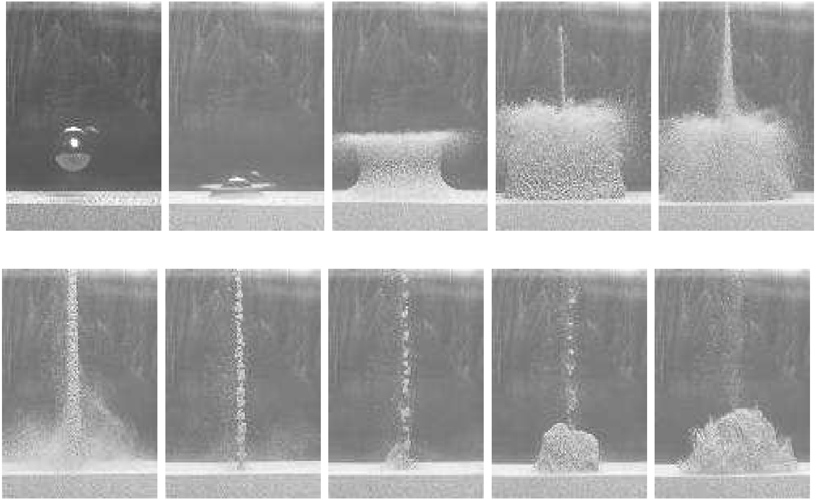
4-way coupling in 'dense' systems

'Large' volume fractions ($\gtrsim 10^{-3}$): (inelastic) collisions important

Dynamic self-organization:

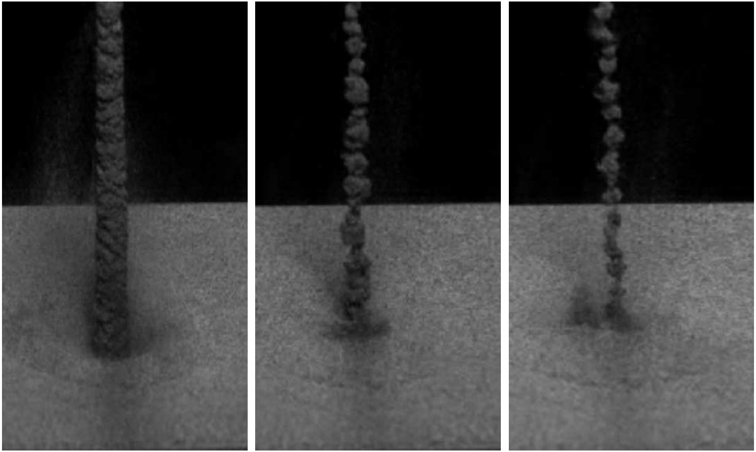
- microscopic dynamics expresses itself macroscopically

Sand-jet and granular clustering



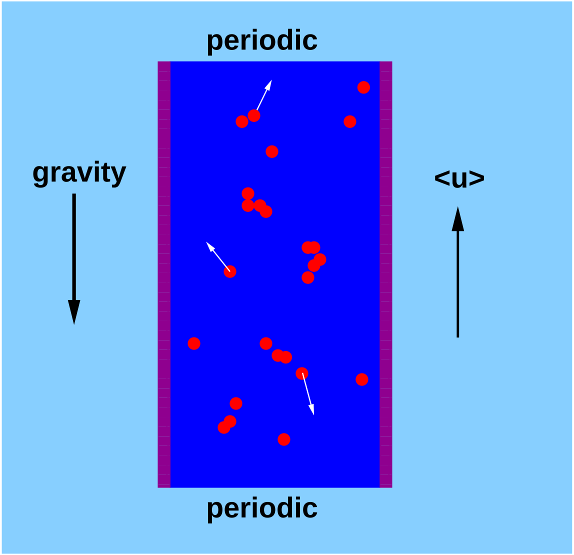
http://www.tn.utwente.nl/pof/

Close-up of granular clustering



Inelastic collisions yield progressive clustering

Gas-solid flow in vertical channel



Treatment of gas-phase

- Fluid: continuity, momentum

$$
\begin{aligned}
\partial_t(\rho\varepsilon) + \partial_j(\rho\varepsilon u_j) &= 0 \\
\partial_t(\rho\varepsilon u_i) + \partial_j(\rho\varepsilon u_i u_j) &= -\varepsilon\partial_i(p) + \partial_j(\varepsilon\sigma_{ij}) \\
&+ (\rho\varepsilon g + \varepsilon p_g)\delta_{i3} + f_i
\end{aligned}
$$

  local porosity ε

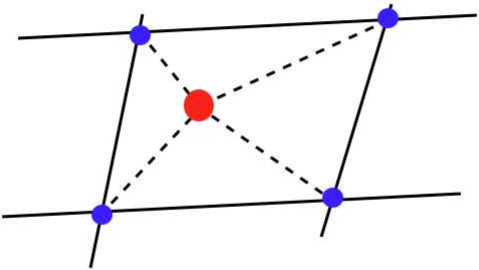
- Gravity ($\rho\varepsilon g$) and pressure gradient (εp_g) drive the flow
- Relative motion particles/fluid induces momentum transfer

Particles represent momentum sink

Momentum transfer (from drag force)

$$\mathbf{f}_{cell} = \frac{1}{V_{cell}} \int_{cell} \sum_{i=0}^{N_p} \frac{\mathbf{u} - \mathbf{v}_i}{\tau_p} D(\mathbf{r}_i - \mathbf{r})\, dV$$

Function D distributes forces onto Eulerian grid



TU/e

Treatment of solids phase

Discrete point-particles:

1. consider motion of single particle
2. add interactions (inelastic collisions)

Motion of small spherical particle

Maxey-Riley: (POF, 1982)

$$
\begin{aligned}
m_p \frac{dv_i}{dt} &= m_f \left(\frac{Du_i}{Dt} - \nu \nabla^2 u_i \right)\Big|_{\mathbf{x}(t)} \\
&- \frac{1}{2} m_f \frac{d}{dt} \Big(v_i(t) - u_i(\mathbf{x}(t), t) \Big) \\
&- 6\pi a \mu \Big(v_i(t) - u_i(\mathbf{x}(t), t) \\
&+ a \int_{-\infty}^{t} d\tau \, \frac{d/d\tau \{ v_i(\tau) - u_i(\mathbf{x}(\tau), \tau) \}}{[\pi\nu(t-\tau)]^{1/2}} \Big) \\
&+ (m_p - m_f) g_i
\end{aligned}
$$

Contributions: pressure gradient, added mass, Stokes drag, Basset viscous drag, buoyancy

Motion of small spherical particle

Maxey-Riley: (POF, 1982)

$$
\begin{aligned}
m_p \frac{dv_i}{dt} &= \\
&- 6\pi a \mu \Big(v_i(t) - u_i(\mathbf{x}(t), t) \Big) \\
&+ (m_p - m_f) g_i
\end{aligned}
$$

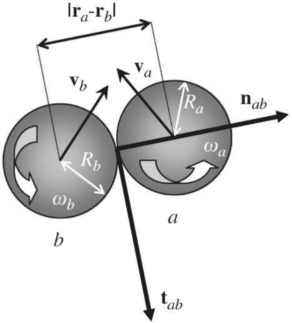
Consider: Stokes drag, buoyancy

Particle motion and collisions

Adding collisions: *pp* and *pw*

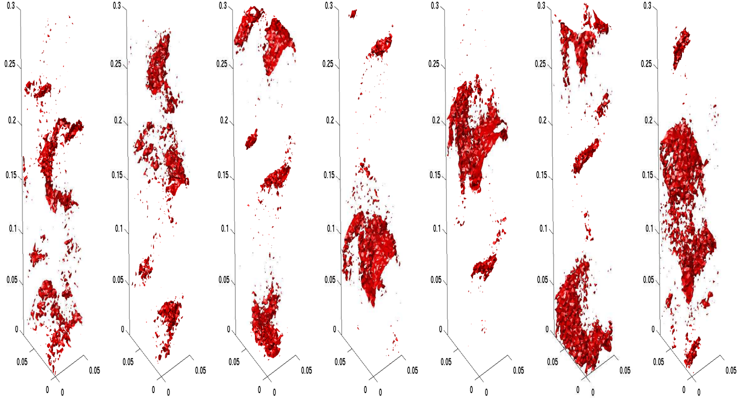
$$m\frac{d\mathbf{v}_i}{dt} = \alpha(Re_p)\Big(\mathbf{u} - \mathbf{v}_i\Big) + m\mathbf{g} + \mathbf{f}_i^{pp} + \mathbf{f}_i^{pw}$$

Inelastic collisions closed by 'restitution' coefficients for normal/tangential velocity, and friction (Hoomans et al., 1996)



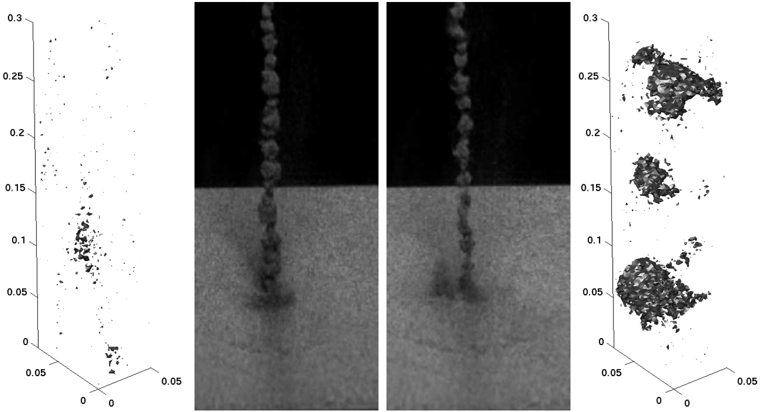
Number of particles: $N_p \approx 4.2\ 10^5$ Volume-fraction $\approx 1.5\%$

Self-organization



- Self-sustained generation/destruction of clusters Go
- Mechanism: turbulent mixing and inelastic collisions

Clustering requires 4-way coupling



2-way

4-way

Particle-particle interactions $\Rightarrow$ Clustering and Modulation

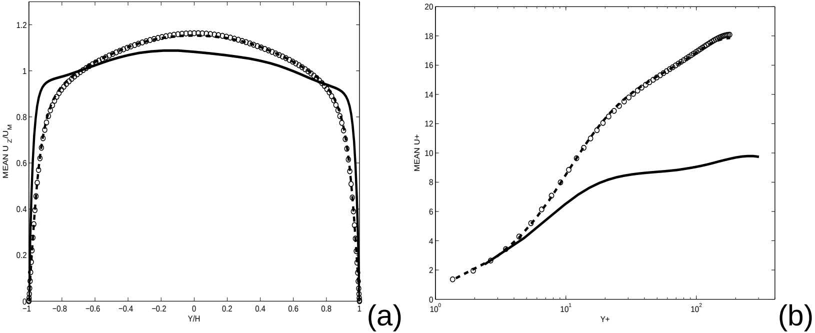
Simulation overview

Effects of collisions and particle-fluid interactions

Simulations considered:

1. clean channel
2. channel + particles, no collisions: 2-way coupling
3. channel + colliding particles: 4-way coupling

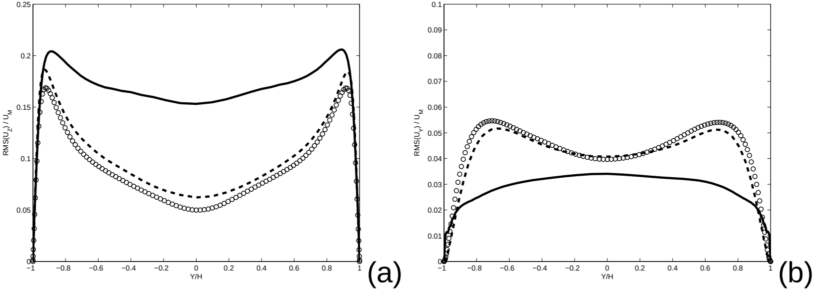
Mean fluid velocity: 4-way



Streamwise velocity $\langle u_z \rangle$: linear (a) and logarithmic (b)
Clean: DNS (○), LES (dash) – Particles: LES (solid)

- boundary layer thinner (Fig. a), skin-friction higher
- log-law changed: Von Kármán ‘constant’ higher (Fig. b)

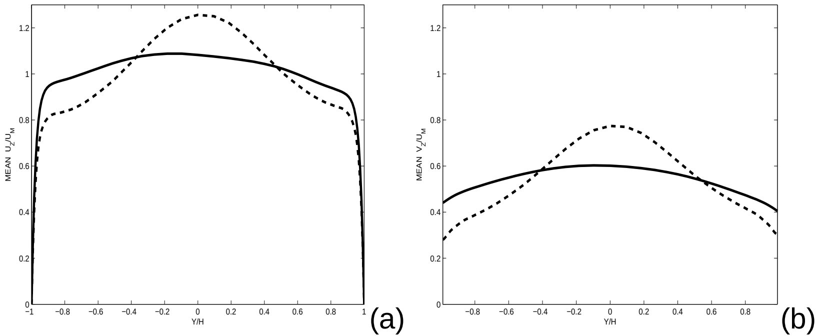
Turbulence intensities: clean and particles



Streamwise (a) and normal (b) component
Clean: DNS (○), LES (dash) – Particles: LES (solid)

- Particles induce higher streamwise and lower normal/spanwise intensities

Mean flow velocities: 2-way and 4-way

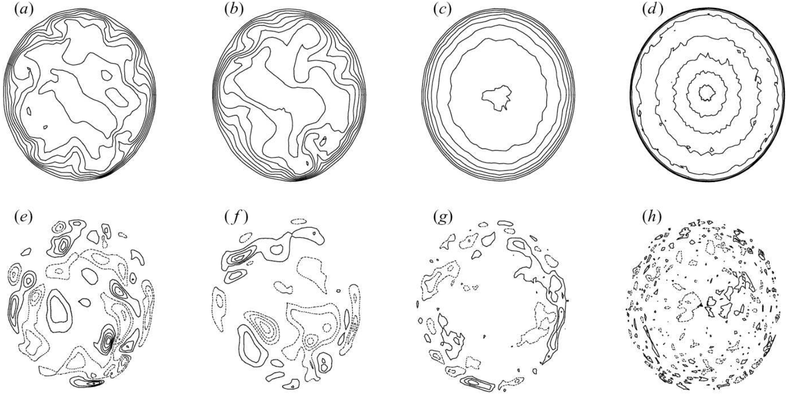


$\langle u \rangle$ of fluid (a) and $\langle v \rangle$ of solids phase (b)
4-way: solid and 2-way: dashed

- experimental observations: flattened profile
- 2-way gives rise to un-physical center-jet

Particle-laden flow in pipe geometry

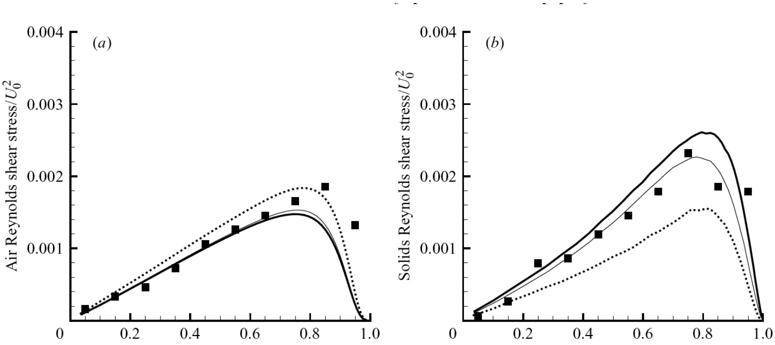
Apply methodology at different mass-loads:



Snapshots u_z (top) and u_θ (bottom) for (left to right) $m = 0$ (unladen), $m = 0.23$, $m = 1.1$, $m = 30$.

Vreman, JFM, 2007

Reynolds shear stress



Unladen (dotted) compared to particle-laden (with and without wall roughness model) at $m = 0.11$: experiment: Caraman et al. (2003).

Left: gas-phase, Right: solids phase at $m = 0.11$

Agreement less accurate in case of higher mass-load

Outline

Concluding Remarks

LES:

- discussed concept - intuitive and mathematical modeling
- illustrated turbulent mixing
- hinted at error-sources and optimal parameter selection

Particle-laden flow:

- overview of regimes: 1-2-4
- considered Euler-Lagrange framework: continuum (DNS/LES) fluid with discrete (point) particles
- turbulent channel and pipe flow
- relevance of sub-filter motions for small particles: turbophoresis
- challenges in multiscale/multiphase systems

Turbulence modulation in particle-laden flow

Bernard J. Geurts

Multiscale Modeling and Simulation (Twente)
Anisotropic Turbulence (Eindhoven)

Jastrzebia Gora, September 2008