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Modelowanie przepływów turbulentnych z fazą dyspersyjną: metoda LES i efekty podsiatkowe

Modelling turbulent dispersed flows: Large-Eddy Simulation and subfilter efects

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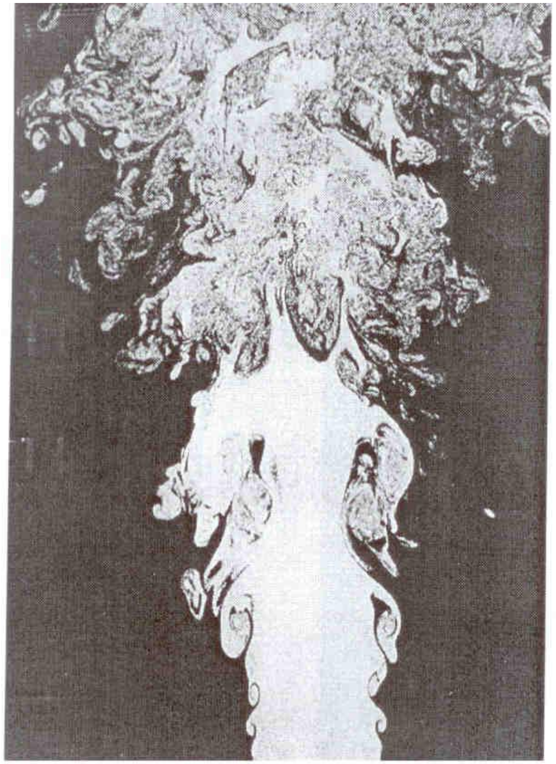
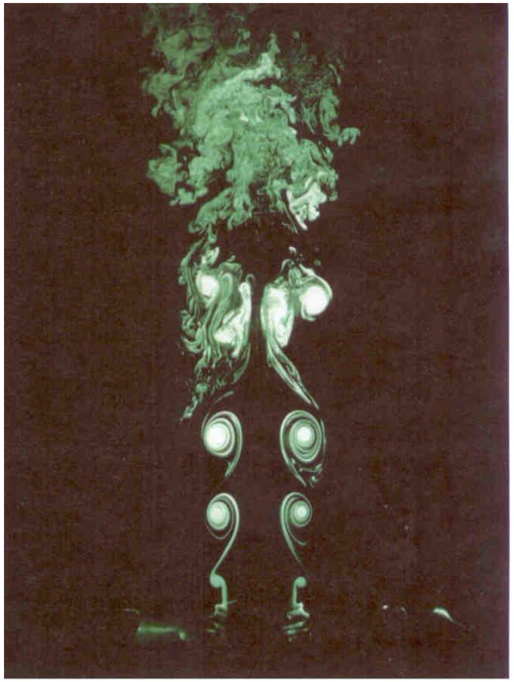
Część I: Przepływy turbulentne
wprowadzenie

Perhaps the holy grail of turbulence is *the statistical resolution of all scales* - a methodology in which representative samples of motions and processes on all scales are resolved and combined (without empiricism) in a way that remains computationally tractable at large Reynolds number."

S. B. Pope ``Ten questions concerning LES (...)'',
New Jornal of Physics **6** (2004) 35



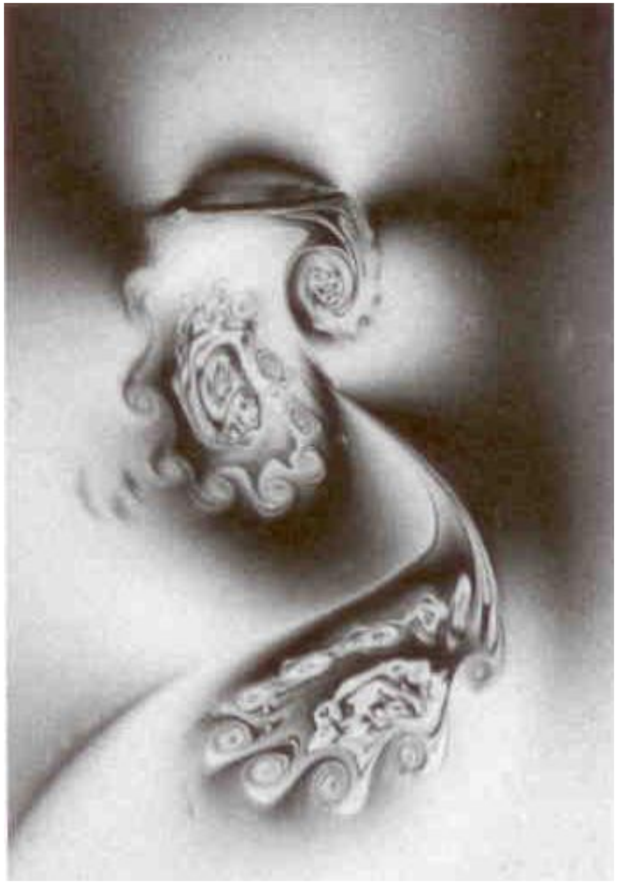
(Lesieur, 1997)



(A Gallery of Fluid Motion, 2003)

← **strugi turbulentne**

A short guide to turbulence (with milestones)



flow past a bluff-body **flow through array of rods** **self-similar (?) flow**

(da Vinci, around 1500) (A Gallery of Fluid Motion, 2003)

Pierwszy kamień milowy: dekompozycja Reynoldsa

$\langle\cdot\rangle$ operator uśredniania; $\mathbf{U} = \langle \mathbf{U} \rangle + \mathbf{u}$

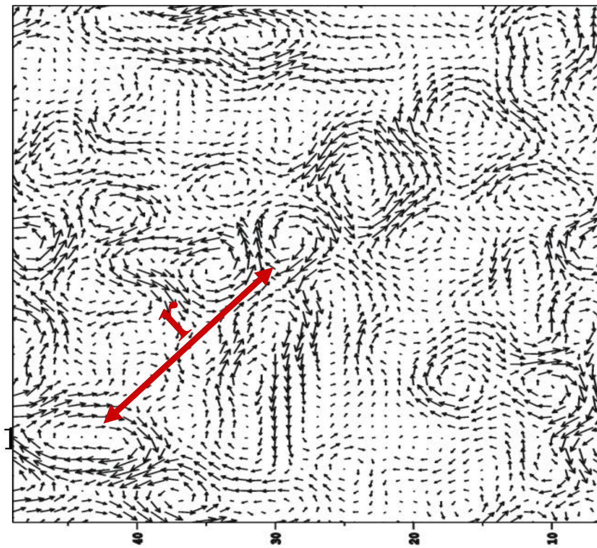
Uśrednienie równań ruchu (Reynolds, 1894)

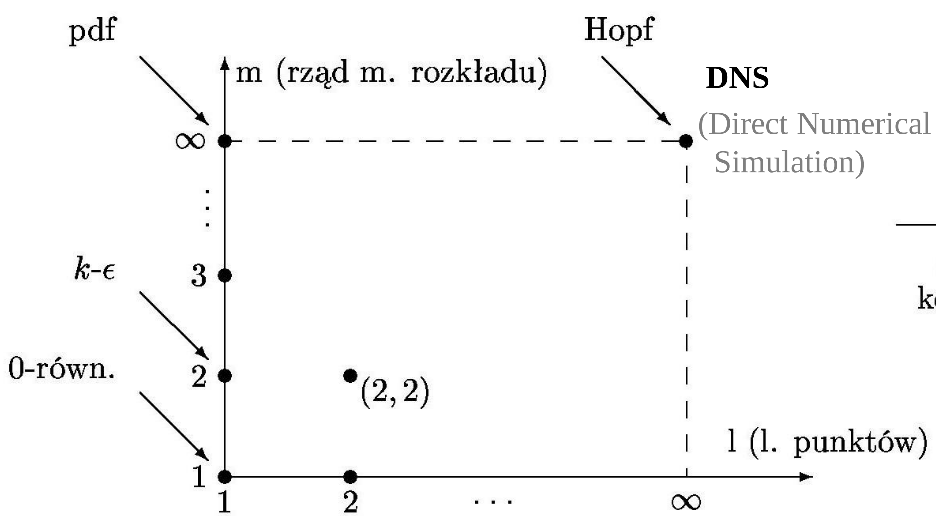
$$\frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U}\cdot\nabla)\mathbf{U} = -\frac{1}{\rho}\nabla p + \nu\nabla^2\mathbf{U}$$

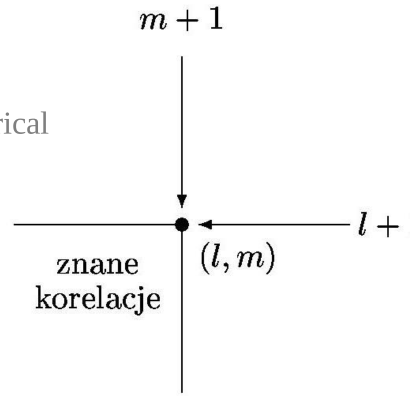
$\langle\cdot\rangle$

tensor naprężeń turbulentnych $R_{ij}(\mathbf{x}) = \langle u_i(\mathbf{x}) u_j(\mathbf{x}) \rangle$

$$\frac{\partial \langle \mathbf{U} \rangle}{\partial t} + (\langle \mathbf{U} \rangle \cdot\nabla)\langle \mathbf{U} \rangle = -\frac{1}{\rho}\nabla\langle p \rangle + \nu\nabla^2\langle \mathbf{U} \rangle - Div\mathbf{R}$$





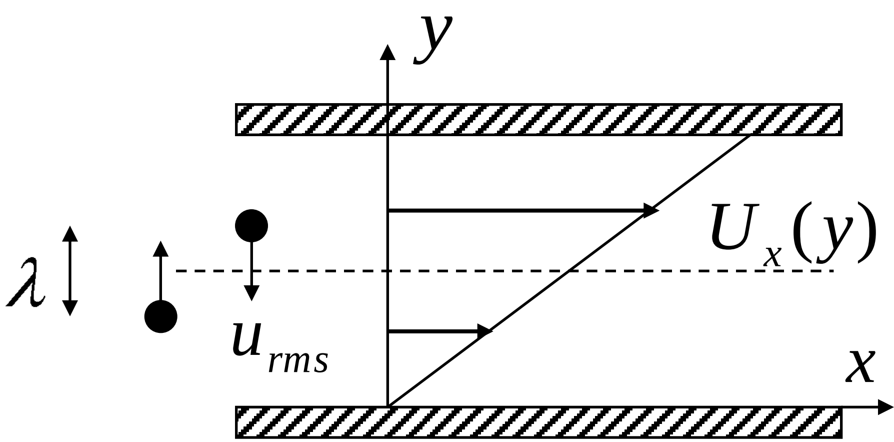


Np. $\langle u_i(\mathbf{x}) u_j(\mathbf{x}+\mathbf{r}) \rangle$
dwupunktowy moment rozkładu (korelacja) drugiego rzędu

Problem domknięcia (gdzie jest LES?) (RANS – struktury?)

Drugi kamień milowy: hipoteza Prandtla

Rozdział skal ruchu średniego i fluktuacji: analogia do teorii kinetycznej gazów



Lepkość molekularna

$$\sigma_{xy} \sim \nu \frac{\partial U_x}{\partial y} \qquad \nu \sim u_{rms}\lambda$$

Hipoteza lepkości turbulentnej (Boussinesq 1877)

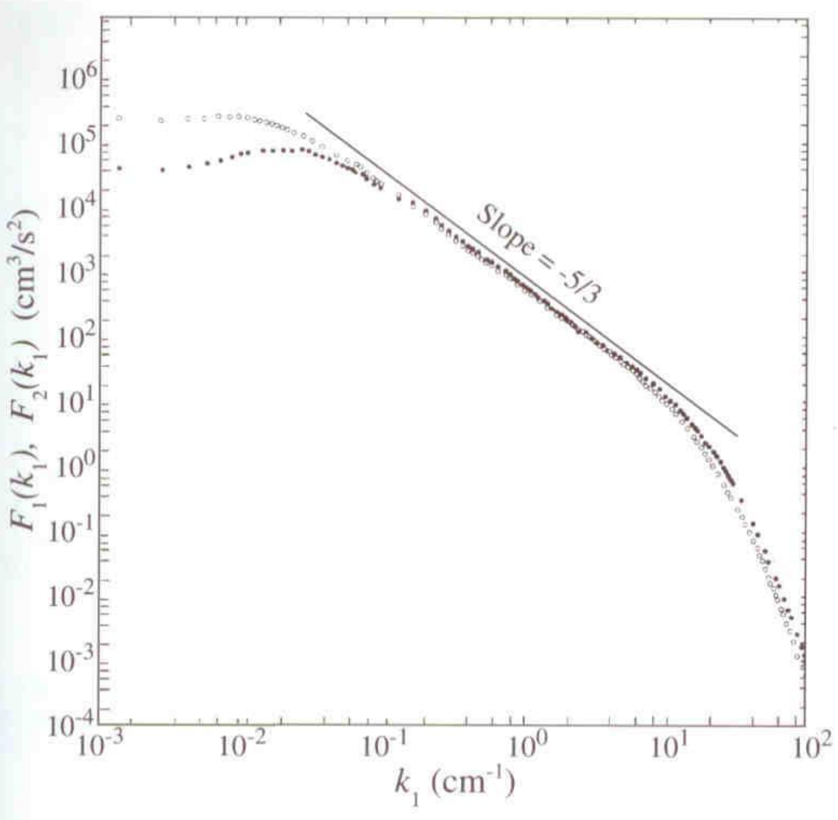
$$R_{xy} \sim \nu_t \frac{\partial \langle U_x \rangle}{\partial y} \qquad \nu_t \sim ? \qquad \boxed{\nu_t \sim u' L}$$

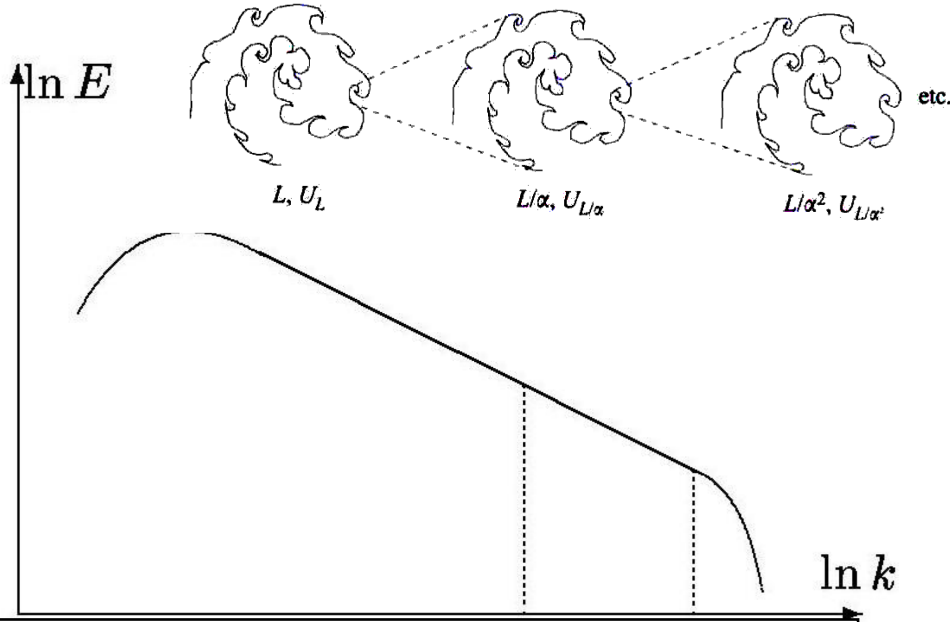
Hipoteza drogi mieszania (Prandtl 1925)

$$\nu_t \sim u' l_m; \qquad u' = l_m \left| \frac{d\langle U_x \rangle}{dy} \right|; \qquad l_m = \kappa y$$

(rozdzial skal?)

Trzeci kamień milowy: hipoteza Kołmogorowa





Widmo energii kinetycznej turbulencji

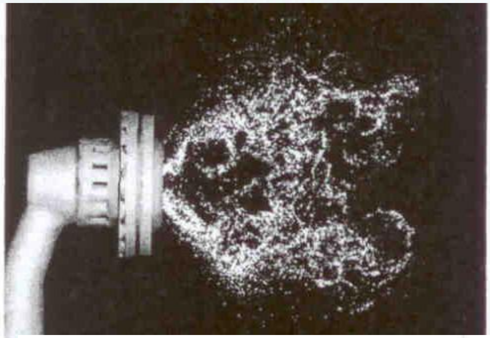
W „środkowym” zakresie skal:

(Kołmogorow, 1941) $E(k) \sim \varepsilon^{2/3} k^{-5/3}$

(konstruowanie domknięć – *similarity models*?)

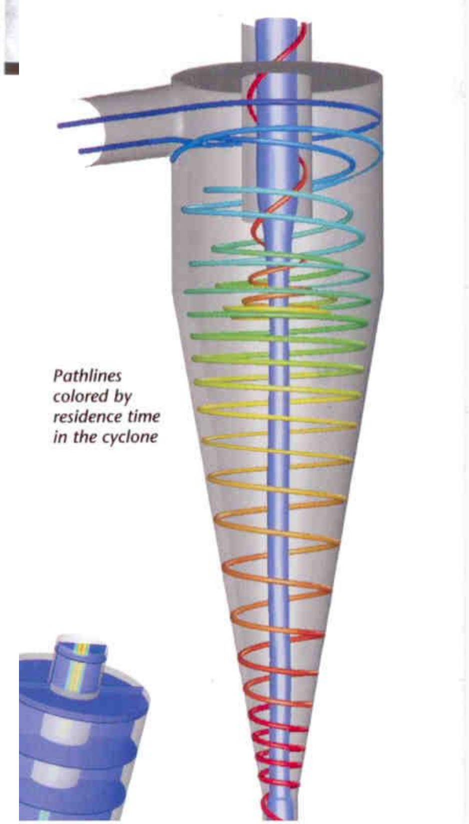
Przepływy z fazą dyspersyjną - wprowadzenie

Przepływ dyspersyjny:
przepływ fazy nośnej (ciągłej, czyli płynu)
z cząstkami (stałymi lub kroplami, ewent. pęcherzykami)



Motywacje: przykłady

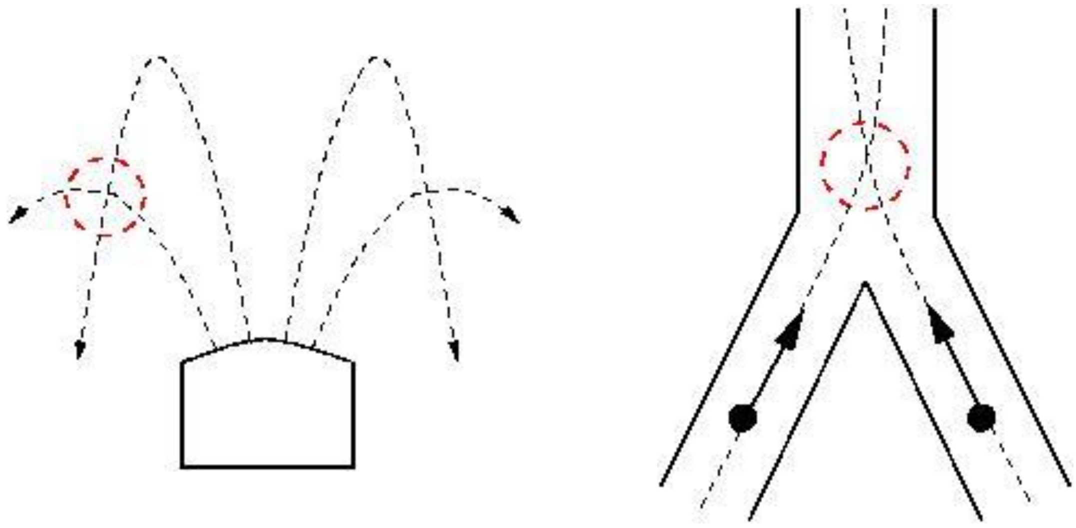
- spalanie kropel paliwa w turbinach gazowych,
- spalanie pyłu węglowego w kotłach energetycznych,
- przepływy pary mokrej (turbiny, energetyka jądrowa)
- inżynieria chemiczna i procesowa: urządzenia i aparaty



Motywacje: sformułowania

- model dwupłynowy (Eulerowsko-Eulerowski):
- śledzenie trajektorii cząstek (Eulerowsko-Lagrange'owski)

Dispersed two-phase flows - computational approaches



Simple examples of dispersed flows

Formulations:

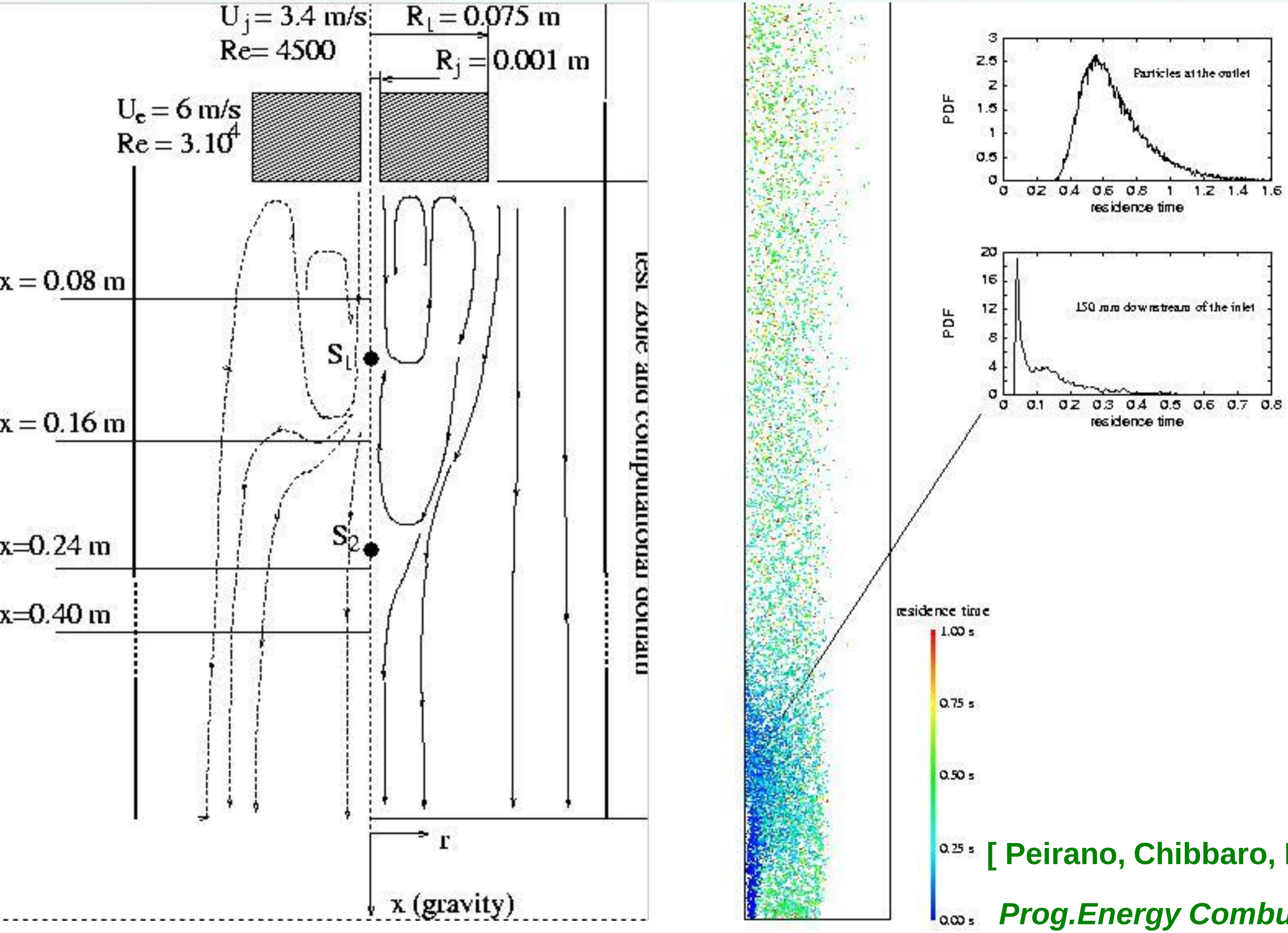
- two-fluid model (Eulerian-Eulerian):
- particle tracking (Eulerian-Lagrangian) – applied here

Remarks: - statistical vs. instantaneous fluid flow resolution

- inadequacy of gradient hypotheses (based on local equilibrium assumption)

$$\vec{j}_m = -D_t \nabla n_p$$

Efektywność podejścia Eulera-Lagrange'a (cd.)



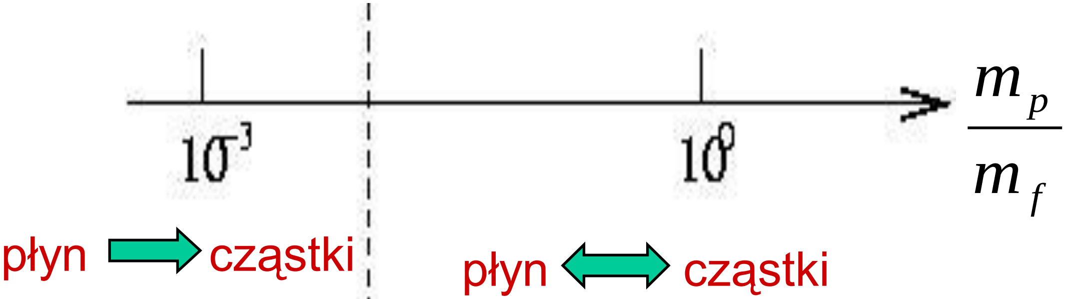
[Peirano, Chibbaro, Pozorski, Minier,
Prog.Energy Combust.Sci, 2006]

Model palnika węglowego – eksperyment i obliczenia

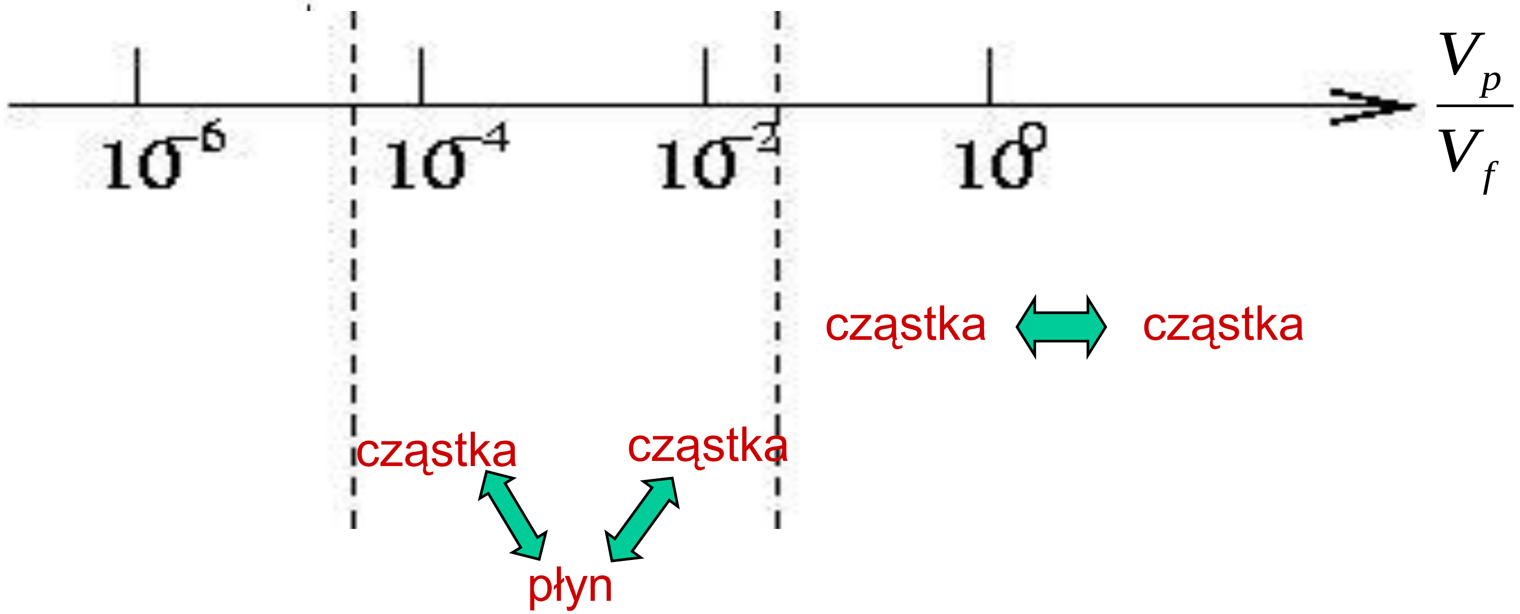
Obliczenia dyspersyjnych przepływów wielofazowych

Udział masowy fazy rozproszonej:

cząstki ciężkie: $\dfrac{\rho_p}{\rho_f} \approx 10^3$



Udział objętościowy fazy rozproszonej:



Opis dyspersyjnych przepływów dwufazowych

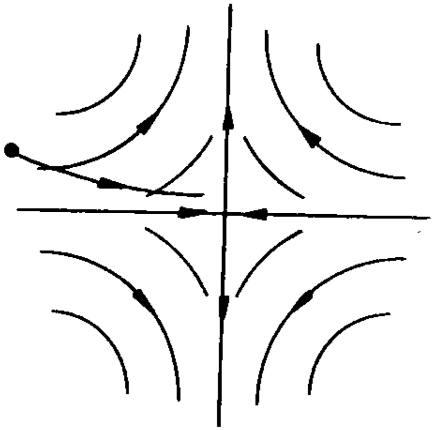
Fizyka zjawisk:

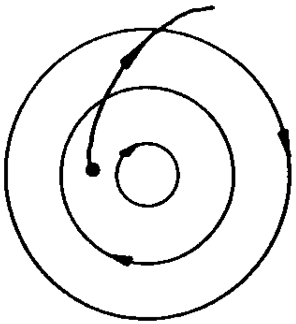
- **ruch cząstek:** siła oporu, nośna, historii, itd.
- **oddziaływania cząstka-ścianka:** uderzenie/odbicie, separacja
- przemiany fazowe: odparowanie kropel lub kondensacja
- zderzenia cząstek, niestabilności hydrodynamiczne powierzchni kropel
- efekty ściśliwości (w przepływach gaz-ciecz): zjawiska falowe, zadławienie

Problemy modelowania:

- **wpływ turbulencji fazy nośnej na cząstki** oraz *vice versa*
- warunki brzegowe na ściance (modele dwupłynowe), **separacja**
- przemiany fazowe (nukleacja, *flashing*, nierównowaga termodynamiczna)
- atomizacja strugi, rozpad i koalescencja kropel, rozkład wielkości cząstek

Korelacja położeń cząstek z polem przepływu





$$2S_{ij} = U_{i,j} + U_{j,i}$$

$$2\Omega_{ij} = U_{i,j} - U_{j,i}$$

strefa ścinania (obszar siodłowy) **wir**

$$|S| >> |\Omega| \qquad |\Omega| >> |S|$$

Struktury pola przepływu

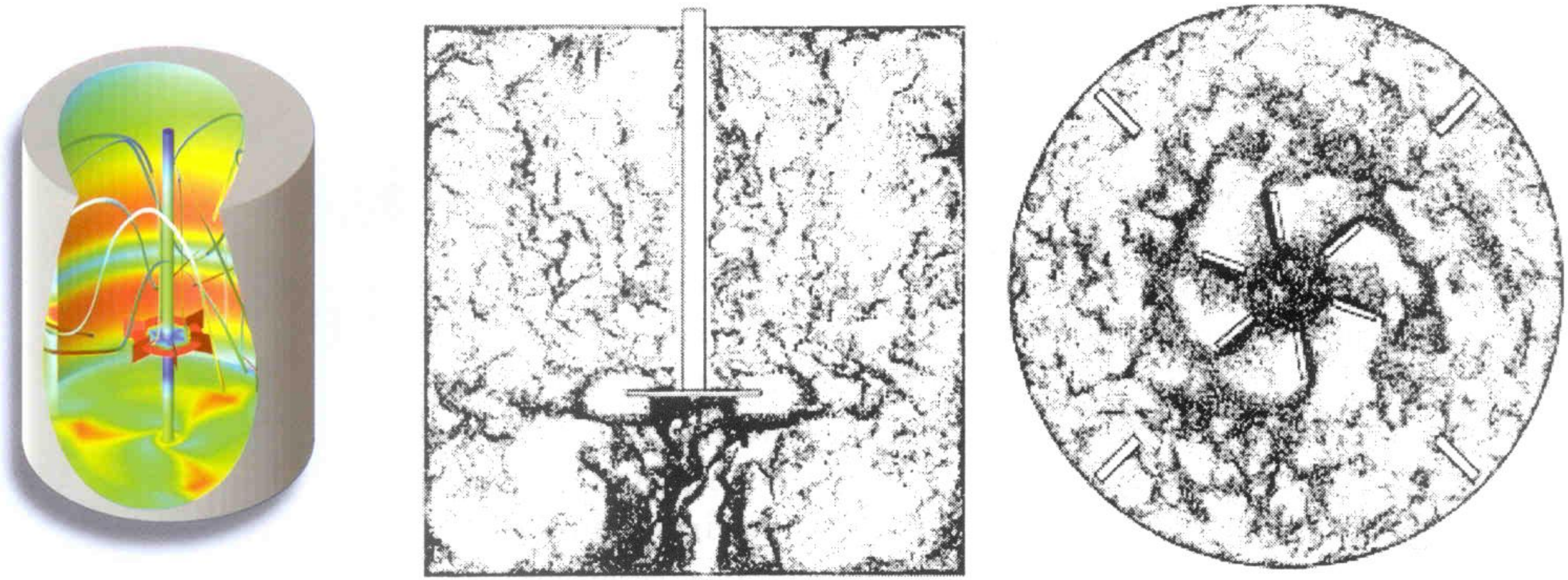
drugi niezmiennik tensora gradientu prędkości:

$$Q = S_{ij}S_{ij} - \Omega_{ij}\Omega_{ji}$$

[Eaton & Fessler, Int. J.Multiphase Flow, 1994]

Nierównomierność koncentracji cząstek

W przepływach dyspersyjnych, położenia cząstek są skorelowane ze strukturami przepływu (obszary siodłowe, wiry)



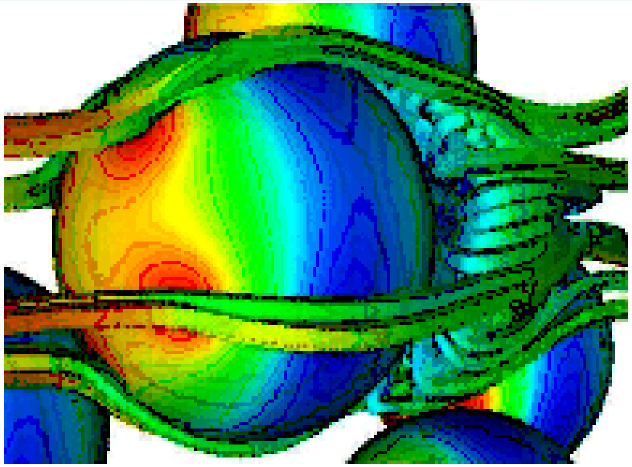
Przepływ z fazą dyspersyjną w reaktorze zbiornikowym

(Derksen, 2003)

Siły działające na cząstkę w przepływie

Równanie ruchu cząstki

Boussinesq-Basset-Oseen (XIX/XX w.),
Maxey & Riley (1983)



$$\frac{\pi d^3}{6}\rho_p\frac{d\mathbf{v}_p}{dt} = \mathbf{F}_d + \mathbf{F}_p + \mathbf{F}_b + \mathbf{F}_a + \mathbf{F}_h\ ,$$

gdzie

$$\mathbf{F}_d = 3\pi d\rho_f\nu(\mathbf{v}-\mathbf{v}_p) \quad - \text{ siła oporu lepkiego}$$

$$\mathbf{F}_p = \frac{\pi d^3}{6}\rho_f\frac{D\mathbf{v}}{Dt} \quad - \text{ siła gradientu ciśnienia}$$

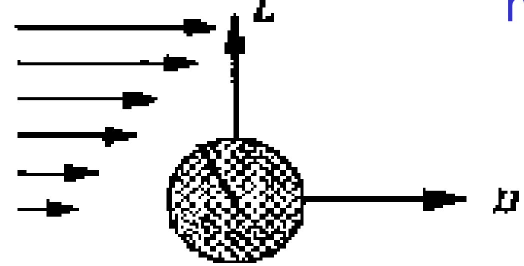
$$\mathbf{F}_b = \frac{\pi d^3}{6}(\rho_p-\rho_f)\mathbf{g} \quad - \text{ siła wyporu (grawitacji)}$$

$$\mathbf{F}_a = \frac{\pi d^3}{12}\rho_f\left(\frac{D\mathbf{v}}{Dt}-\frac{d\mathbf{v}_p}{dt}\right) \quad - \text{ składnik masy dołączonej}$$

$$\mathbf{F}_h = \frac{3}{2}d^2\rho_f\sqrt{\pi\nu}\int_{-\infty}^{t}\frac{d(\mathbf{v}-\mathbf{v}_p)}{d\tau}\frac{d\tau}{\sqrt{t-\tau}} \quad - \text{ składnik Basseta (historii)}$$

Particle equation of motion (drag and lift only)

$$\frac{4}{3}\pi r_p^3 \rho_p \frac{d\mathbf{U}_p}{dt} = \mathbf{F}_d + \mathbf{F}_l$$



heavy particles: $\frac{\rho_p}{\rho_f} \approx 10^3$

$$\mathbf{V}_s = \mathbf{U}_f - \mathbf{V}_p$$

particle Reynolds number:

$$\mathrm{Re}_p = \frac{2 r_p V_s}{\nu_f}$$

$$\mathbf{F}_d = 6\pi r_p \mu \mathbf{V}_s = \frac{1}{2}\pi r_p^2 \rho_f C_d(\mathrm{Re}_p)|\mathbf{V}_s|\mathbf{V}_s$$

for $\mathrm{Re}_p << 1$ (Stokes) $C_d = \frac{24}{\mathrm{Re}_p}$

particle Reynolds number (shear-based):

$$\mathrm{Re}_G = \frac{(2r_p)^2 G}{\nu_f}$$

$$F_l = -\frac{9}{\pi}\mu r_p^2 |\mathbf{V}_s| (|G|/\nu)^{1/2} \mathrm{sgn}(G) J(\varepsilon)$$

where $\varepsilon = \frac{\mathrm{Re}_G^{1/2}}{\mathrm{Re}_p} = \frac{(|G|\nu)^{1/2}}{|\mathbf{V}_s|}$

for $\mathrm{Re}_p, \mathrm{Re}_G << 1,\ \mathrm{Re}_p << \mathrm{Re}_G^{1/2}$ (Saffman) $J = 2.255$

[McLaughlin, JFM 1991]

Część II: METODA LES

Obliczenia dyspersyjnych przepływów turbulentnych

DNS jest kosztowne obliczeniowo (nawet w przybliżeniu cząstek punktowych),
a niezwykle kosztowne dla cząstek o skończonych obszarach traktowanych jako ruchome granice obszaru obliczeniowego (Tryggvason etal., Balachandar & Bagchi, 2000+)

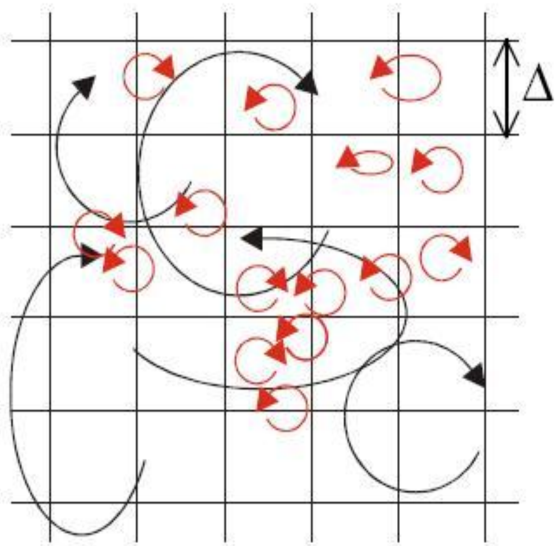
RANS nie może odtworzyć cech strukturalnych przepływów z cząstkami

(np. korelacji położeń cząstek z chwilowymi strukturami przepływu)

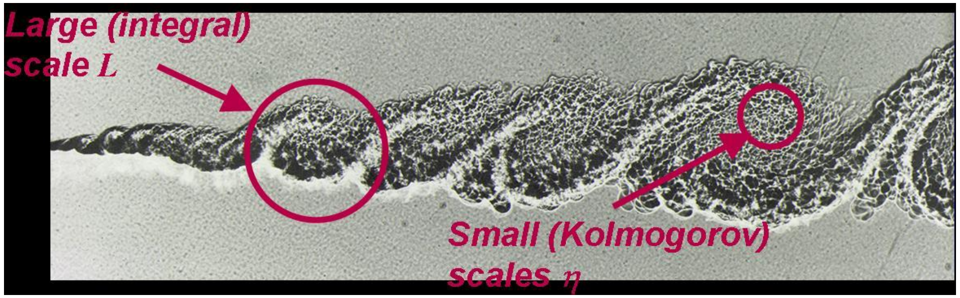
Remedium: częściowe rozwiązanie chwilowych pól przepływu

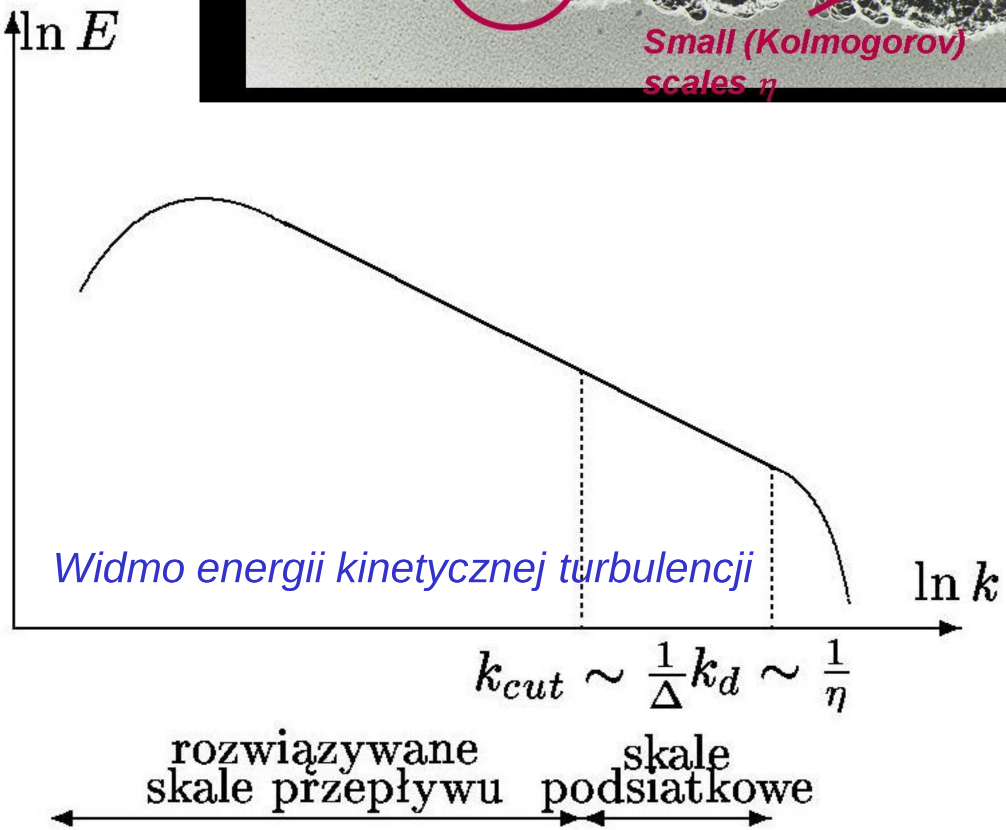
→LES (ang. large eddy simulation), CVS (metody falkowe) lub POD

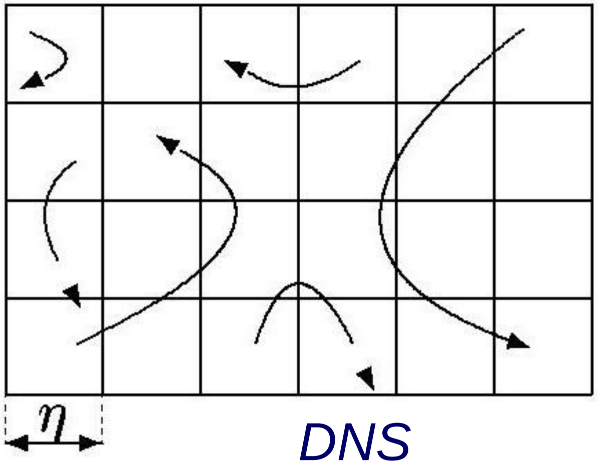
+ przybliżenie cząstek punktowych

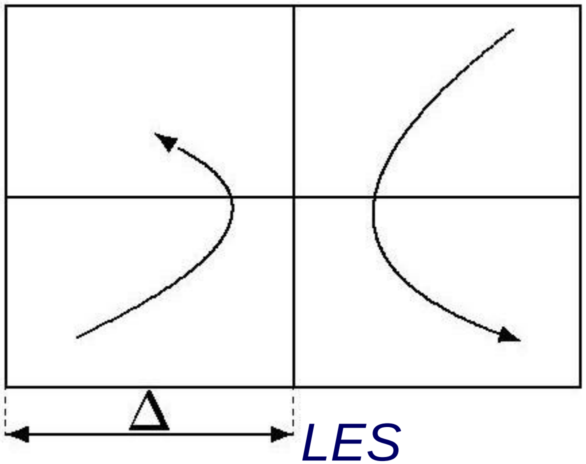


Metoda symulacji dużych wirów: LES
(ang. *Large Eddy Simulation*)









Uwaga: modelowanie LES przepływów złożonych fizykalnie (reaktywne, 2F)

Metoda LES: podstawy

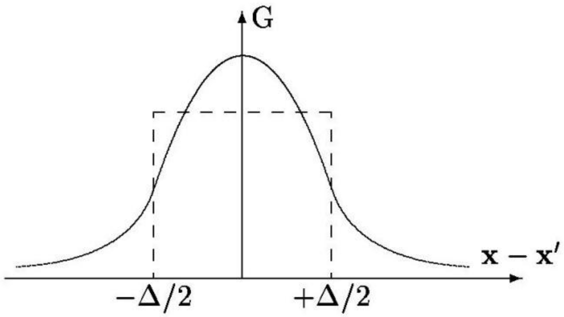
$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\mathbf{U})=S_\rho$$

$$\frac{\partial\mathbf{U}}{\partial t}+(\mathbf{U}\cdot\nabla)\mathbf{U}=-\frac{1}{\rho}\nabla p+\nu\Delta\mathbf{U}+S_U$$

Zmienne wielkoskalowe (filtrowane):

$$\tilde{U}_i(x)=\int G(x-x')U_i(x')dx',$$

$$Supp(G)\sim\Delta=\frac{1}{k_{cut}}$$



Dynamikę dużych wirów opisuje filtrowane r-nie N-S:

$$\frac{\partial\tilde{\mathbf{U}}}{\partial t}+(\tilde{\mathbf{U}}\cdot\nabla)\tilde{\mathbf{U}}=-\frac{1}{\rho}\nabla\tilde{p}+\nu\Delta\tilde{\mathbf{U}}+\nabla\cdot\mathbf{T}+\tilde{S}_U$$

Tensor naprężeń podsiatkowych **T wymaga domknięcia (tu: Smagorinski)**

$$T_{ij}=\frac{1}{3}\delta_{ij}T_{kk}-2\nu_{SGS}S_{ij},\qquad \nu_{SGS}=C_S{}^2\Delta^2(S_{ij}S_{ij})^{1/2}$$

por. Pope (2000)

metoda LES dla przepływów z fazą dyspersyjną

dwojakie znaczenie filtrowania

* Wyznaczanie pól przepływu w turbulencji swobodnej i przyściennej:

z definicji, pomija się fluktuacje podsiatkowe

* Przepływy dwufazowe z fazą rozproszoną:

fluktuacje podsiatkowe wielkości przepływowych

mogą mieć znaczenie (konieczność modelowania)

- W ogólności, cząstki „filtrują” skale przepływu

  (reagują na skale rzędu czasu relaksacji pędu)

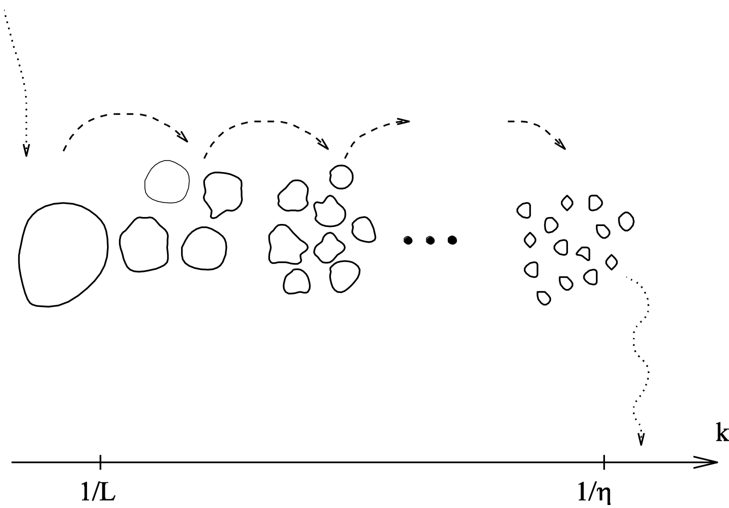
- W LES, cząstki poruszają się w filtrowanym

  polu prędkości (dużych skal)

  niektóre statystyki ruchu cząstek bardziej

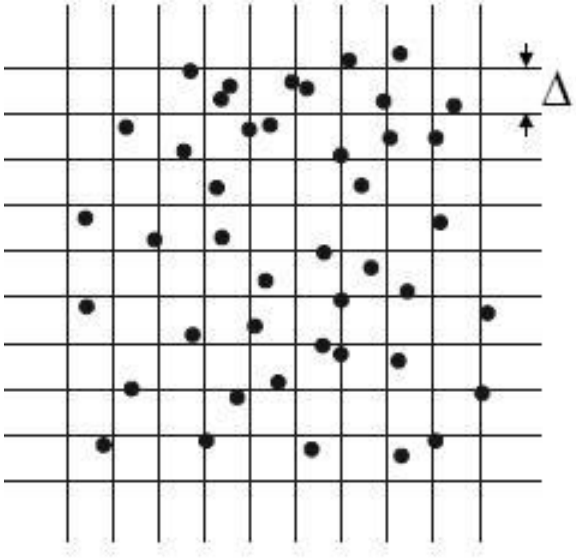
  wrażliwe na efekty podsiatkowe

  (nierównomierność koncentracji, częstość zderzeń)



Szkic kaskady energii

Reconstruction of SGS flow velocity in particle-laden flows



In particle equation of motion,
fluid velocity at particle location is needed:
- tri-linear interpolation (results presented)
- second-order interpolation, cf. Squires (2007)

- DNS

$$\mathbf{U}^* = \mathbf{U}(\mathbf{x}_p, t) = \tilde{\mathbf{U}} + \mathbf{u}'$$

- LES with no SGS particle dispersion

$$\mathbf{U}^* = \tilde{\mathbf{U}}(\mathbf{x}_p, t)$$

- modelled/reconstructed SGS fluid velocity fluctuations

  along particle trajectories, i.e. u'

LES filtering impacts on: pref.conc., slip vel. → collision rate
particle tke → wall deposition
slip vel., rel.temp. → cooling/heatig, evaporation

Reconstruction of SGS flow velocity in particle-laden flows

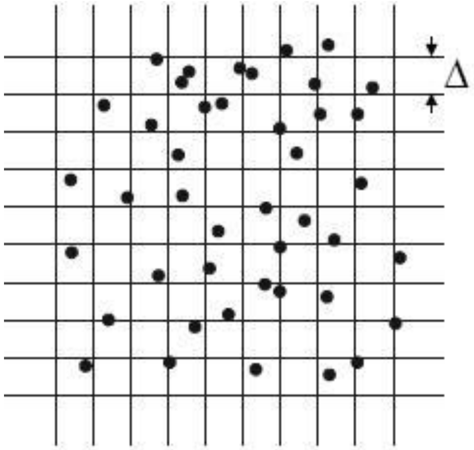
„functional" approaches: (in line with effective diffusivity concept for fluid LES):

modelling the impact of subfilter scales on resolved ones

-***stochastic diffusion model***

(Pozorski et al. 2004, Shotorban & Mashayek 2006):

Langevin eq. for fluid velocity along particle trajectories



„structural" approaches: resolving (part of) subfilter velocity field

- ***approximate deconvolution*** (Kleiser etal. 2001, Kuerten & Vreman 2005)

- ***linear-eddy model*** (Kerstein 1990s): triplet map

- ***fractal reconstruction*** (Scotti & Meneveau 1999; Salvetti & Soldati 2006)

Reconstruction of subfilter field (cntd.)

Structural approaches:

1) *Approximate deconvolution* (Kleiser etal. 2001, Kuerten PoF 2006)

$$\tilde{\mathbf{U}} = G * \mathbf{U} \quad \longrightarrow \quad \mathbf{U} = G^{-1} * \tilde{\mathbf{U}}$$

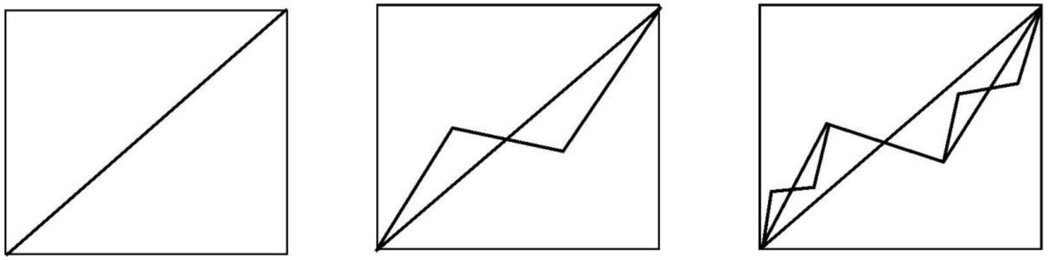
truncated van Cittert series expansion:

$$U_i = \sum_{m=0}^{M} (1-G)^m * \tilde{U}_i = \tilde{U}_i + (\tilde{U}_i - \tilde{\tilde{U}}_i) + \ldots$$

2) *Linear-eddy model* (Kerstein 1990s): triplet map

3) *Fractal reconstruction* (Scotti & Meneveau 1999)

two-parameter, 1D affine velocity transformation



SGS particle dispersion model: Langevin-type eq.

Functional approach:

Langevin eq. for SGS fluid velocity along particle trajectories

$$d\mathbf{u}_i^* = -\frac{\mathbf{u}_i^*}{\tau_L^*}dt + \sqrt{\frac{4k_{sg}}{3\tau_L^*}}dW_i$$

Estimation of SGS fluid kinetic energy k_{sg} (Yoshizawa, 1982; Moin *et al.*, 1991):

$$k_r = C_I \bar{\Delta}^2 |\bar{S}|^2 \qquad \text{where} \qquad |\bar{S}| = (2\bar{S}_{ij}\bar{S}_{ij})^{1/2}$$

analogously to C_G, dynamic procedure applied to solve for C_I

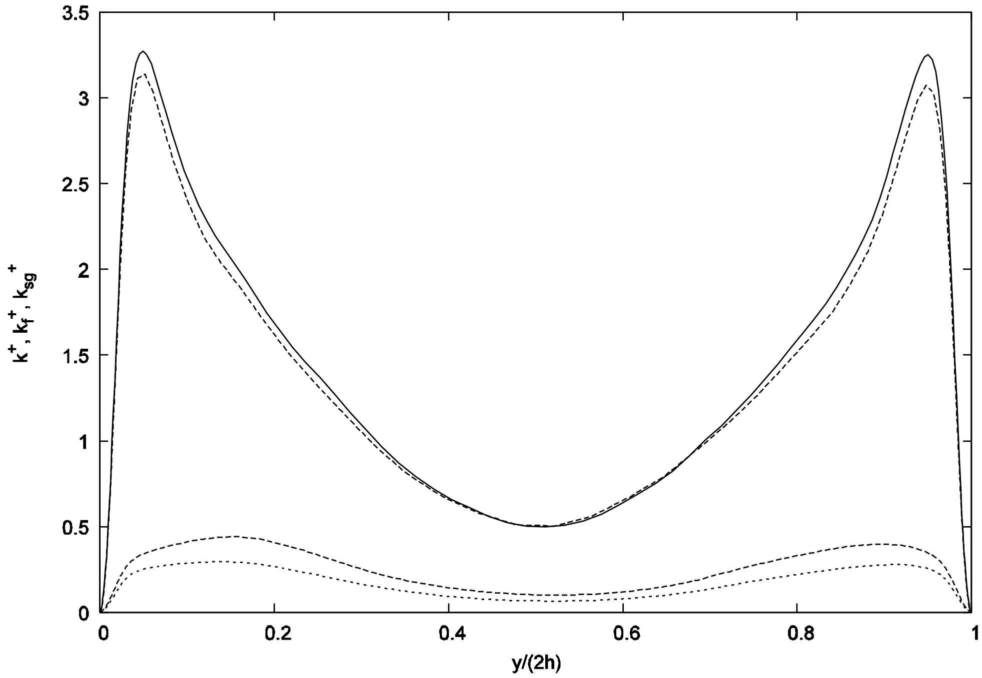
$$C_I = \frac{1}{2}\frac{\langle \widehat{\bar{U}_k \bar{U}_k} - \hat{\bar{U}}_k \hat{\bar{U}}_k \rangle_{av}}{\langle \bar{\Delta}^2 \widehat{|\bar{S}|^2} - \hat{\bar{\Delta}}^2 |\hat{\bar{S}}|^2 \rangle_{av}}$$

Estimation of the SGS fluid time scale:

$$\tau_L^* = C_{sg}\frac{\bar{\Delta}}{\sigma_{sg}} \qquad \sigma_{sg} = \sqrt{\frac{2}{3}k_{sg}}_{\;i}$$

Energia kinetyczna skal podsiatkowych w LES

Obliczenia przepływu turbulentnego w kanale
solver CFD FASTEST (kod opracowany na politechnice w Darmstadt)



Obliczenia DNS oraz *a priori* LES

[J.Pozorski & T.Wacławczyk, 2006]

Dynamika cząstek w przepływie turbulentnym

Równania ruchu cząstek:

$$\frac{d\mathbf{x}_p}{dt} = \mathbf{U_p}$$
$$\frac{d\mathbf{U}_p}{dt} = \frac{\mathbf{U}_f^* - \mathbf{U}_p}{\tau_p^e} + \mathbf{g}$$

(cząstki punktowe
o skończonej masie)

czas relaksacji pędu cząstek:

$$\tau_p = \frac{\rho_p}{\rho_f}\frac{d_p^2}{18\nu_f}$$

$$\tau_p^e = \tau_p / f_D \qquad f_D = 1 + 0.15 Re_p^{0.687}$$

• obliczenia DNS

$$\mathbf{U}^* = \mathbf{U}(\mathbf{x}_p, t) = \tilde{\mathbf{U}} + \mathbf{u}'$$

• LES bez dyspersji podsiatkowej

$$\mathbf{U}^* = \tilde{\mathbf{U}}(\mathbf{x}_p, t)$$

• model rekonstrukcji fluktuacji podsiatkowych prędkości płynu

wzdłuż trajektorii cząstek, i.e. u’

DNS oraz *a priori* LES przepływu dwufazowego

-DNS turbulencji izotropowej

(na siatce 96*96*96) przy $\mathrm{Re}_{\lambda} = 40$

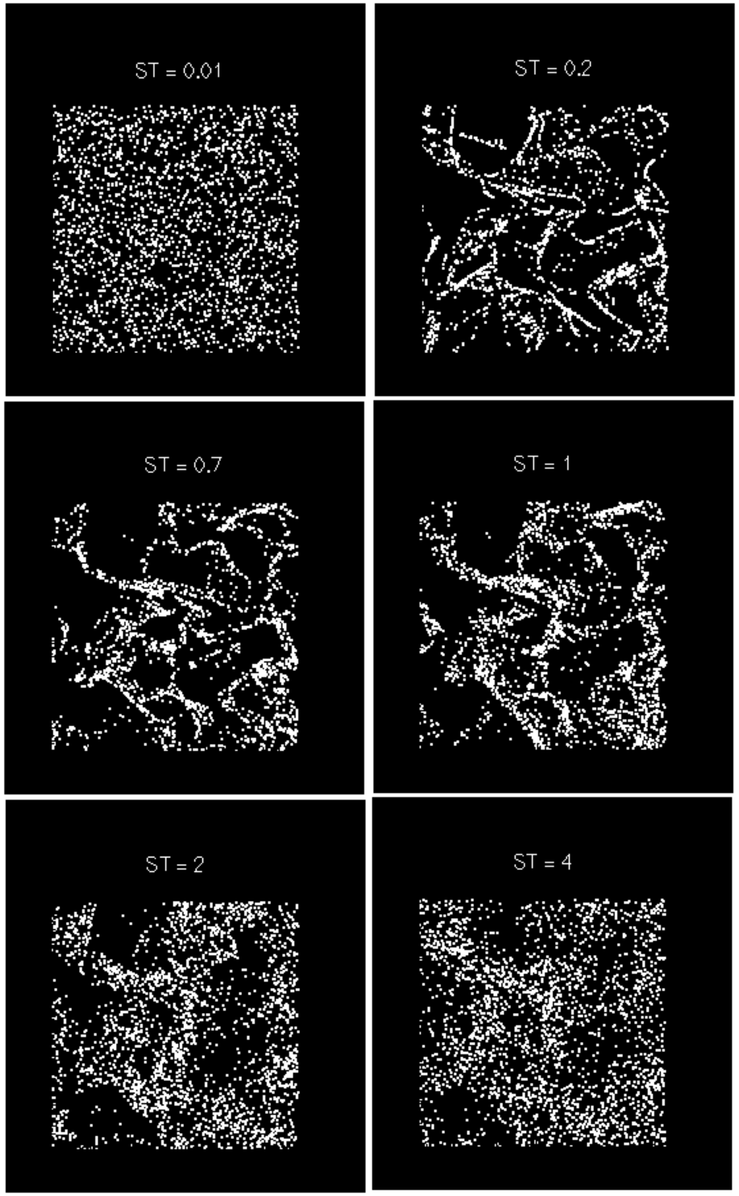
- modelowanie Lagrange'owskie ruchu cząstek dla różnych liczb Stokesa

$$St = \frac{\tau_p}{\tau_\eta}$$

- nierównomierność koncentracji cząstek dla

$$0.2 < St < 2$$

(Pozorski, Apte & Raman 2004)



DNS turbulencji z cząstkami: rozkład przestrzenny

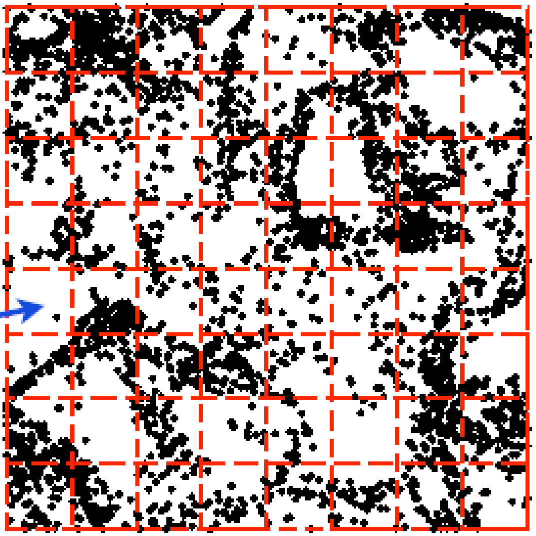
-nierównomierność rozkładu cząstek (ang. *preferential concentration*) szacowana na podstawie PDF ich gęstości/koncentracji (ang. *bin-counting)*

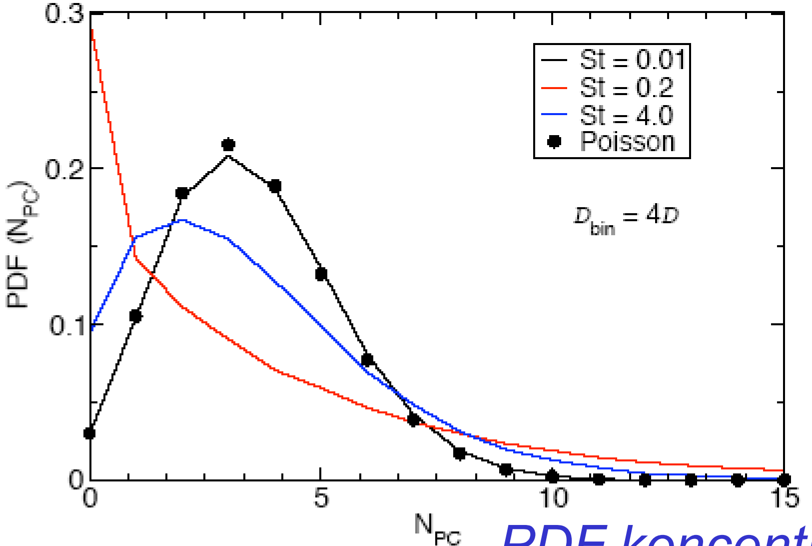
- PDF zależy od St oraz rozdzielczości (ang. *bin size*)

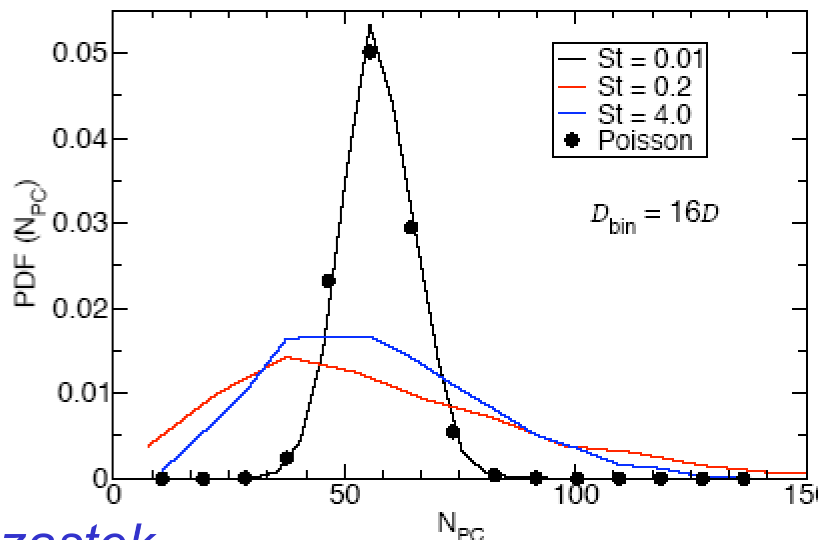
- równomierną koncentrację opisuje rozkład Poissona

$$f_P(n) = \frac{e^{-\lambda}}{n!}\lambda^n \qquad \lambda = \langle N_{PC} \rangle$$

Bin



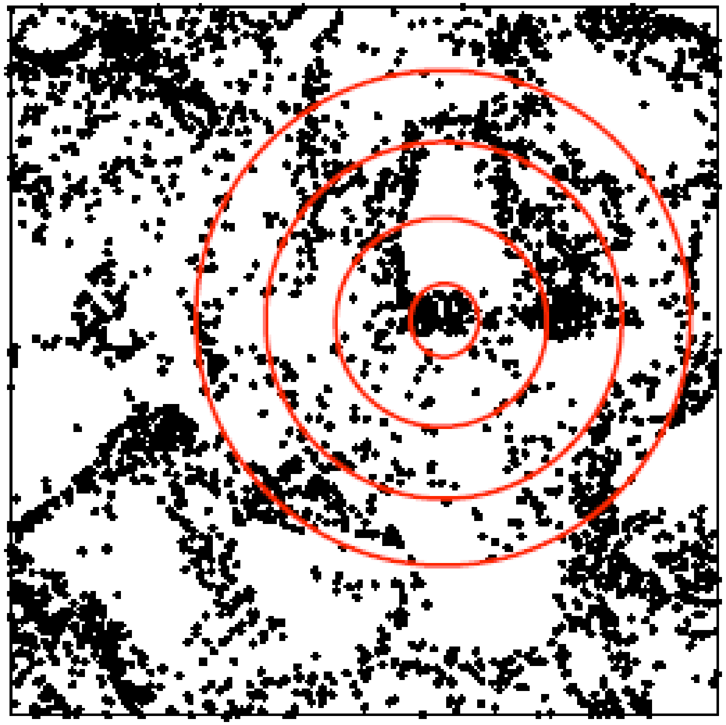




PDF koncentracji cząstek

DNS przepływu z cząstkami: wynikowe RDF

- nierównomierność koncentracji cząstek w obszarze przepływu szacowana za pomocą radialnej funkcji rozkładu (ang. RDF - *radial distribution function*)

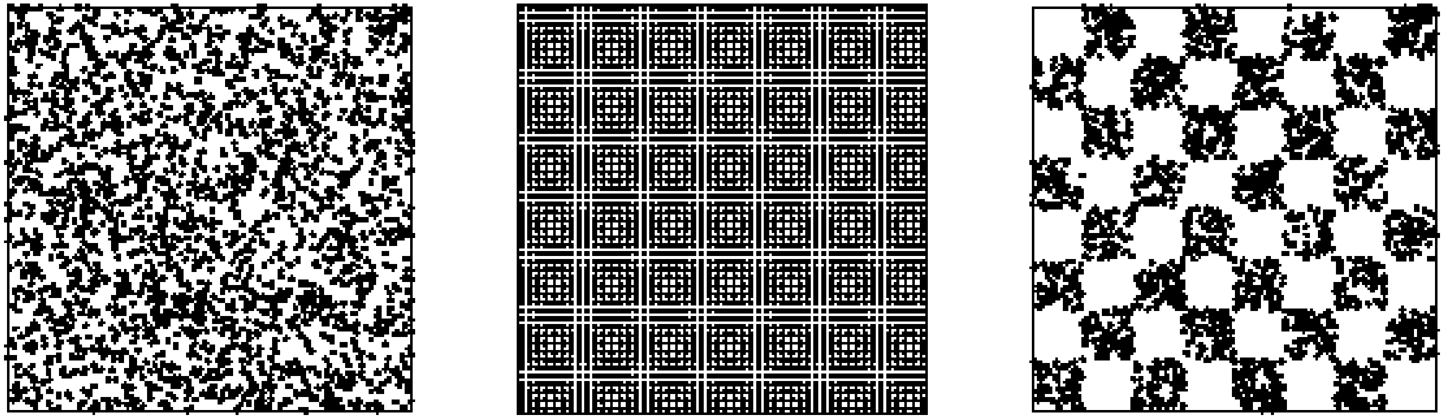


$g(r)dr$ **jest liczbą cząstek w powłoce kulistej** $(r, r+dr)$

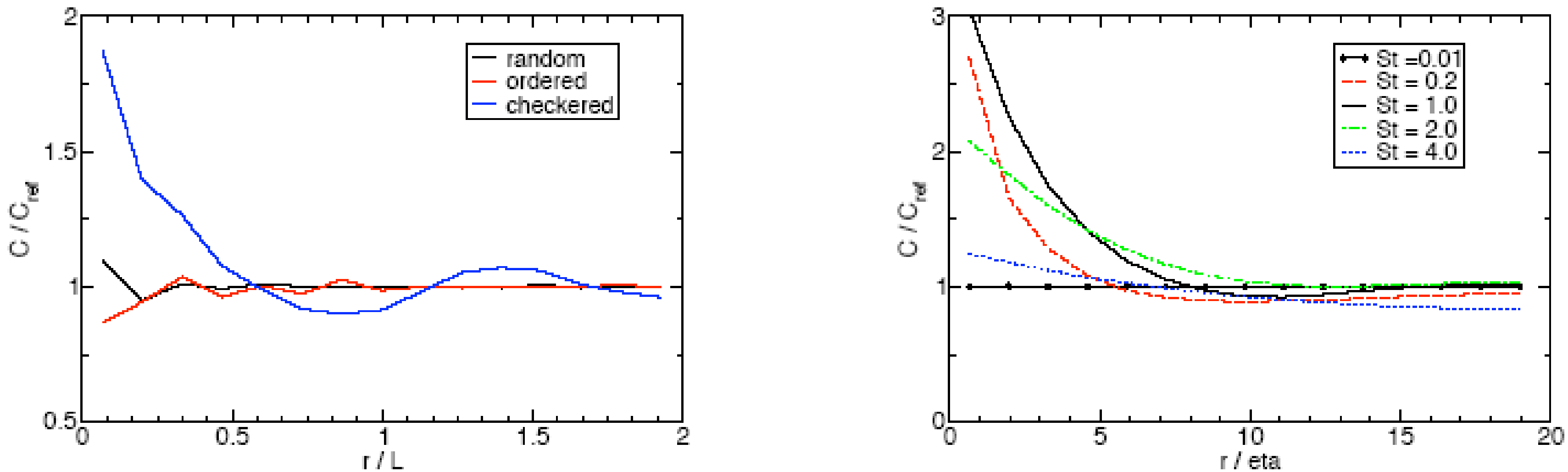
- RDF stanowi miarę nierównomierności rozkładu cząstek

- RDF daje oszacowanie skali korelacji przestrzennej

Nierównomierność koncentracji cząstek: RDF



Testy dla różnych rozkładów cząstek



RDF: nierównomierność rozkładu i skala długości

Turbulencja z cząstkami: model dyspersji podsiatkowej

→DNS oraz *a priori* LES turbulencji z cząstkami

$$k_{resolved} \approx 0.65 k_{DNS}$$

→ uwzględnienie wpływu fluktuacji podsiatkowych pola prędkości LES na ruch cząstek

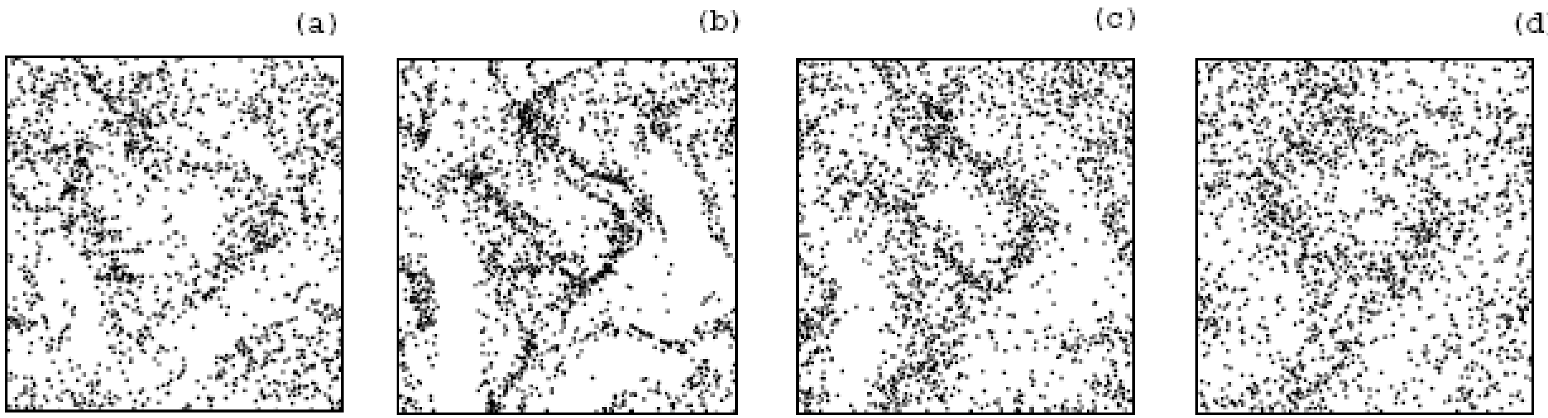


FIGURE 9. Snapshots of particle positions; runs for particles of St = 2. a) DNS; b) *a priori* LES with no FPT model; c) *a priori* LES with FPT model and C=0.05; d) DNS for St = 4.

→ wyniki obliczeń jakościowo poprawne dla cząstek o większej bezwładności

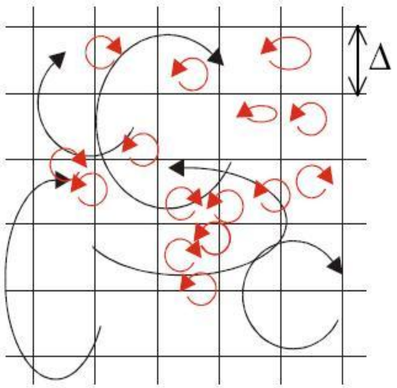
[Pozorski & Apte, Int. J. Multiphase Flow, 2009]

Part III

LES of dispersed flows – examples of results

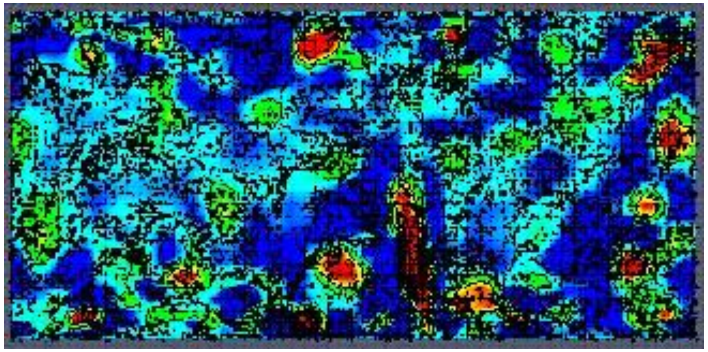
Results from regular particle-laden LES

and LES with subfilter dispersion modelling



1) **Turbulent channel flow**

(also with particle wall separation)

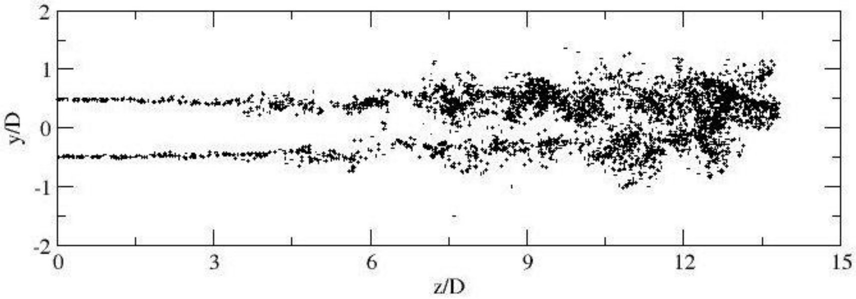


2) **Non-isothermal channel**

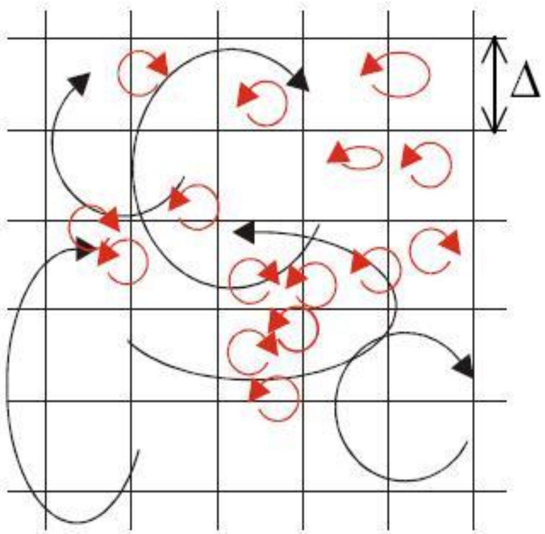
(heated/cooled and isoflux)

3) **Jet flows**

(single axisymmetric and coaxial jets)



LES for fluid: reminder on governing equations



Dynamics of large-eddy motion (filtered N-S eq.):

$$\frac{\partial \bar{U}_i}{\partial t} + \bar{U}_j \frac{\partial \bar{U}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \nu \nabla^2 \bar{U}_i - \frac{\partial \tau_{ij}}{\partial x_j}$$

Closure of the SGS stress tensor: **dynamic model (Germano & Lilly)**

$$\tau_{ij}^d = -2\nu_r \bar{S}_{ij} \text{ where } \nu_r = C_G \bar{\Delta}^2 |\bar{S}|$$

Temperature treated as a passive scalar (filtered energy eq.):

$$\frac{\partial \bar{T}_f}{\partial t} + \bar{U}_{f,i} \frac{\partial \bar{T}_f}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\frac{\nu_f}{\mathrm{Pr}} + \frac{\nu_t}{\mathrm{Pr}_t}\right)\frac{\partial \bar{T}_f}{\partial x_i}\right]$$

LES and particle solvers

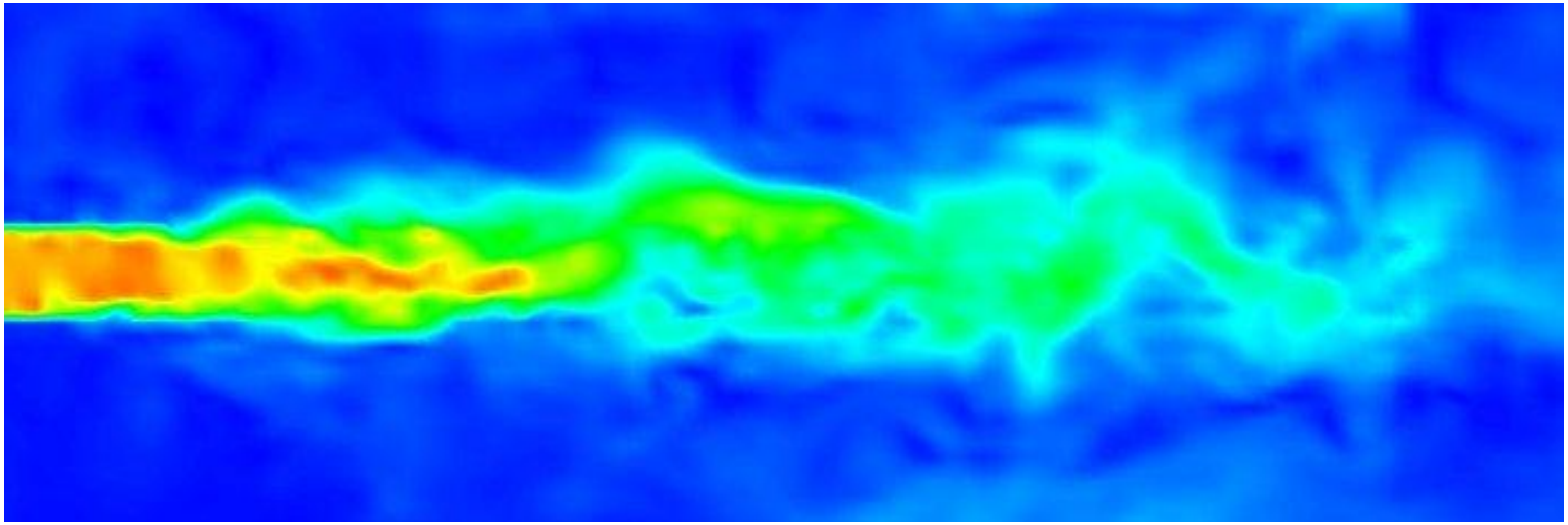
`FASTEST3D:` academic LES code (Darmstadt, Germany)

-finite volume, second-order accuracy, dynamic (Germano) SGS stress model

`SAILOR:` monoblock, spectral LES code (TU Częstochowa, Poland) – single jet only

`PTSOLV:` particle solver (in-house)

- Lagrangian tracking, one-way coupled to fluid LES (dilute regime)



Velocity magnitude: *Eulerian LES computed with FASTEST3D code*

Summary of evolution equations
for particle velocity and temperature (point-particle approximation)

particle velocity U_p; fluid velocity U_f; in LES: $\mathrm{U}_f = \bar{\mathrm{U}}_f + \mathrm{u}_f$

fluid velocity along particle trajectory: $\mathrm{U}_f^* = \mathrm{U}_f(\mathrm{x}_p, t)$, or $\mathbf{U}_f^* = \bar{\mathbf{U}}_f(\mathbf{x}_p, t) + \mathbf{u}_f^*$

fluid temperature seen by particles: $T_f^* = T_f(\mathrm{x}_p, t)$, in general $T_f^* = \bar{T}_f(\mathbf{x}_p, t) + \theta_f^*$

$$
\begin{aligned}
\frac{d\mathrm{x}_p}{dt} &= \mathrm{U_p} \\
\frac{d\mathrm{U}_p}{dt} &= f_D \frac{\mathbf{U}_f^* - \mathrm{U}_p}{\tau_p} \\
\frac{dT_p}{dt} &= f_\theta \frac{T_f^* - T_p}{\tau_\theta}
\end{aligned}
$$

the particle momentum and thermal relaxation times, respectively:

$$
\tau_p = \frac{\rho_p}{\rho_f} \frac{d_p^2}{18\nu_f}, \quad \tau_\theta = \frac{\rho_p c_p}{\rho_f c_f} \frac{d_p^2}{12\alpha_f}
$$

moreover, $f_D = 1 + 0.15 Re_p^{0.687}$ and $f_\theta = \mathrm{Nu}/2 = 1 + 0.3\,\mathrm{Re}_p^{1/2}\mathrm{Pr}^{1/3}$

(correction factor f_θ taken from the Ranz-Marshall correlation for the Nusselt number)

LES results for non-isothermal particle-laden turbulent channel flow

Flow case: turbulent channel flow at $\mathrm{Re}_\tau = 150$ (benchmark of COST Action LES-AID)

- domain size in streamwise (x), wall-normal (y) and spanwise (z) directions:

  $4\pi h \times 2h \times (4/3)\pi h$
- discretisation: $64 \times 84 \times 64$ FV meshes
- the mesh: uniform with $\Delta x^+ = 29.5$, $\Delta z^+ = 9.8$,

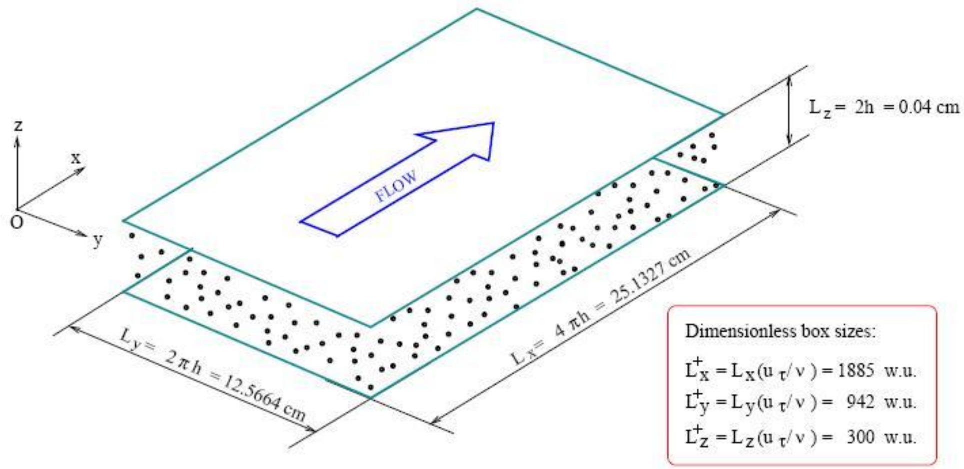
  $\Delta y^+ = 0.17$ at the wall up to $\Delta y^+ = 10$ at the CL

DNS data available for particle dynamics:

[Marchioli, Soldati, Kuerten et al., ICMF 2007]

also, for temperature of particles:

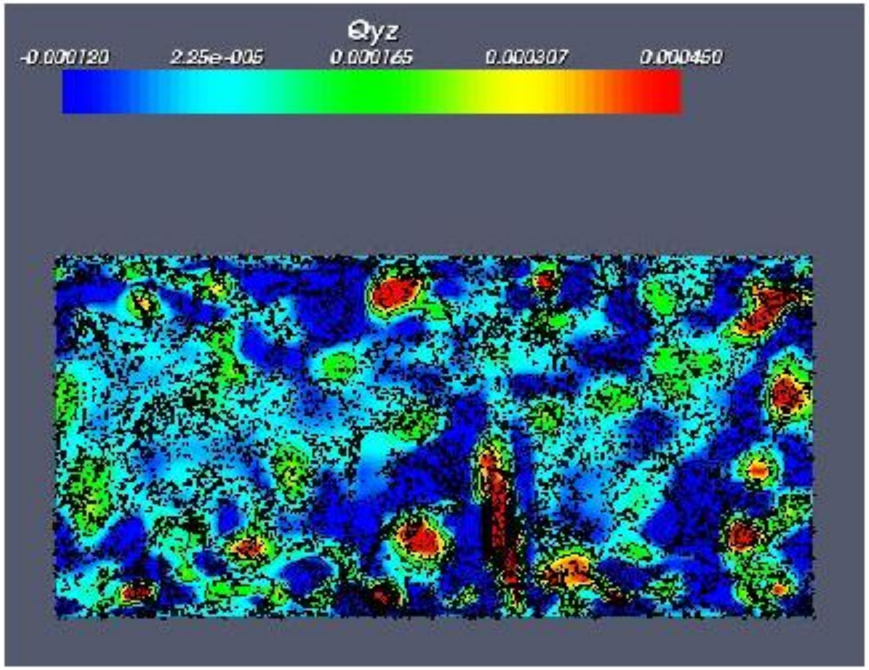
[Jaszczur & Portela, QLES 2007]

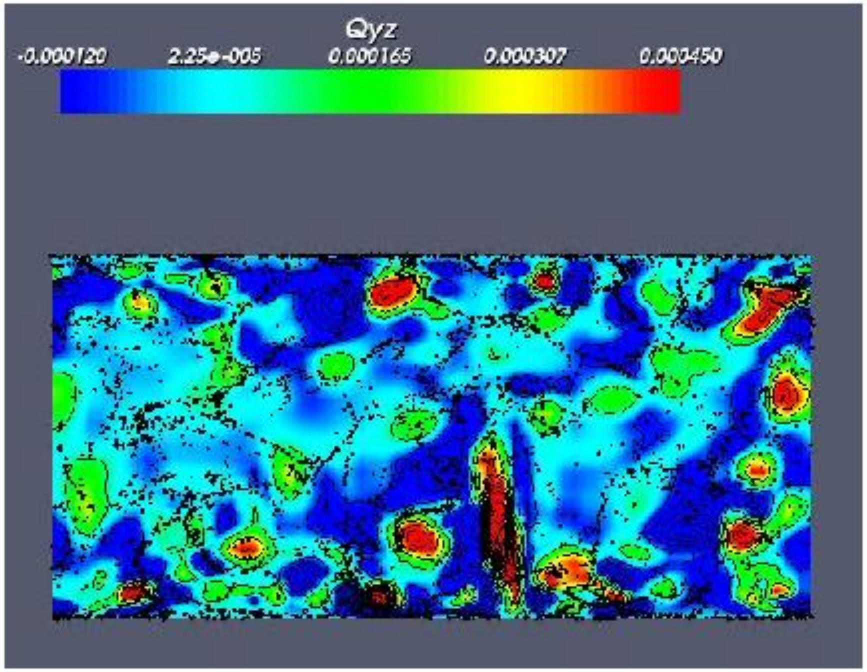


for **non-isothermal** channel flow: either isotemperature (heated/cooled) or isoflux wall b.c.; Pr=0.71 (air)

Correlation of particle location with fluid velocity

$$Q = S_{ij} S_{ij} - \Omega_{ij} \Omega_{ji}$$





Particle Stokes number: a) St=2 , b) St=10

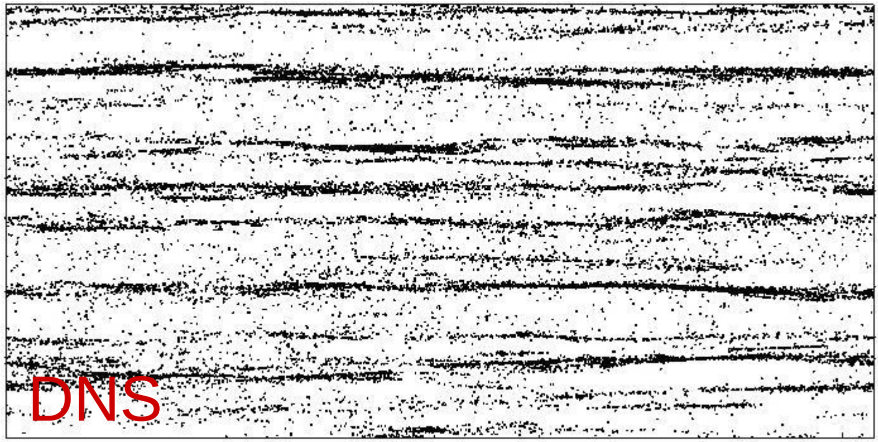
$$St = \frac{\tau_p}{(\nu / u_\tau^2)} = \tau_p{}^+$$

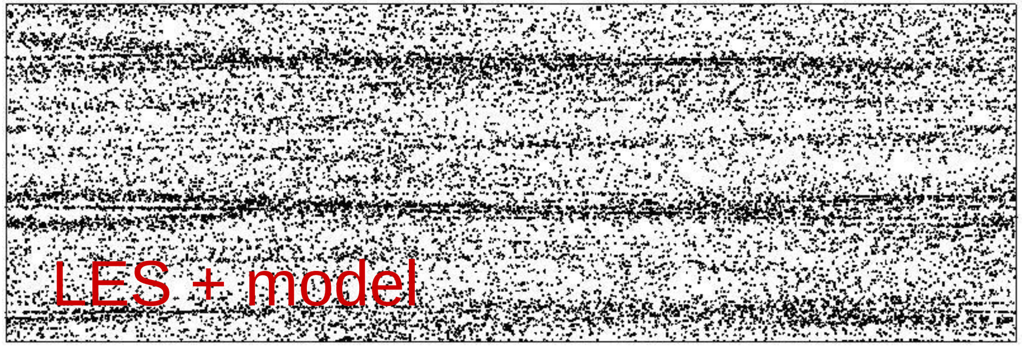
Particle-laden channel flow: particle locations

Near-wall layer: $0.5 < y^{+} < 5$

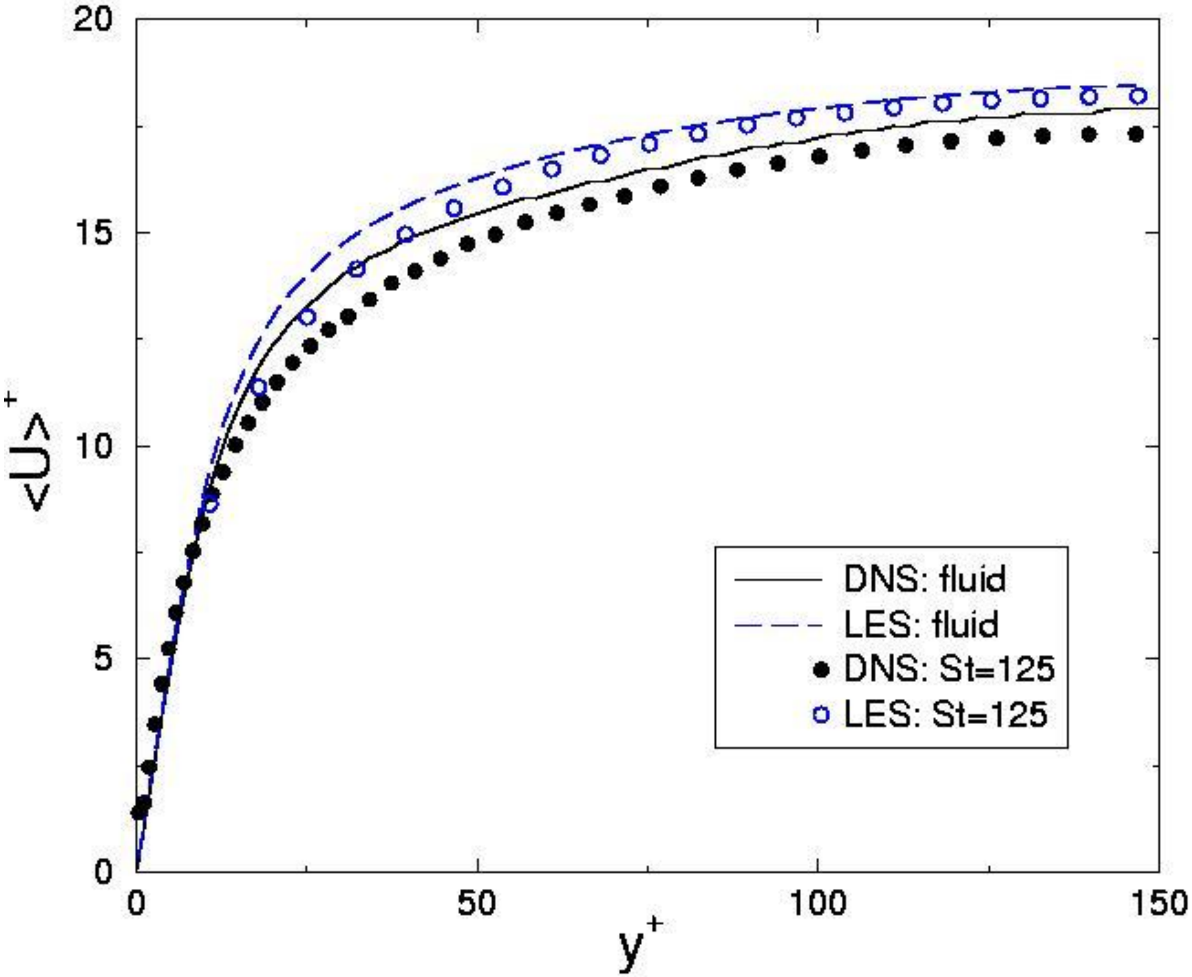
- DNS,
- LES + no model,
- LES + Langevin eq.
  for SGS particle dispersion

particles of St=25





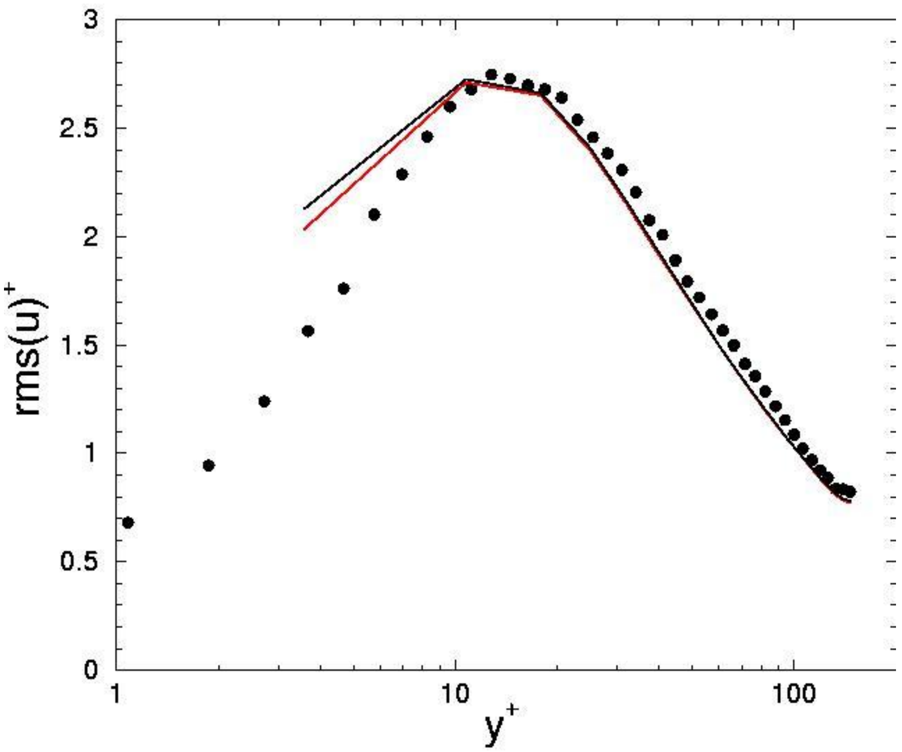
Channel flow: particle velocity statistics

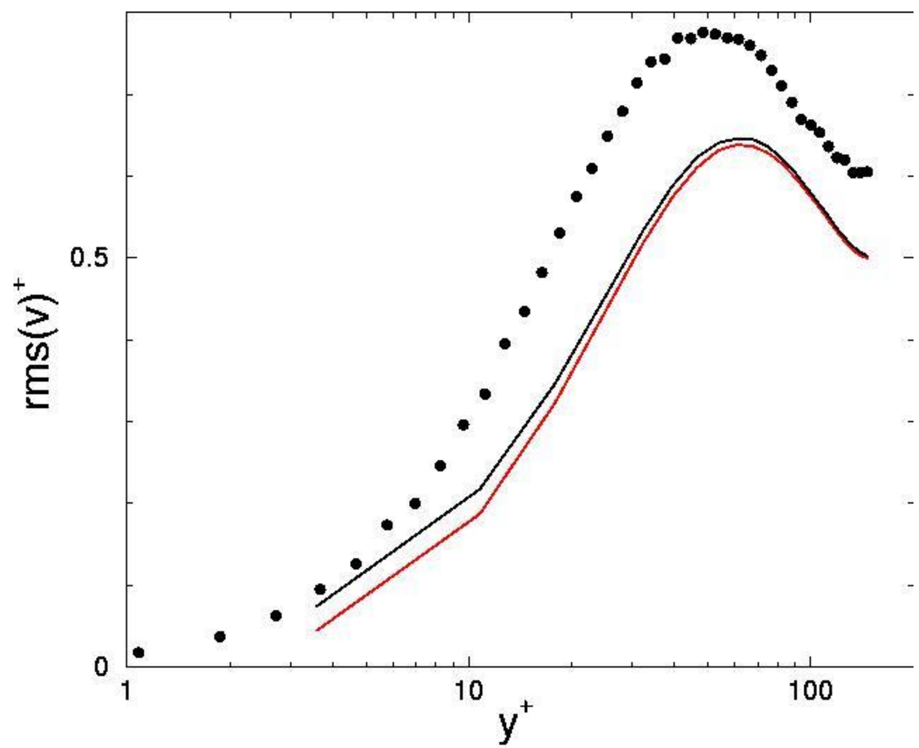


Mean velocity profile for particles of St=125

Reference data (●): DNS of Marchioli & Soldati (`cfd.cineca.it/CFD/repository`)

Channel flow: intensity of particle velocity fluctuations

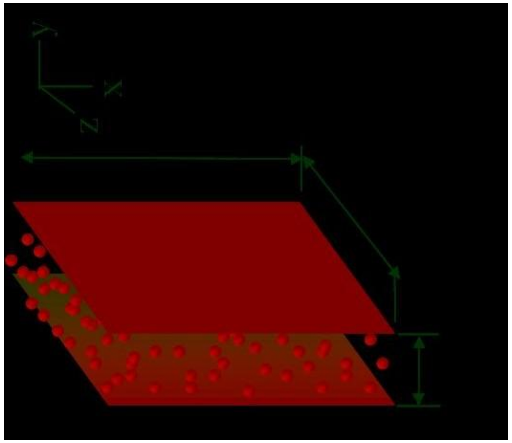




Particle rms velocity: a) streamwise, b) wall-normal. Particles of St=1.
Symbols: DNS reference data; red lines: LES; black lines:
LES with stochastic SGS particle dispersion model.

[Pozorski & Łuniewski, QLES 2007]

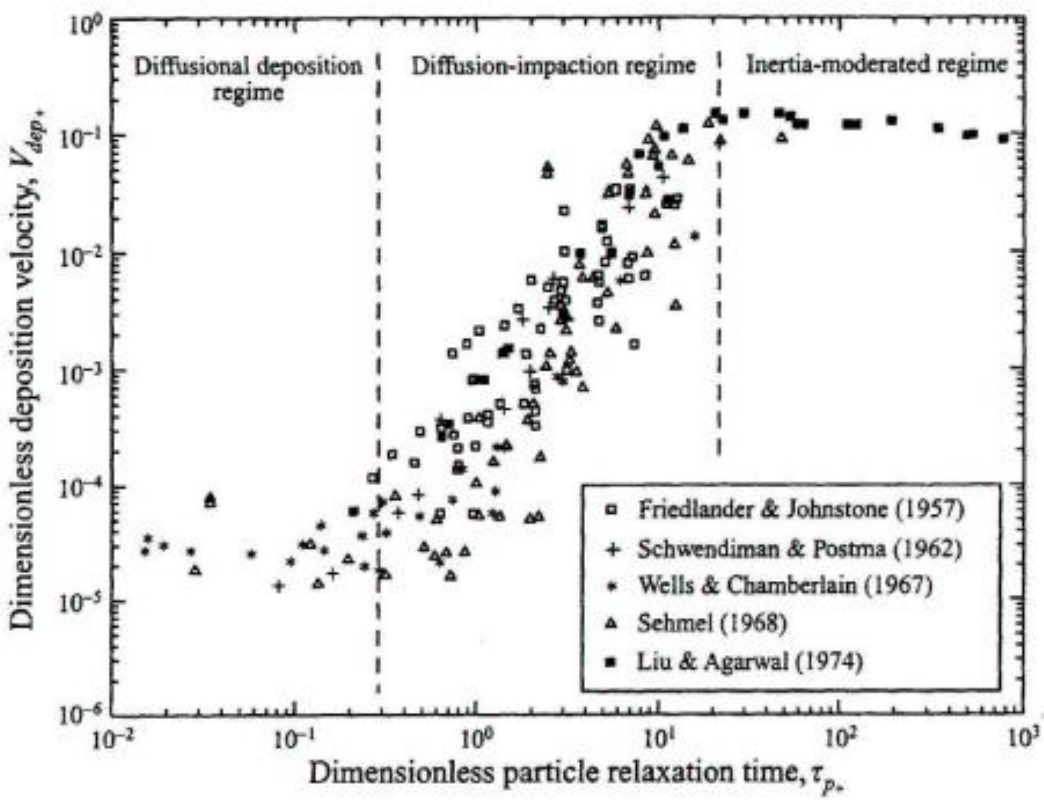
Particle separation from turbulent flow



Deposition velocity

(mass flux of separating particles):

$$V_{dep}^{+} = \frac{J_w}{\rho_{dp} u_\tau} = \frac{n_{dep}}{n_{tot}} \frac{\Delta L / \Delta t}{u_\tau}$$

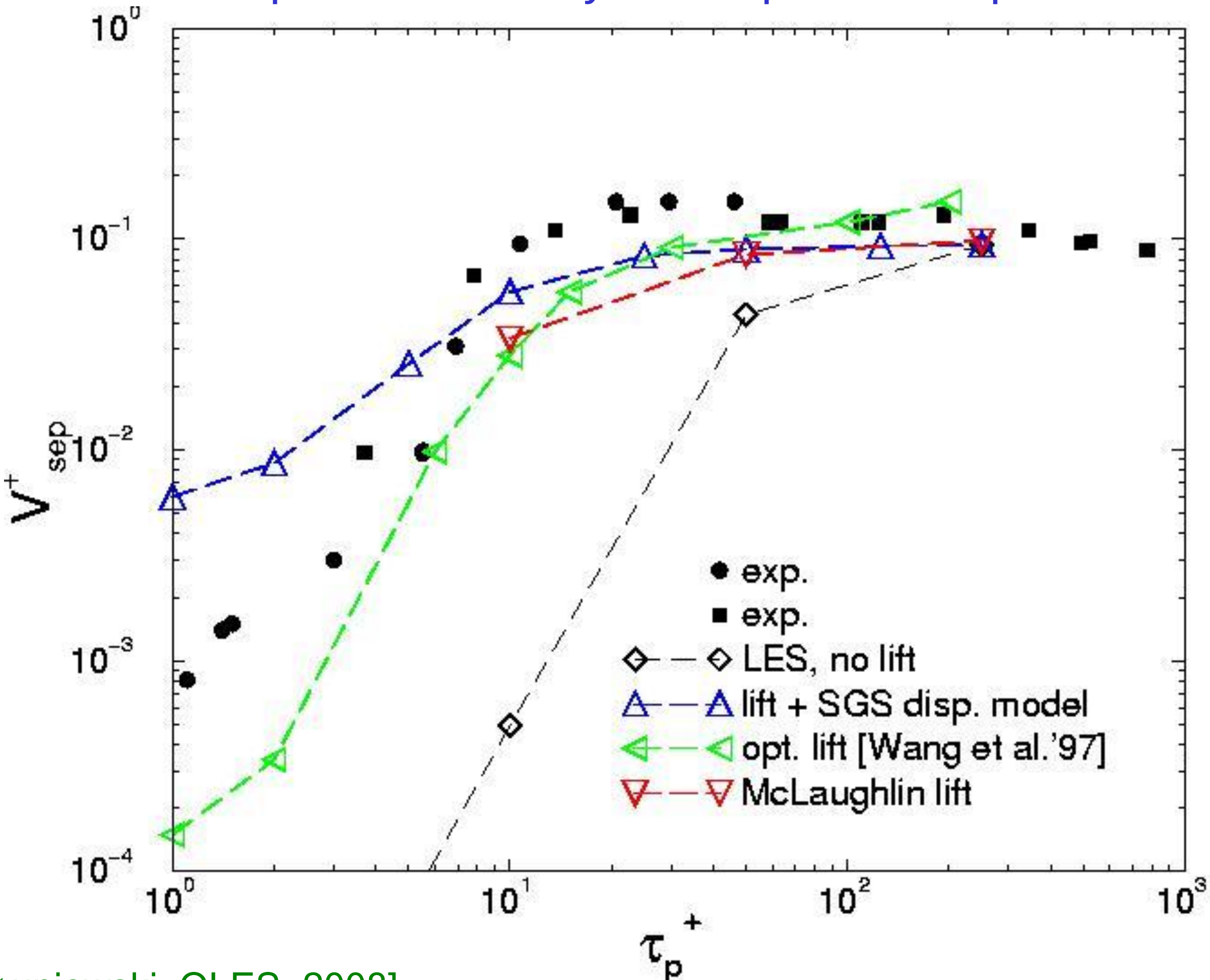


← experimental data
for turbulent pipe flow

[Young & Leeming, JFM 1997]

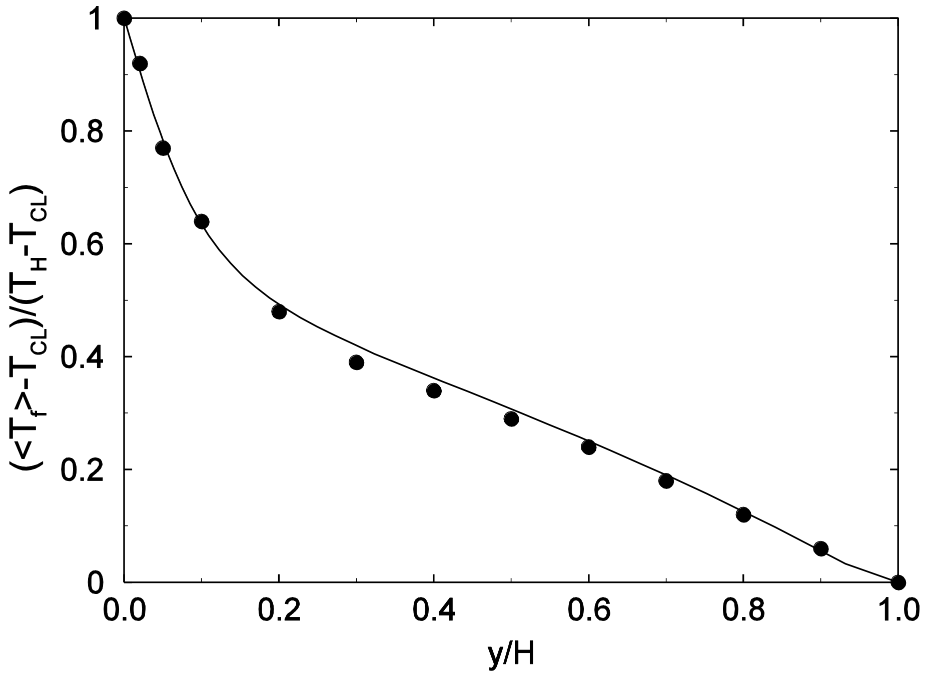
Particle wall deposition (cntd.)

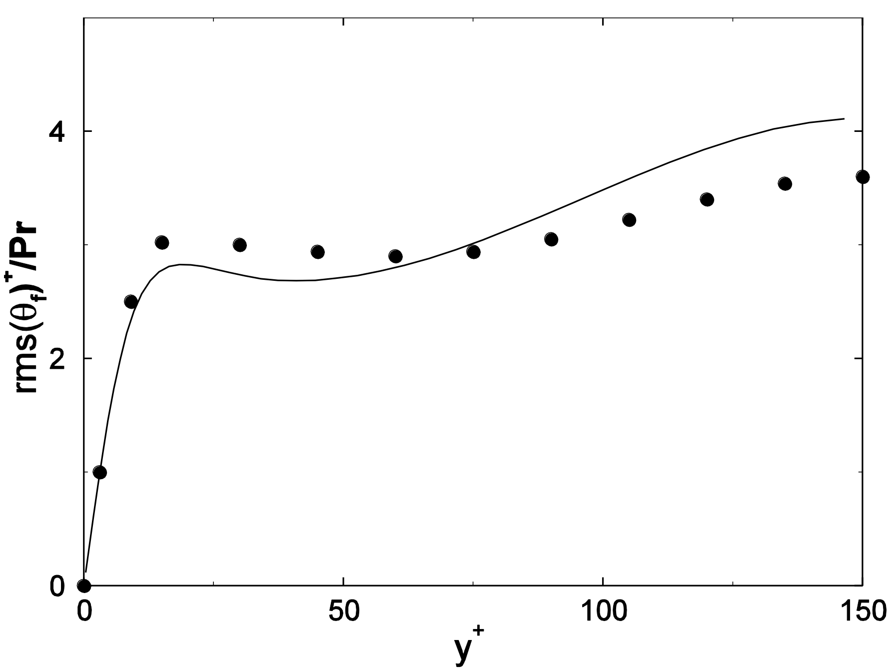
LES computation of deposition velocity: SGS particle dispersion + lift force



[Pozorski & Łuniewski, QLES, 2008]

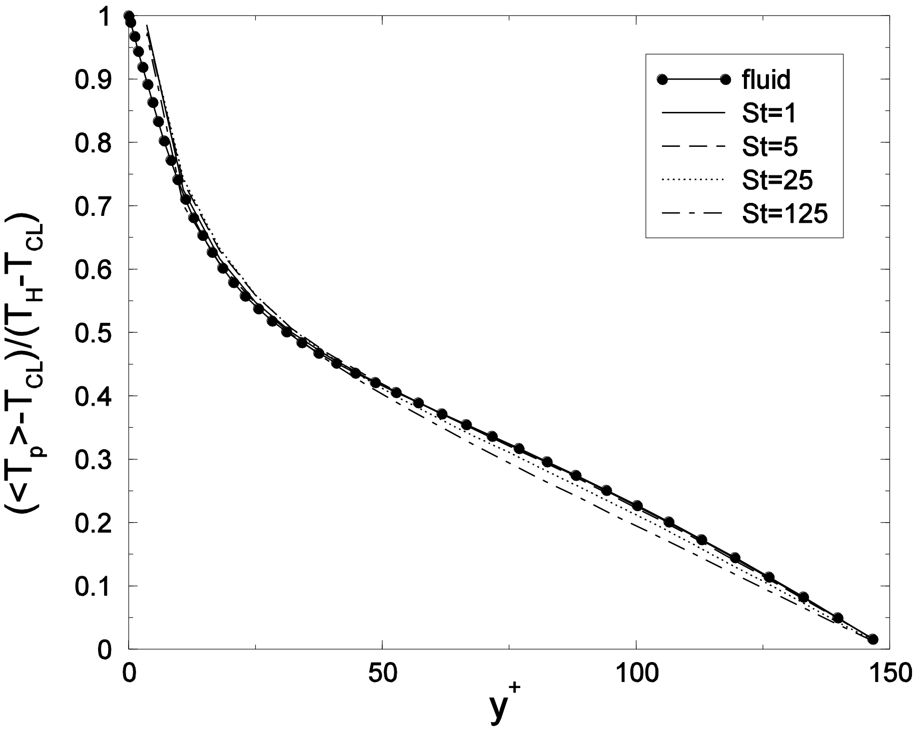
Heated/cooled channel flow: fluid temperature statistics

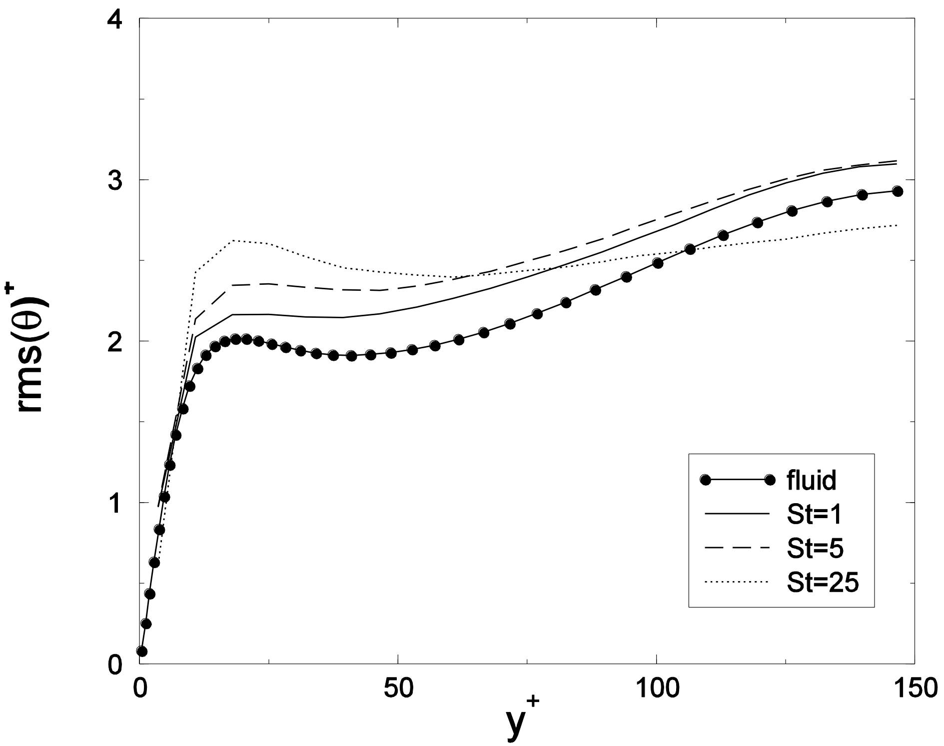




Mean temperature profile; temperature r.m.s.

Heated/cooled channel flow: fluid and particle statistics

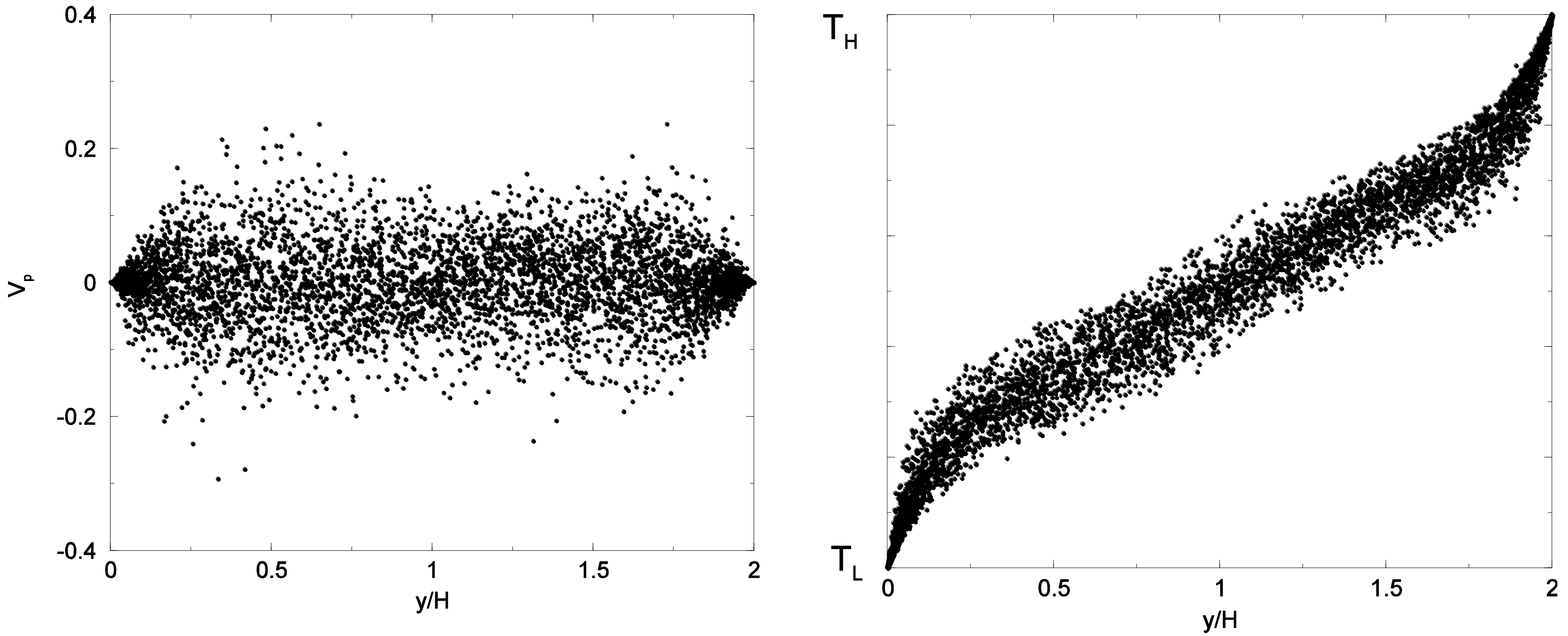




Mean temperature profile;   temperature r.m.s.

[Pozorski & Łuniewski, QLES II, 2010 (to appear)]

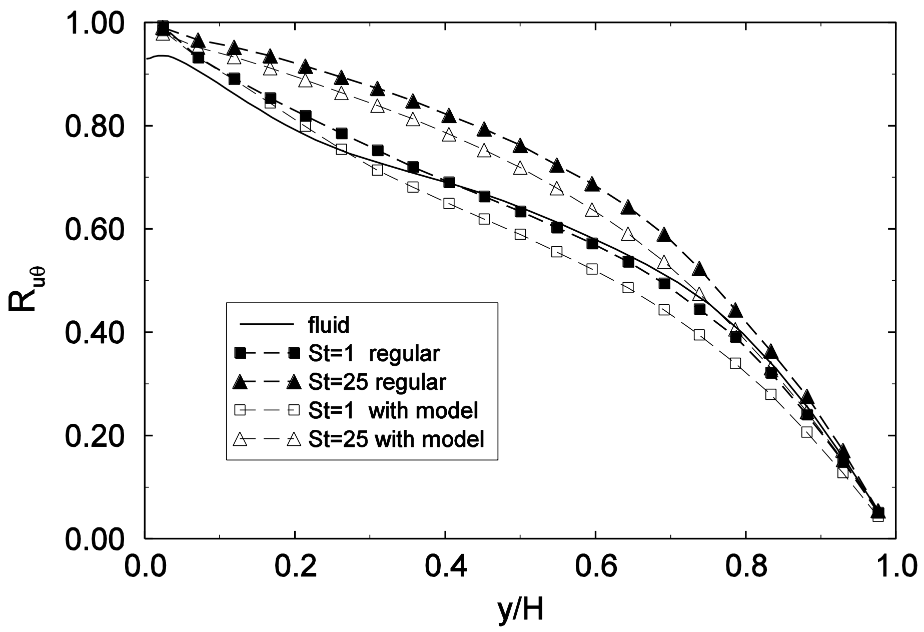
Heated/cooled channel flow: scatter plots for particles of St=5

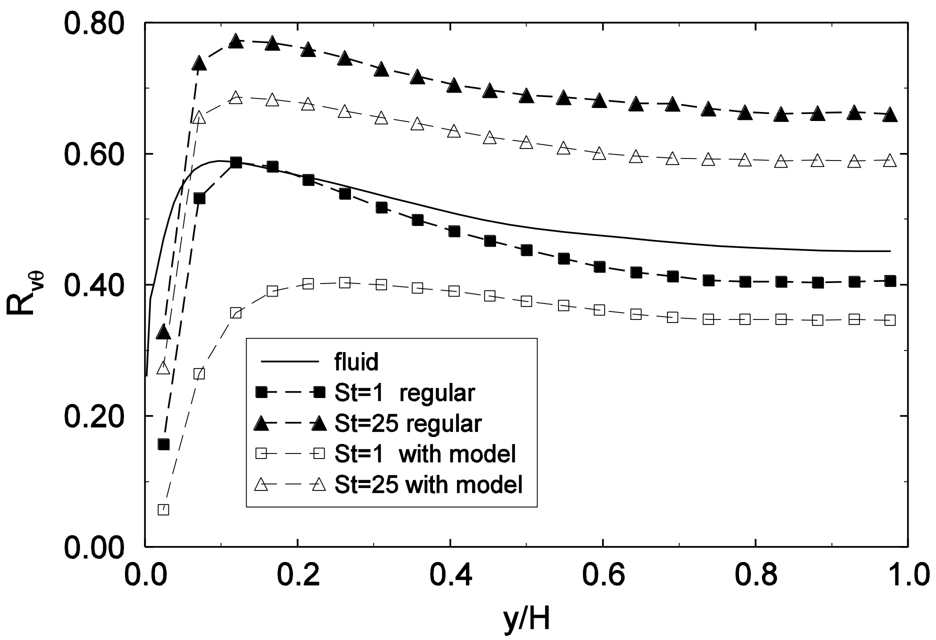


(a) particle wall-normal velocity, (b) particle temperature

…scalar boundedness constraint should be preserved
if a model for SGS temperature fluctuation is attempted

Heated/cooled channel flow: particle velocity-temperature correlation coefficients





Velocity-temperature correlation: a) streamwise, b) wall-normal

Solid lines: regular LES; dot-dashed lines:LES with SGS dispersion model

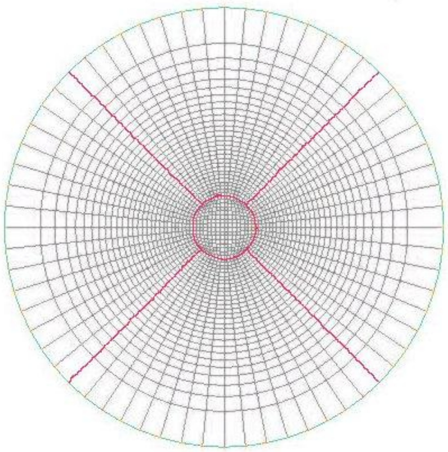
[Pozorski & Łuniewski, QLES II, 2010 (to appear)]

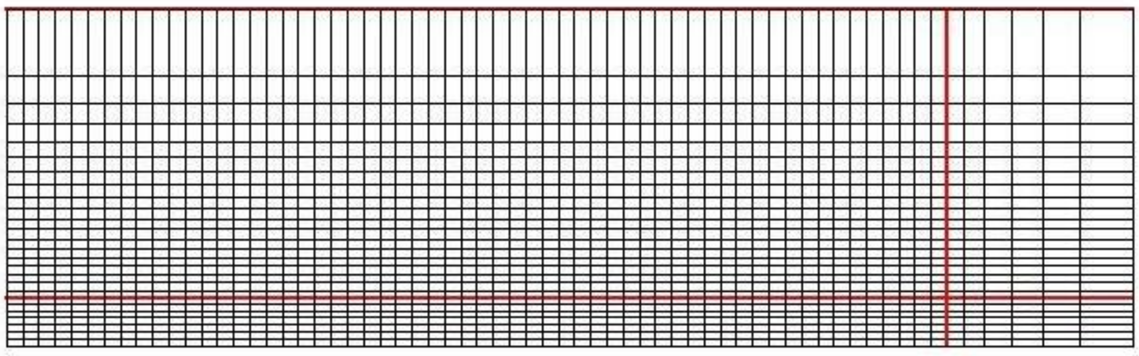
LES results for particle-laden axisymmetric and coaxial jets

Benchmark problem, experimental data available

[Hishida et al., JCMF 2000]

$$\mathrm{Re}_J = u_z^J D / \upsilon = 27500$$





present LES:

computational domain:
(r,θ,z): 3.5D x 2π x 18D

Inlet b.c.: $$U_Z = \frac{u_z^J}{2}\left(1 + \tanh\left[7.5\left(1 - \frac{R}{R_J}\right)\right]\right)$$

Outlet b.c.: $$\frac{\partial U_Z}{\partial t} + U_C \frac{\partial U_Z}{\partial z} = 0$$

Jet discretisation (cntd.)

Implementation issues for particle-laden flow

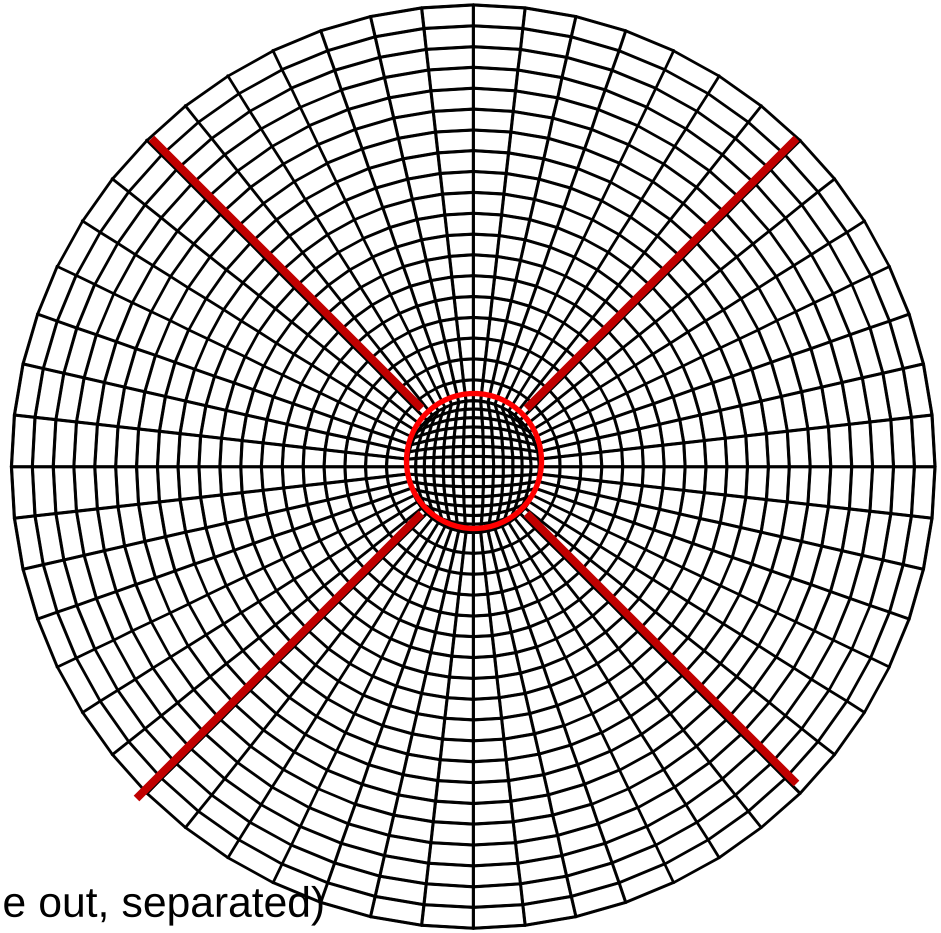
Block-structured grid**: t**otal ~200 000 cells;

Central part: „O-grid" of 15*15*130 ce**lls**

Outer part: 4 regular (r,*θ*,z) blocks

of 20*15*130 cells

parallel comp. with domain decomposition



→ Efficient update of particle data arrays:

- particle localisation : global (b.c.)

  and local (within blocks)

- particle „exchange" between processors

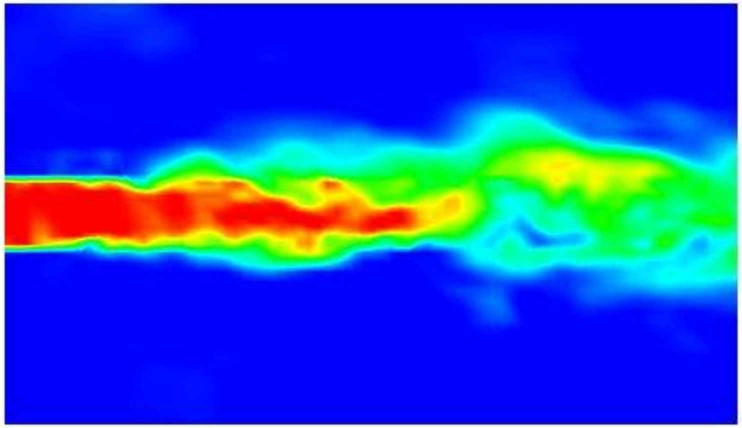
  (parallel computing, MPI library)

- handling new (inlet) and „dead" particles (gone out, separated)

→ Fluid velocity interpolation at particles:

- „quarter-blocks" - linear interpolation on regular *(r,θ)* meshes
- „O-grid" – interpolation using tabulated (pre-computed) fine grid

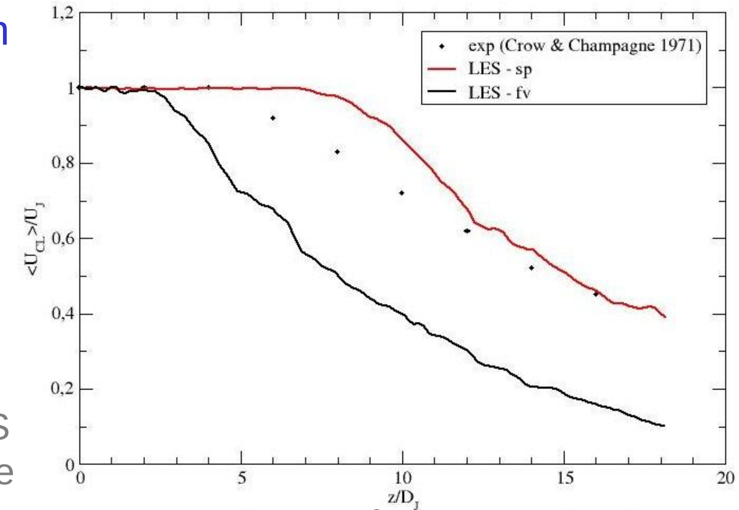
LES for fluid: streamwise (axial) velocity statistics



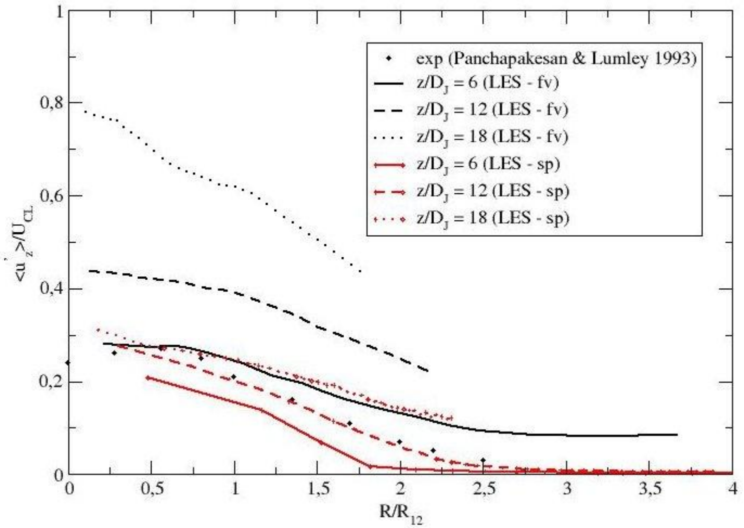
Axial velocity:
close-up of the near field (up to z=10D)

- potential core length
- effects of i.c. & b.c.

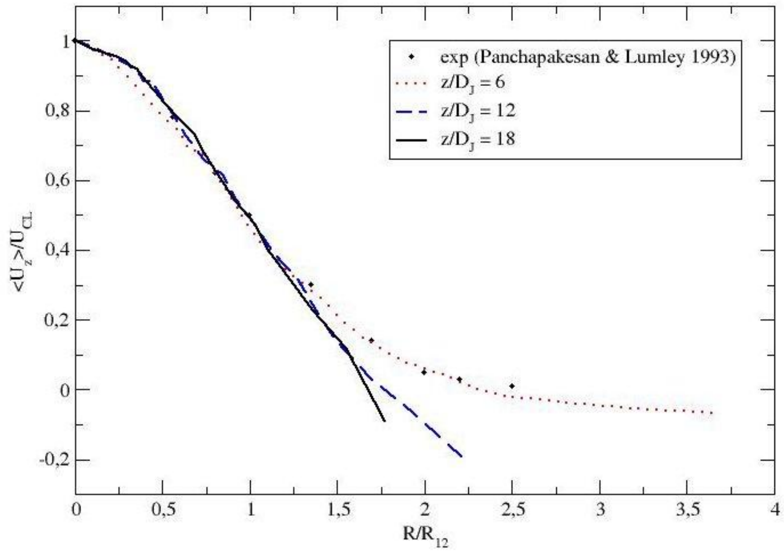
- fv: Finite-Volume LES
- sp: spectral LES code



Downstream decay of mean axial velocity at jet centerline



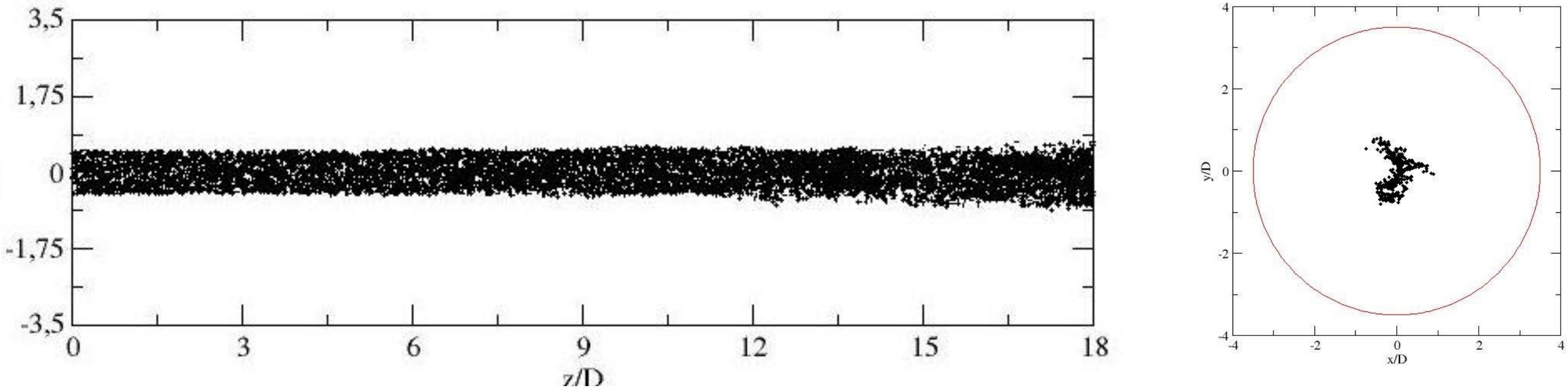
Mean and rms axial velocity profiles



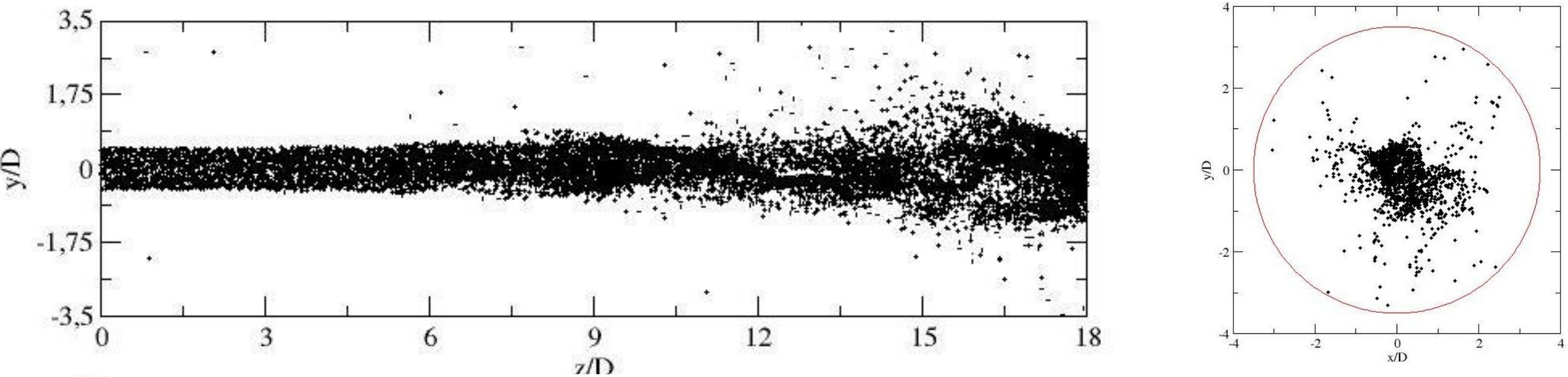
[Łuniewski & Pozorski, 2008]

Axisymmetric jet: particle number and patterns

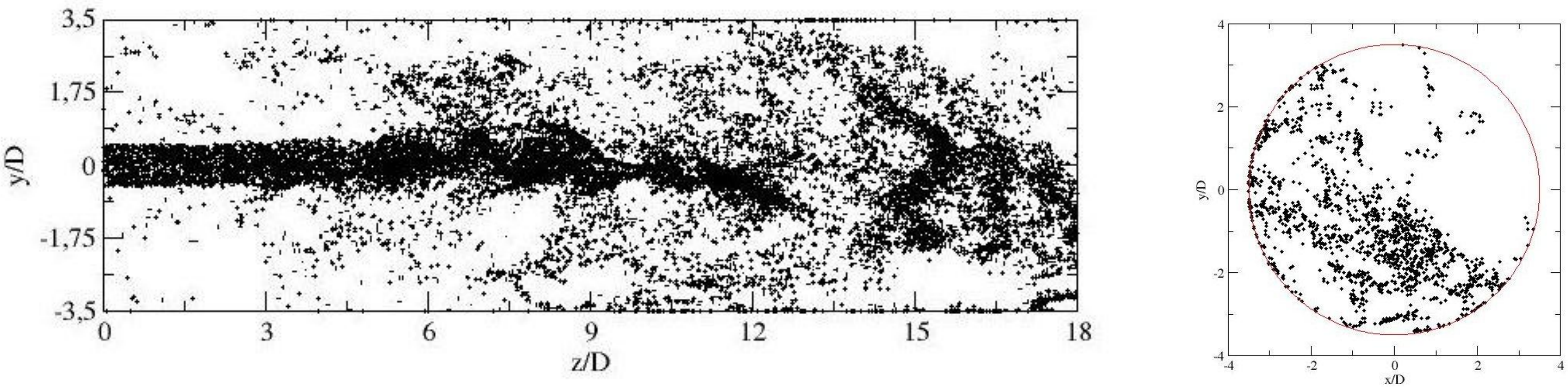
St=125



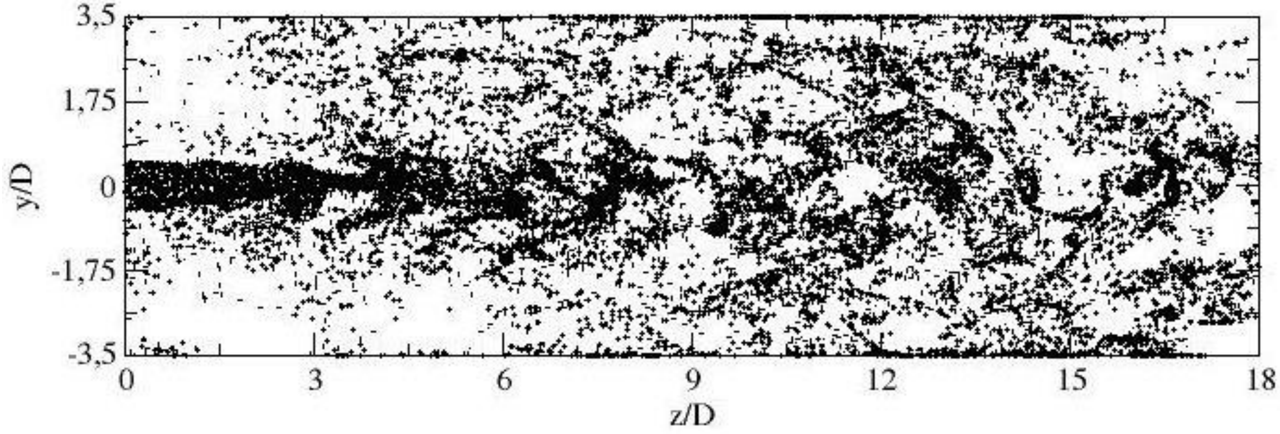
St=25



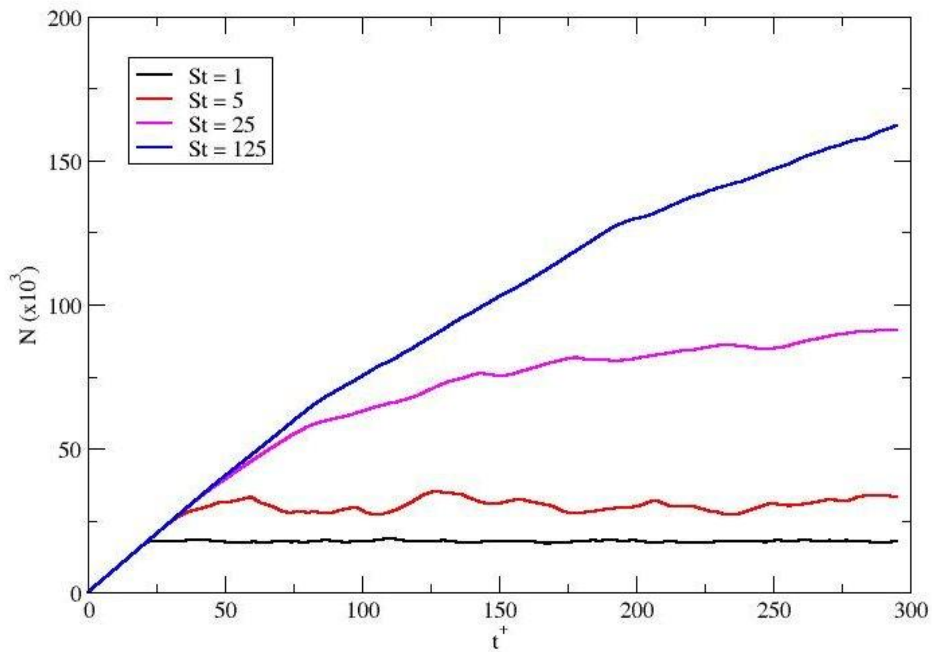
St=5

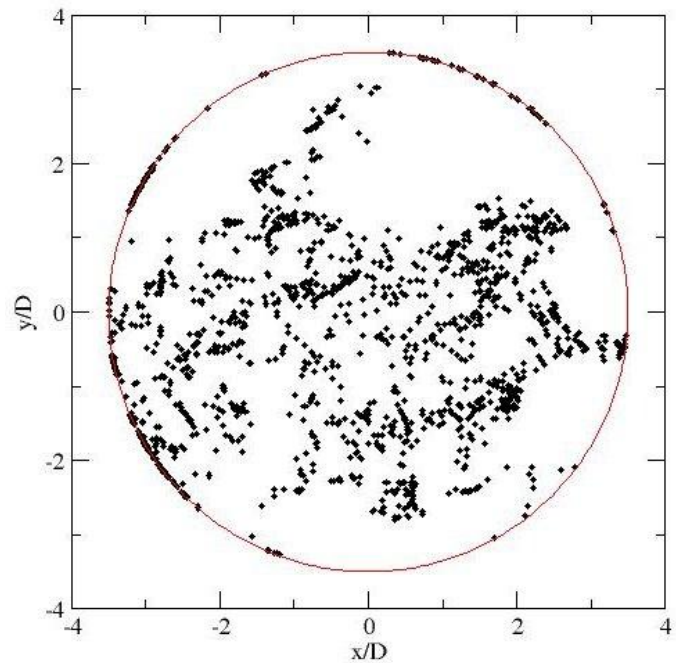


Axisymmetric jet: particle number and patterns



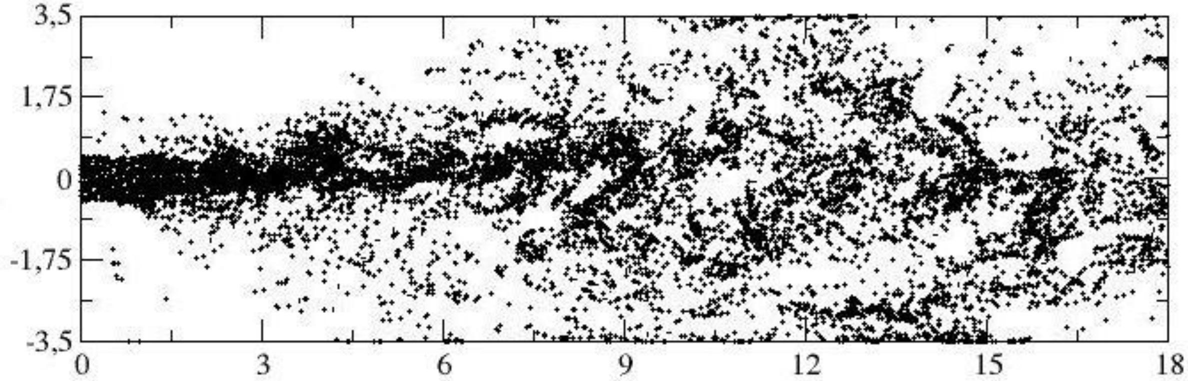
St=1



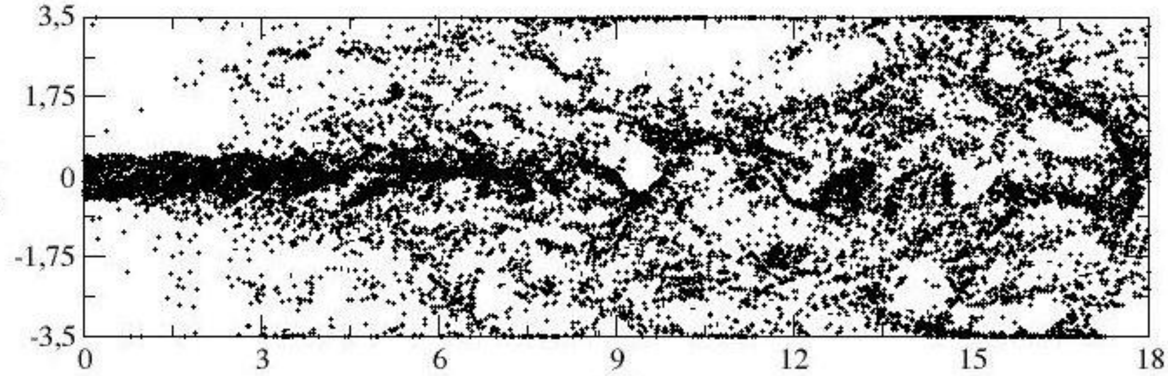


Axisymmetric jet: particles of St=1

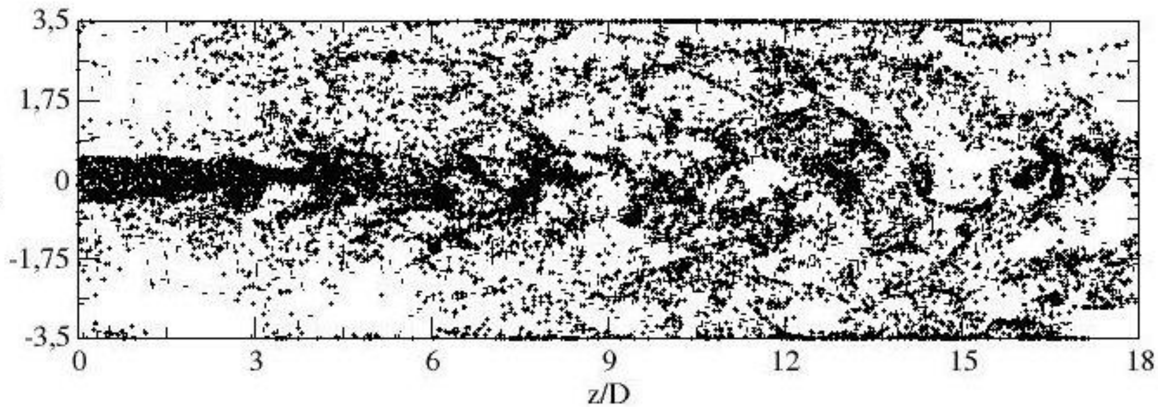
$t^+ = 100$



$t^+ = 200$



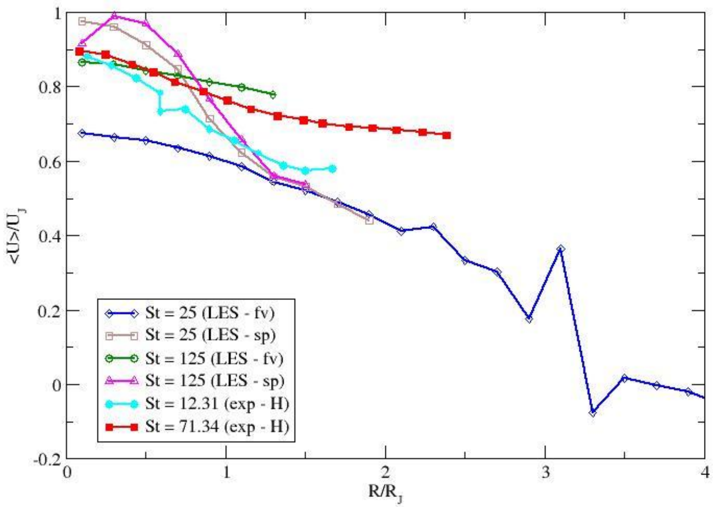
$t^+ = 300$

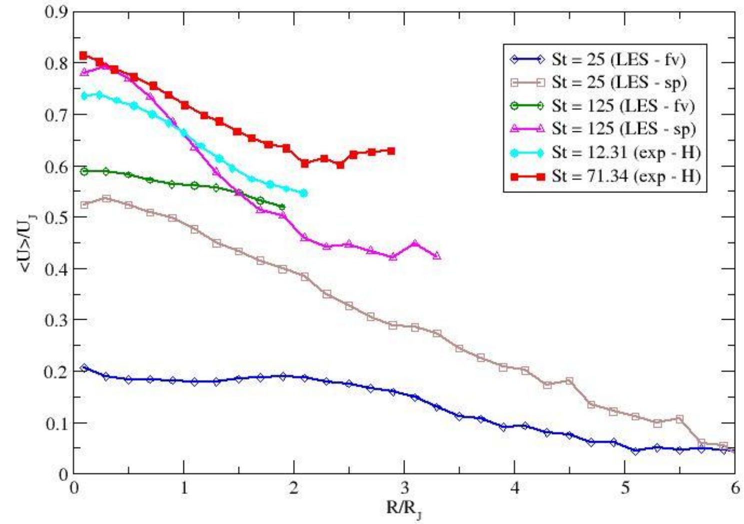


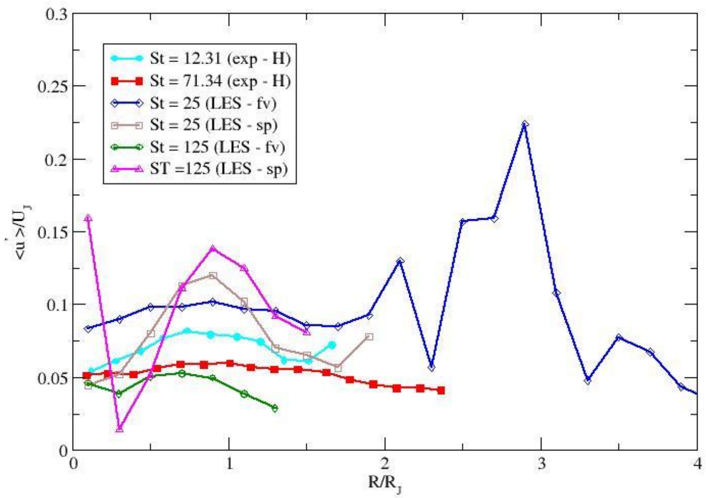
Axisymmetric jet: particle statistics (axial)

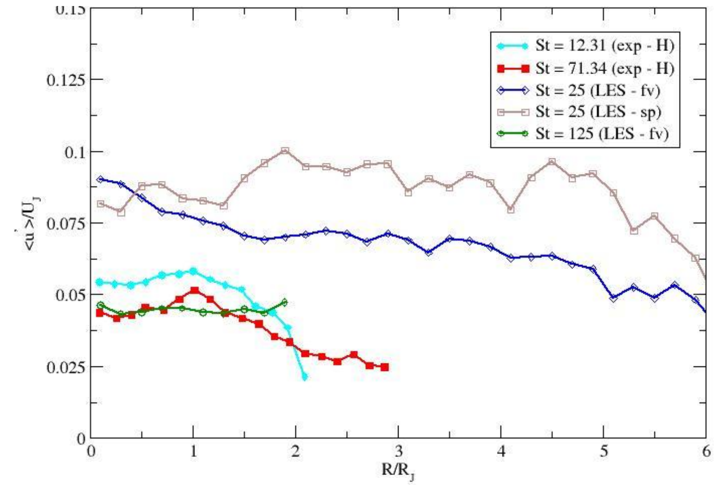
z/D = 10

z/D = 20

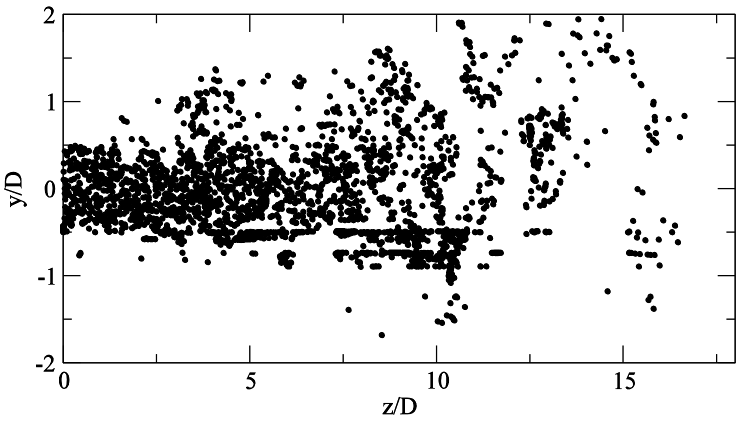








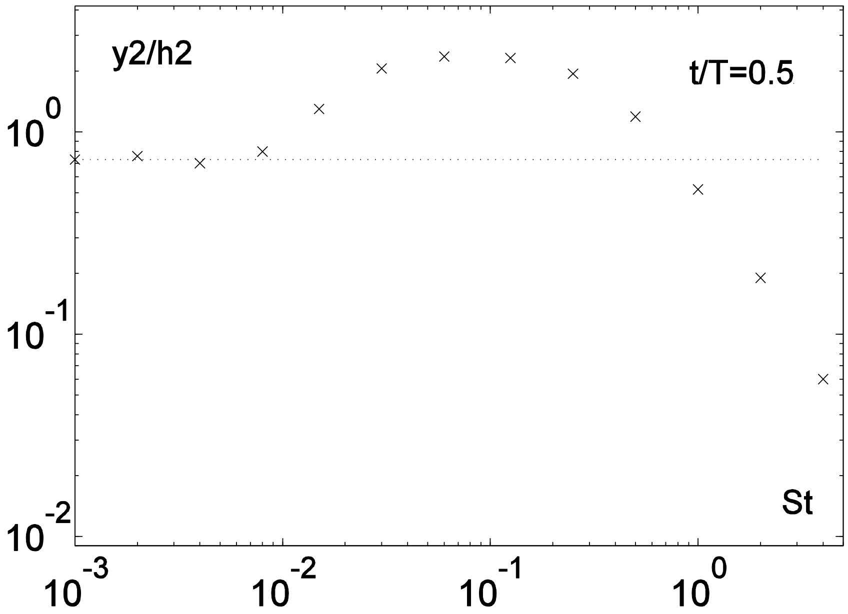
Comment on „anomalous” particle dispersion



Effects of fluid-particle velocity correlation:

* for intermediate inertia,
  cross-stream particle dispersion is faster
  than that of Lagrangian fluid particles

* relationship to turbophoresis
  and preferential concentration



***Wake flow:** mean-square dispersion*

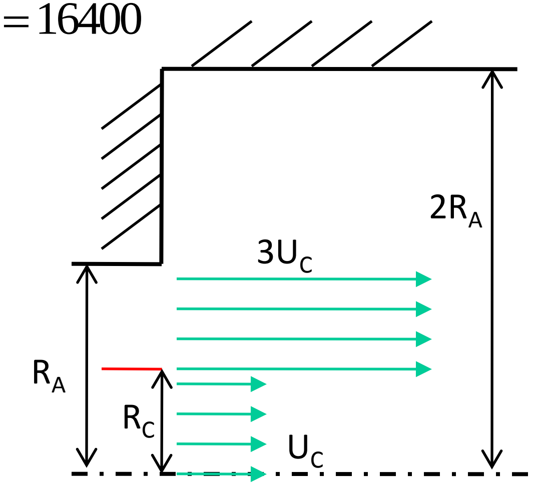
[Pozorski 1995]

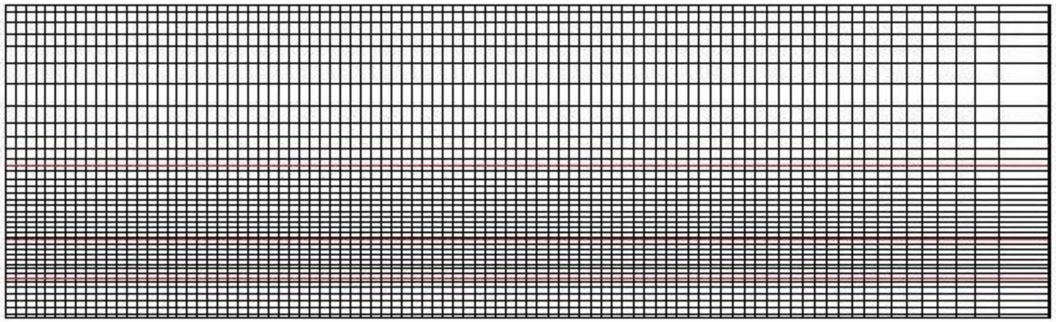
Coaxial jets

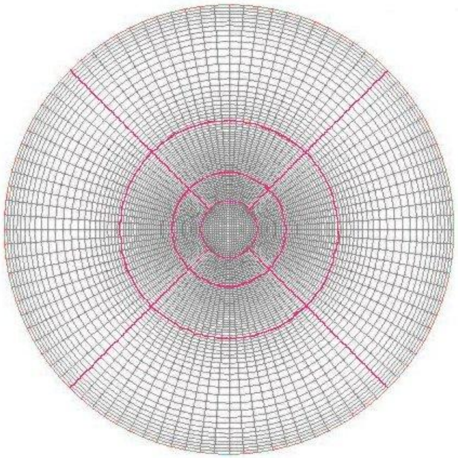
$$Re = u_z^C (R_{\max} - R_A)/\upsilon = 16400$$

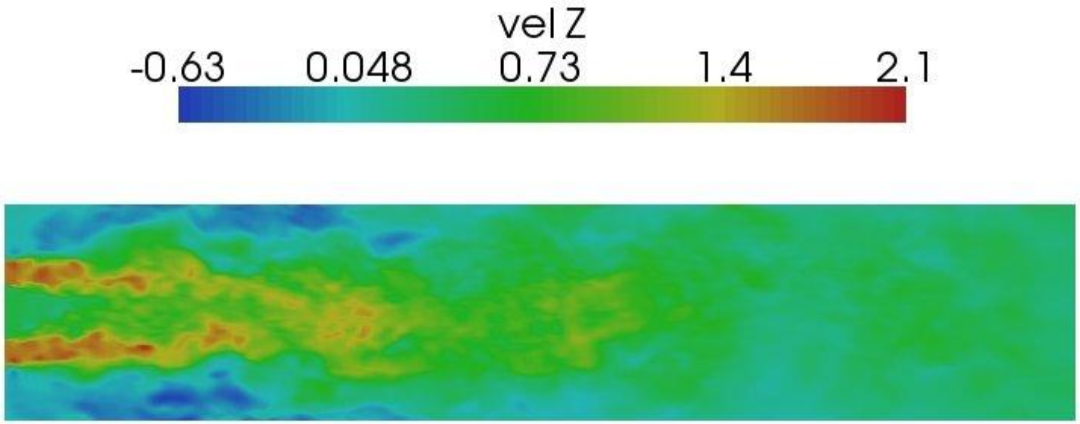
Inlet: $\lambda = \dfrac{U_A}{U_C} = 3 \qquad \lambda_A = \dfrac{\pi(R_A^2 - R_C^2)}{\pi R_C^2} = 2.72$

Outlet b.c.: $\dfrac{\partial U_Z}{\partial t} + U_C \dfrac{\partial U_Z}{\partial z} = 0$

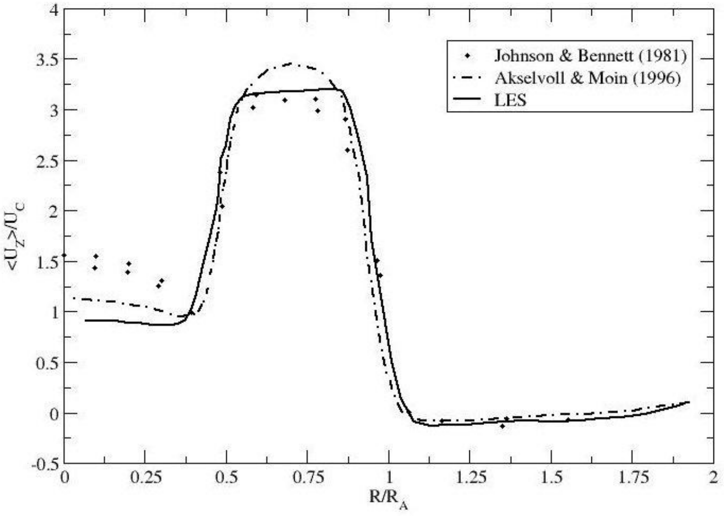




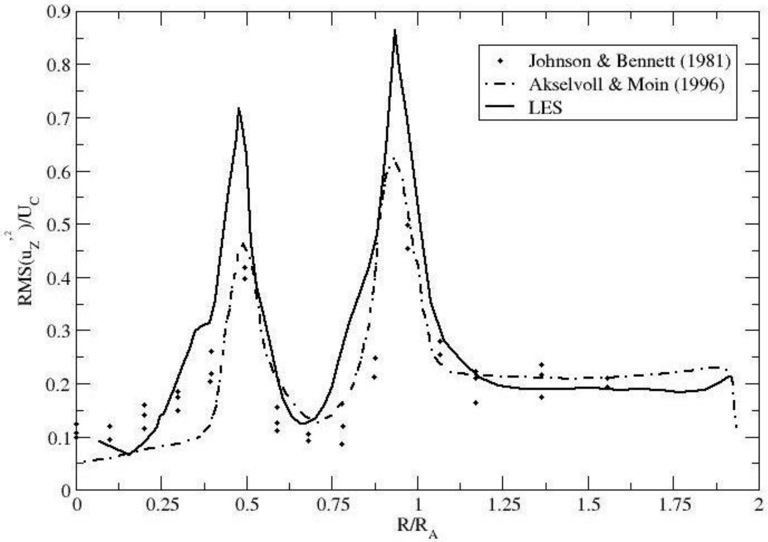


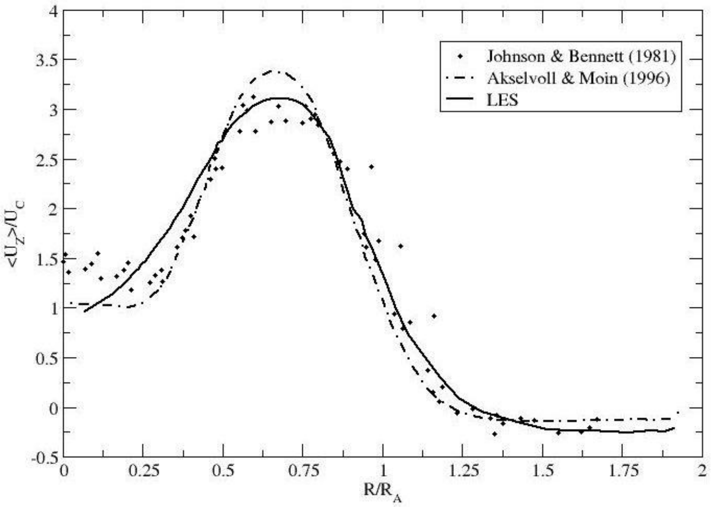


Coaxial jets: fluid statistics
mean and r.m.s stremwise velocity profiles

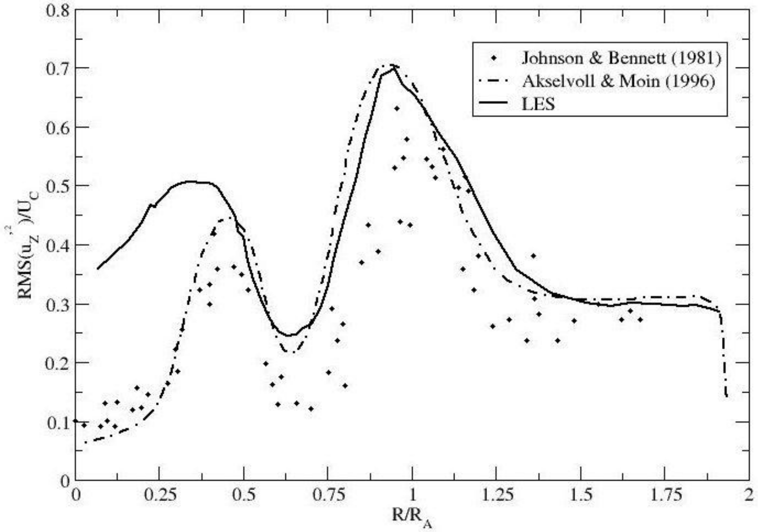


z/D =0.22



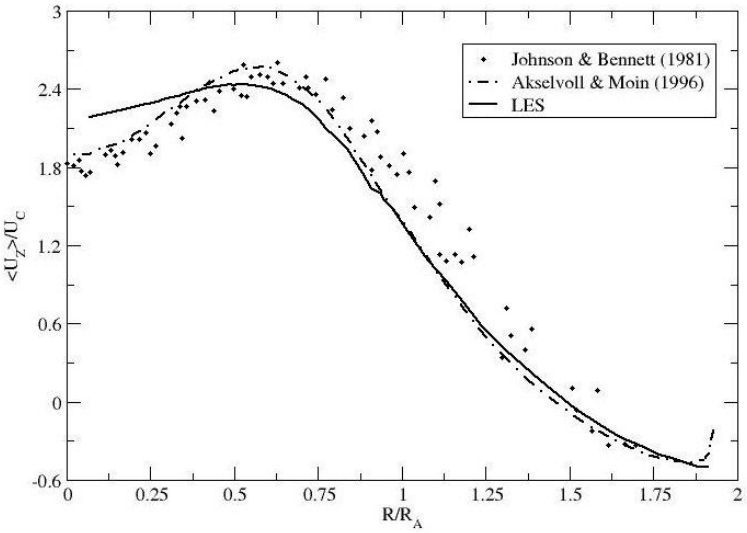


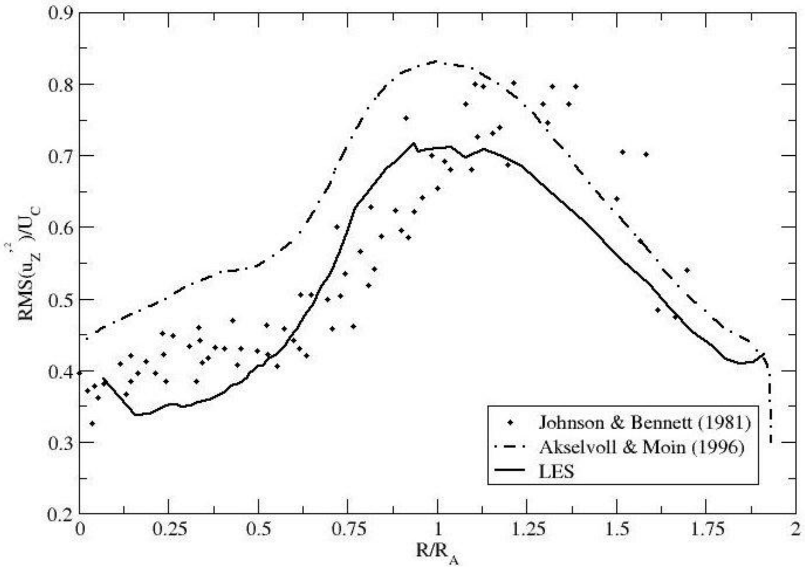
z/D =0.87



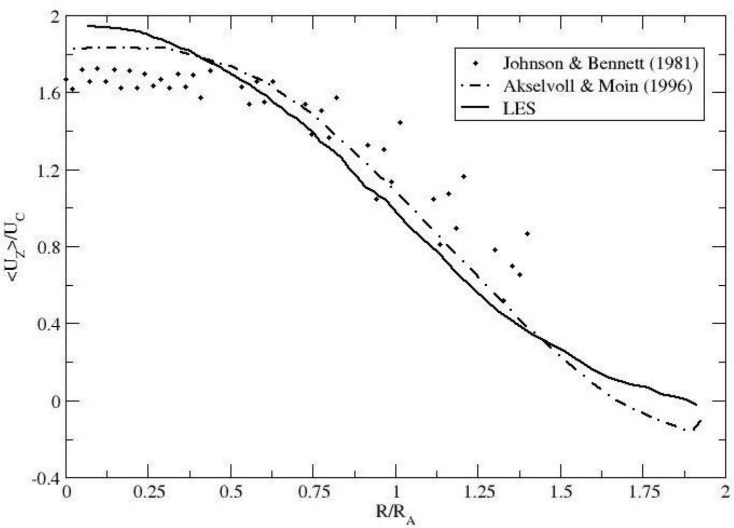
Coaxial jets: fluid statistics (cntd.)

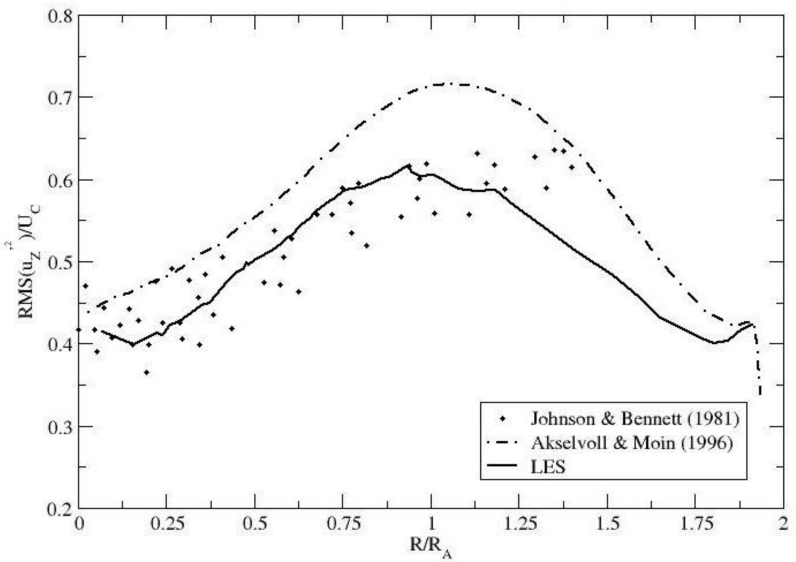
z/D =2.58



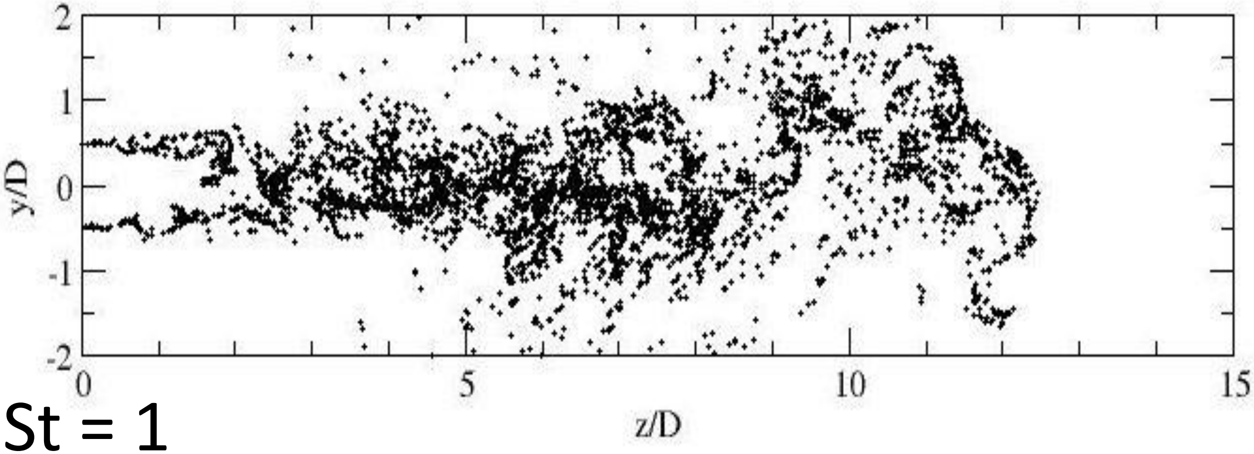


z/D =4.3

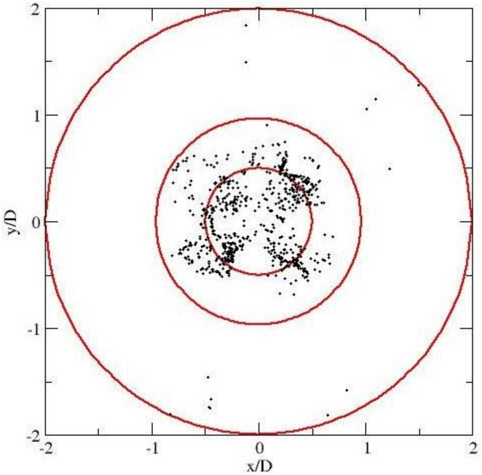




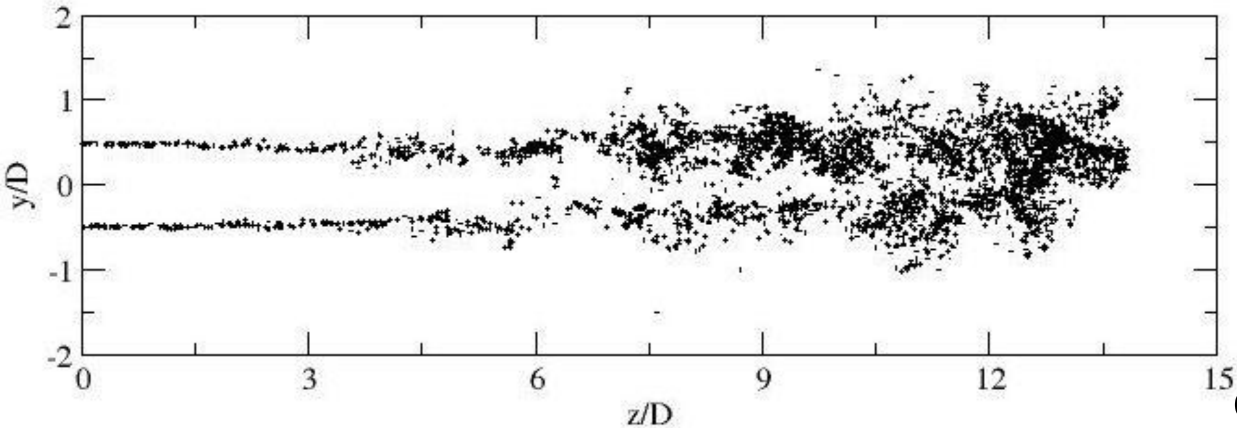
Coaxial jets: particle snapshots



St = 1



z/D = 3



St = 125

[Łuniewski & Pozorski, 2009]

quantitative comparison with exp. of (Fan,Zhao & Jin, 1996) is worked on

Summary of Part III (results)

→ Channel flows:

- statistics of particle velocity and temperature computed
- stochastic model for SGS particle dispersion included

→ Jet flows:

- parallel implementation developed
- effect of flow domain tested; single axisymmetric and coaxial jets computed
- statistics of fluid and some particle classes gathered

→ Next-term objectives:

- heated channel: compute more thermal statistics, compare with DNS

  [Jaszczur & Portela, 2007]
- coaxial jets: develop inflow b.c. to compare particle results with experiment

  [Hishida, 2000]
- LES of jet flow with particle heating and evaporation

  (towards combustion)

Conclusion: perspectives for further work

→ Modelling of flow-particle interactions:

- **mass and energy coupling** (F←→P: evaporation, condensation, combustion)

- **momentum coupling** (F→P: preferential concentration, P→F: SGS stress)

- **structural changes:** complex→ disperse (liquid jet atomisation)

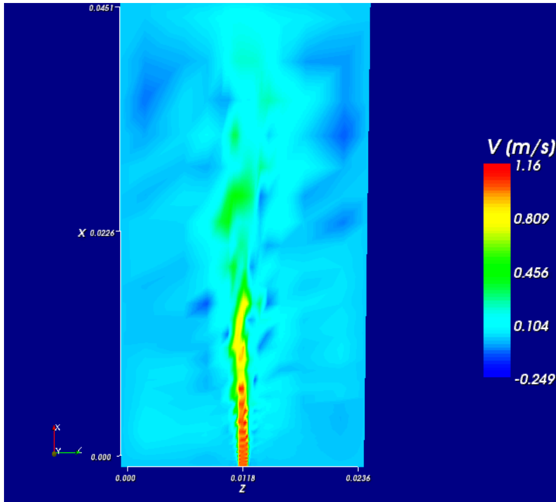
→ Sub-filter models, theoretical developments:

- **subgrid-scale particle dispersion:** stochastic and structural models

- **Filtered Density Function** (FDF) formalism for polydispersed flows

→ Applications :

- **coaxial particle/droplet – laden jets** with swirl, burners



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