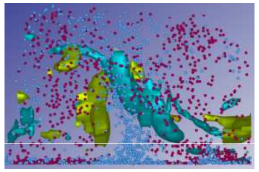


Doctoral Course in:

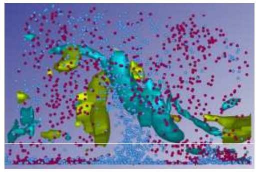
Modelling Turbulent Dispersed Flows

UNIVERSITAS STUDIORUM UTINENSIS

Lesson Three:

Particles, Vortices, and Turbulence

Lausanne, 21 May 2008

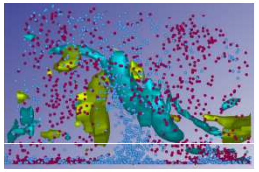


A complicated scientific application…

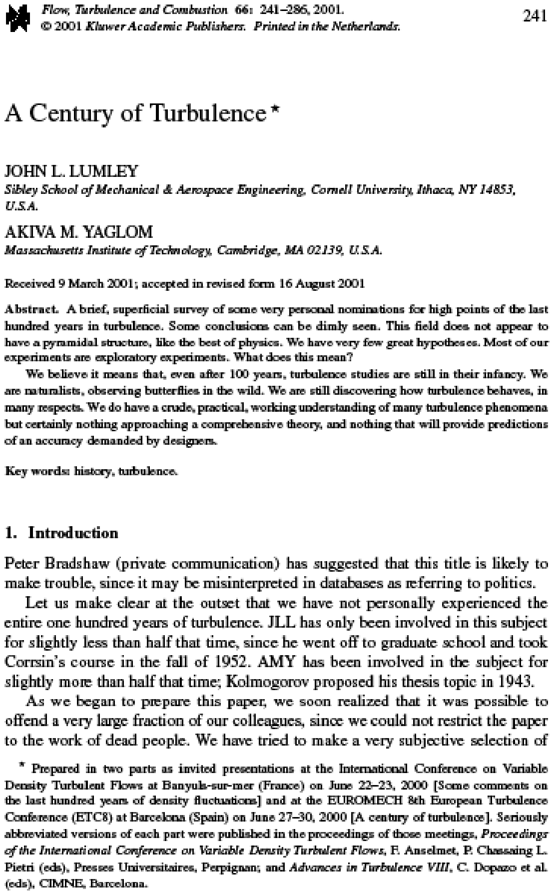
Our motivation is turbulent dispersed and reactive flow modelling

UNIVERSITAS STUDIORUM UTINENSIS

1. **Wednesday May 7: 14 pm to 17 pm**
   - ☑ **Introductory seminar. Fundamentals on Stokes flow around a sphere.**
2. **Wednesday May 14: 14 pm to 17 pm**
   - ☑ **Forces acting on a sphere. Steady and transient forces**
   - ☑ **Heat and Mass transfer from a sphere.**
   - ☑ **Introduction to DNS of Turbulent Flow.**
3. **Wednesday May 21: 14 pm to 17 pm**
   - ☑ **Particles Interaction with Vortices;**
   - ☑ **Characterization of a Vortex;**
   - ☑ **Vortex Dynamics in Boundary Layers**
   - ☑ **Particle dispersion in synthetic turbulence. Project description**
4. **Wednesday May 28: 14 pm to 17 pm**
   Special topic on PDF approaches: Dr Abdel Dehbi, PSI.
5. **Wednesday June 4: 14 pm to 17 pm**
   NOT COVERED (JRT Course).
6. **Wednesday June 18: 14 pm to 17 pm**
   Particle Turbulence Interactions.
   Are particles a compressible flow? Indicators for particles segregation
   Dynamics of particles in Boundary Layers
7. **Wednesday June 11: 14 pm to 17 pm**
   Particle dispersion in synthetic turbulence. Project Advancement/Discussion
8. **Wednesday June: 25:14 pm to 17 pm**
   Project Discussion.
9. **Wednesday July: 2: 14 pm to 17 pm**
   To be confirmed. Final Remarks



Starting from Turbulence…where we left



Flow, Turbulence and Combustion 66: 241–286, 2001. 241
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A Century of Turbulence *

JOHN L. LUMLEY
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AKIVA M. YAGLOM
Massachusetts Institute of Technology, Cambridge, MA 02139, U.S.A.

Received 9 March 2001; accepted in revised form 16 August 2001

Abstract. A brief, superficial survey of some very personal nominations for high points of the last hundred years in turbulence. Some conclusions can be dimly seen. This field does not appear to have a pyramidal structure, like the best of physics. We have very few great hypotheses. Most of our experiments are exploratory experiments. What does this mean?

We believe it means that, even after 100 years, turbulence studies are still in their infancy. We are naturalists, observing butterflies in the wild. We are still discovering how turbulence behaves, in many respects. We do have a crude, practical, working understanding of many turbulence phenomena but certainly nothing approaching a comprehensive theory, and nothing that will provide predictions of an accuracy demanded by designers.

Key words: history, turbulence.

1. Introduction

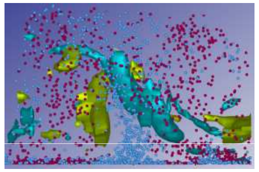
Peter Bradshaw (private communication) has suggested that this title is likely to make trouble, since it may be misinterpreted in databases as referring to politics.

Let us make clear at the outset that we have not personally experienced the entire one hundred years of turbulence. JLL has only been involved in this subject for slightly less than half that time, since he went off to graduate school and took Corrsin's course in the fall of 1952. AMY has been involved in the subject for slightly more than half that time; Kolmogorov proposed his thesis topic in 1943.

As we began to prepare this paper, we soon realized that it was possible to offend a very large fraction of our colleagues, since we could not restrict the paper to the work of dead people. We have tried to make a very subjective selection of

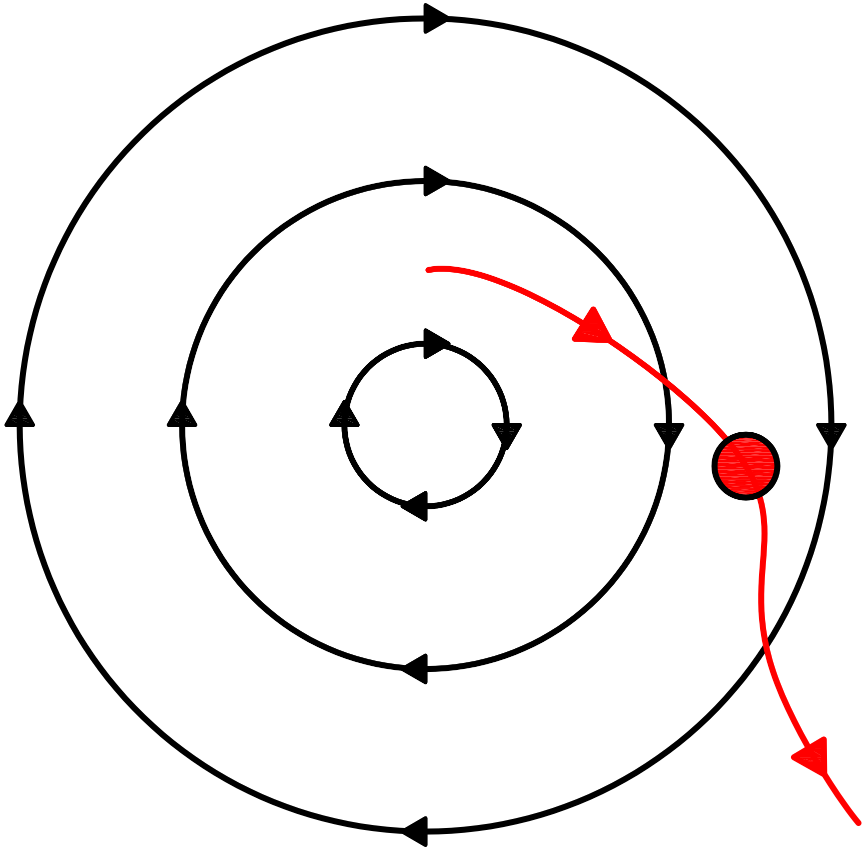
---

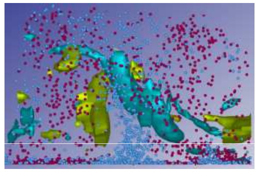
* Prepared in two parts as invited presentations at the International Conference on Variable Density Turbulent Flows at Banyuls-sur-mer (France) on June 22–23, 2000 [Some comments on the last hundred years of density fluctuations] and at the EUROMECH 8th European Turbulence Conference (ETC8) at Barcelona (Spain) on June 27–30, 2000 [A century of turbulence]. Seriously abbreviated versions of each part were published in the proceedings of those meetings, *Proceedings of the International Conference on Variable Density Turbulent Flows*, F. Anselmet, P. Chassaing L. Pietri (eds), Presses Universitaires, Perpignan; and *Advances in Turbulence VIII*, C. Dopazo et al. (eds), CIMNE, Barcelona.



A particle and a Vortex…

- *Basic Concept.*





.. But Then, what is turbulence made up of?…

- *Many vortices…more, coherent structures*

“*Fluid motions [in turbulent boundary layers] are intermittent and have a strongly organized and coherent nature represented by the large scale motions. These motions, even though not exactly repeatable and only quasi-deterministic, control the transport of the dispersed species in such a way that the overall distribution will resemble not at all those given by methods in which these motions are ignored.*”
Godfrey Mungal

Coherent structures—reality and myth[a)]

A. K. M. F. Hussain
University of Houston, Houston, Texas 77004

(Received 18 August 1982; accepted 10 May 1983)

The nature and significance of large-scale coherent structures in turbulent shear flows are addressed. A definition for the coherent structure is proposed and its implications discussed. The characteristic coherent structure properties are identified and the analytical and experimental constraints in the eduction of coherent structures are examined. Following a few comments on coherent motions in wall layers, the accumulated knowledge from a number of recent and ongoing coherent structure investigations in excited and unexcited free shear flows in the author's laboratory is reviewed. Also briefly addressed are effects of initial conditions, the role of coherent structures in jet noise production and broadband noise amplification, the feedback effect of coherent structures, the use of the Taylor hypothesis in coherent structure description, negative production, turbulence suppression via excitation, validity of the Reynolds number similarity hypothesis, etc. From the detailed quantitative results, a picture of the state of the art in coherent structure studies emerges. While coherent structures are highly interesting characteristic features of (perhaps all) turbulent shear flows, it is argued that their dynamical significance has been overemphasized. These are predominant only in their early stages of formation following instability, or in resonant situations and excited flows, or in regions adjacent to a wall of a turbulent boundary layer. The coherent Reynolds stress, vorticity, and production are comparable to (and not an order of magnitude larger than) the time-average Reynolds stress, vorticity, and production, respectively, in fully developed states of turbulent shear flows, where incoherent turbulence is also important and cannot be ignored. The concept and importance of coherent structures are here to stay; understanding and modeling of turbulent shear flows will be incomplete without them; but they are not all that matter in turbulent shear flows.

I. INTRODUCTION

The significance of turbulence in most natural and technological flows as well as its inherent complexity cannot be overemphasized. Despite dedicated efforts of many able scientists over the decades, turbulence continues to persist as one of the least understood arenas of the natural sciences. New ideas and interpretations are highly desirable, but also must be carefully examined. Such a scrutiny risks the possibility of discouraging progress, but has the potential of saving unfruitful digressions and wasted efforts. While the "rise and fall of ideas" is not new to turbulence, there is continuing, albeit slow and sporadic, progress in our understanding of turbulent shear flows.[1,2]

Turbulence research has experienced two revolutions in the past decade. The first, rather profound, is the discovery of large-scale coherent structures. The second is the integration of the digital computer as an active (even interactive) component of the turbulence research arsenal.

A. Computer as a research tool

Today computer-controlled experimental research in turbulence is more the rule than the exception. Apart from the obvious advantage of being able to rapidly process high-frequency signals and large volumes of data, computers have facilitated automated and accurate sensor calibration and traverse, experiment control, and data acquisition; measurement of phase-average properties, precise use of event-dependent criteria like conditional sampling to capture random events and their spatial features; simultaneous recording of multivariable data and use of multiple criteria for signal enhancement, pattern recognition, structure eduction, and classification; etc. The computer has not only improved signal processing and data accuracy but also has reduced operator interference. [In free shear flow experiments (for example, jets), data acquisition under remote computer control has eliminated errors introduced by the physical presence of the operator.] In many sophisticated experiments, the computer has enabled the researcher to relegate to it reliable executions of tedious or complex chores. The computer thus has encouraged the experimentalist to explore subtle but important features of turbulence which would otherwise have been prohibitive or even impossible.

In parallel with its on-line usage as a versatile laboratory instrument, the computer has also been used extensively in numerical solutions of the partial differential equations governing turbulent flows. The solution of the time-dependent Navier–Stokes equation in three dimensions is thus an aspect of the second revolution. The computation of the time-dependent solutions and their graphic presentations have advanced to such a level of sophistication and perfection that the computer generated "flow-visualization" movies amazingly mimic laboratory flow-visualization movies and even provoke many researchers to fantasize that laboratory experiments would no longer be necessary. In many ways, the computed realizations appear attractive: the computed results can be "visualized" in any arbitrary plane with-

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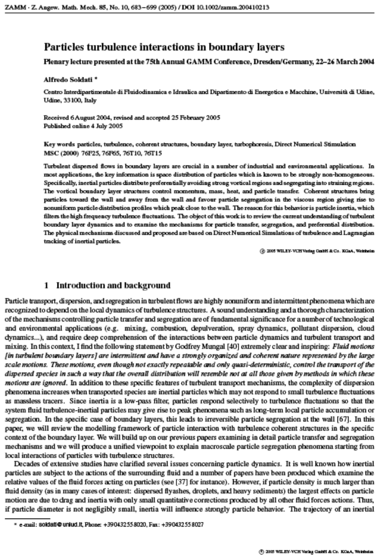
[a)] This paper was presented 22 November 1982 at a special session of the annual meeting of the Division of Fluid Dynamics of the American Physical Society in Monterey, California honoring the memory of L. S. G. Kovasznay.

2816 Phys. Fluids 26 (10), October 1983 0031-9171/83/102816-35$01.90 © 1983 American Institute of Physics 2816



ZAMM · Z. Angew. Math. Mech. 85, No. 10, 683 – 699 (2005) / DOI 10.1002/zamm.200410213

Particles turbulence interactions in boundary layers

Plenary lecture presented at the 75th Annual GAMM Conference, Dresden/Germany, 22–26 March 2004

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Centro Interdipartimentale di Fluidodinamica e Idraulica and Dipartimento di Energetica e Macchine, Università di Udine, Udine, 33100, Italy

Received 6 August 2004, revised and accepted 25 February 2005

Key words particles, turbulence, coherent structures, boundary layer, turbophoresis, Direct Numerical Stimulation
MSC (2000) 76F25, 76F65, 76T10, 76T15

Turbulent dispersed flows in boundary layers are crucial in a number of industrial and environmental applications. In most applications, the key information is space distribution of particles which is known to be strongly non-homogeneous. Specifically, inertial particles distribute preferentially avoiding strong vortical regions and segregating into straining regions. The vortical boundary layer structures control momentum, mass, heat, and particle transfer. Coherent structures bring particles toward the wall and away from the wall and favour particle segregation in the viscous region giving rise to nonuniform particle distribution profiles which peak close to the wall. The reason for this behavior is particle inertia, which filters the high frequency turbulence fluctuations. The object of this work is to review the current understanding of turbulent boundary layer dynamics and to examine the mechanisms for particle transfer, segregation, and preferential distribution. The physical mechanisms discussed and proposed are based on Direct Numerical Simulations of turbulence and Lagrangian tracking of inertial particles.

1 Introduction and background

Particle transport, dispersion, and segregation in turbulent flows are highly nonuniform and intermittent phenomena which are recognized to depend on the local dynamics of turbulence structures. A sound understanding and a thorough characterization of the mechanisms controlling particle transfer and segregation are of fundamental significance for a number of technological and environmental applications (e.g. mixing, combustion, depulveration, spray dynamics, pollutant dispersion, cloud dynamics...), and require deep comprehension of the interactions between particle dynamics and turbulent transport and mixing. In this context, I find the following statement by Godfrey Mungal [40] extremely clear and inspiring: *Fluid motions [in turbulent boundary layers] are intermittent and have a strongly organized and coherent nature represented by the large scale motions. These motions, even though not exactly repeatable and only quasi-deterministic, control the transport of the dispersed species in such a way that the overall distribution will resemble not at all those given by methods in which these motions are ignored*. In addition to these specific features of turbulent transport mechanisms, the complexity of dispersion phenomena increases when transported species are inertial particles which may not respond to small turbulence fluctuations as massless tracers. Since inertia is a low-pass filter, particles respond selectively to turbulence fluctuations so that the system fluid turbulence-inertial particles may give rise to peak phenomena such as long-term local particle accumulation or segregation. In the specific case of boundary layers, this leads to irreversible particle segregation at the wall [67]. In this paper, we will review the modelling framework of particle interaction with turbulence coherent structures in the specific context of the boundary layer. We will build up on our previous papers examining in detail particle transfer and segregation mechanisms and we will produce a unified viewpoint to explain macroscale particle segregation phenomena starting from local interactions of particles with turbulence structures.

Decades of extensive studies have clarified several issues concerning particle dynamics. It is well known how inertial particles are subject to the actions of the surrounding fluid and a number of papers have been produced which examine the relative values of the fluid forces acting on particles (see [37] for instance). However, if particle density is much larger than fluid density (as in many cases of interest: dispersed flyashes, droplets, and heavy sediments) the largest effects on particle motion are due to drag and inertia with only small quantitative corrections produced by all other fluid forces actions. Thus, if particle diameter is not negligibly small, inertia will influence strongly particle behavior. The trajectory of an inertial

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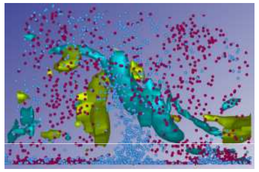
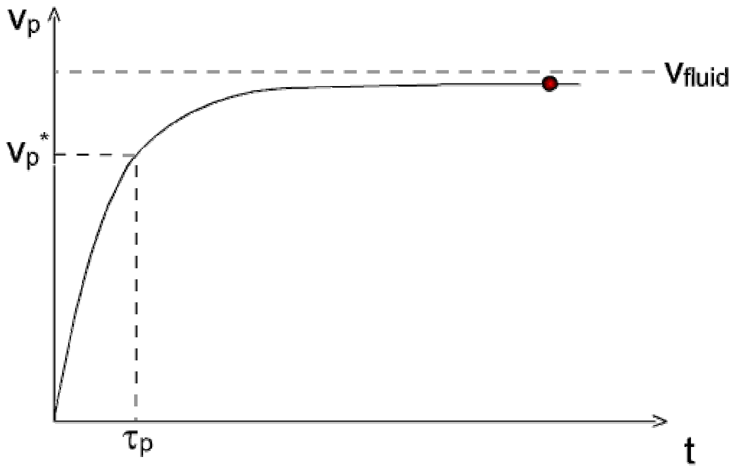
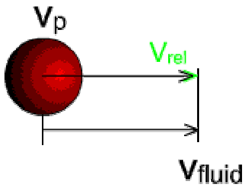


The system and the perturbation

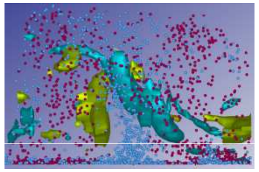
1. Stationary Fluid

Consider for the moment the simplest particle-force model:
we have a particle with initial conditions and it is forced by a fluid motion





With time, the
Particle tries to adjust to
The flow conditions with
Time proportional to its
time constant



The system and the perturbation

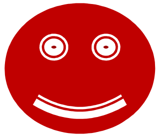
2. Rotating Fluid

If the fluid is rotating (i.e. a vortex) then centrifugal effects arise:

A small particle

taup-small1.avi

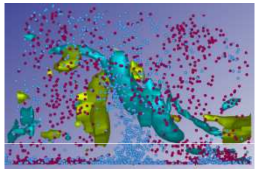
A large particle



taup-large1.avi

A medium-size particle

taup-med1.avi



Just a reminder on the multiscale aspect of Turbulent flows

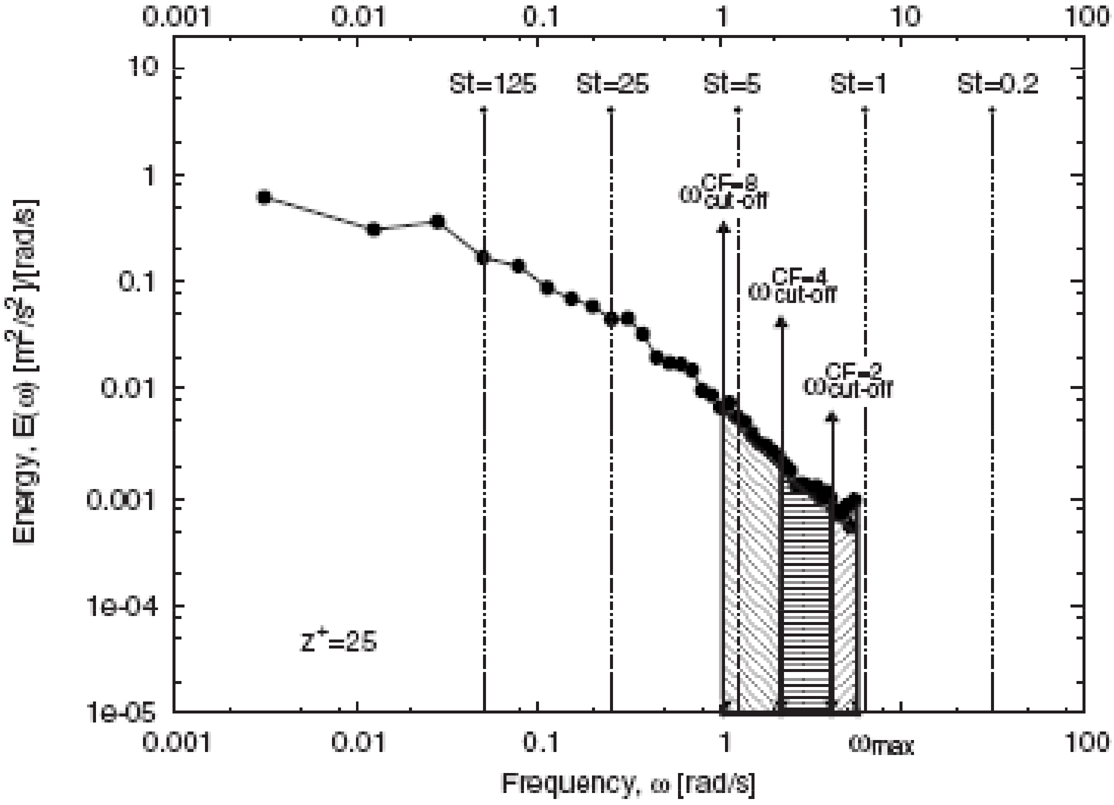


FIG. 2. One-dimensional (streamwise) frequency spectrum for turbulent channel flow computed at $z^+=25$. The different cutoff frequencies, used to perform the *a priori* tests, are indicated as $\omega_{\text{cutoff}}^{\text{CF}=2}$, $\omega_{\text{cutoff}}^{\text{CF}=4}$, and $\omega_{\text{cutoff}}^{\text{CF}=8}$, respectively. Areas filled with patterns below the energy profile represent the relative amount of energy removed by each cutoff.

PHYSICS OF FLUIDS **20**, 040603 (2008)

Some issues concerning large-eddy simulation of inertial particle dispersion in turbulent bounded flows

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[2] *Department of Aerospace Engineering, University of Pisa, 56100 Pisa, Italy*

(Received 30 September 2007; accepted 25 March 2008; published online 30 April 2008)

The problem of accurate Eulerian–Lagrangian modeling of inertial particle dispersion in large-eddy simulation (LES) of turbulent wall-bounded flows is addressed. We run direct numerical simulation (DNS) of turbulent channel flow at shear Reynolds number $Re_\tau=150$ and corresponding *a priori* and *a posteriori* LES on two coarser grids. For each flow field, we tracked swarms of particles with different inertia to examine the behavior of particle statistics, specifically focusing on particle preferential segregation and accumulation at the wall. Our object is to discuss the necessity of a closure model for the particle equations when using LES and we verify if the influence of the subgrid turbulence filtered by LES is an important effect on particle motion according to particle size. The results show that well-resolved LES gives particle velocity statistics in satisfactory agreement with DNS. However, independent of the grid, quantitatively inaccurate predictions are obtained for local particle preferential segregation, particularly in the near-wall region. Inaccuracies are observed for the entire range of particle size considered in this study, even when the particle response time is much larger than the flow time scales not resolved in LES. The satisfactory behavior of LES in reproducing particle velocity statistics is thus counterbalanced by the inaccurate representation of local segregation phenomena, indicating that closure models supplying the particle motion equation with an adequate rendering of the flow field might be needed. Finally, we remark that recovering the level of fluid and particle velocity fluctuations in the particle equations does not ensure a quantitative *replica* of the subgrid turbulence effects, thus implying that accurate subgrid closure models for particles may require information also proportional to the higher-order moments of the velocity fluctuations. © *2008 American Institute of Physics.*
[DOI: 10.1063/1.2911018]

I. INTRODUCTION

The dispersion of inertial particles in turbulent flows is characterized by macroscopic phenomena such as nonhomogeneous distribution, large-scale clustering, and preferential concentration due to the inertial bias between the denser particles and the lighter surrounding fluid.[1,2] In homogeneous isotropic turbulence,[1,3,4] clustering and preferential concentration may be crucial in determining collision frequency, breakage efficiency, agglomeration, and reaction rates. In turbulent boundary layers, besides controlling particle interaction rates, clustering and preferential concentration also influence settling, deposition and entrainment.[5]

Both direct numerical simulation[6] (DNS) and large-eddy simulation[7–9] (LES) together with Lagrangian particle tracking (LPT) have been used to investigate and quantify the behavior of particles near the wall, for instance, in channel flow[2,8,9] or in pipe flow.[6,7] DNS-based Eulerian–Lagrangian studies are used to investigate the physics of particle-turbulence interactions, whereas LES has yet to demonstrate its full capabilities in predicting correctly particle-turbulence statistics[10] and macroscopic segregation phenomena.[4,9] To elaborate, in LES-based Eulerian–Lagrangian simulations of particle dispersion, a *subgrid* error is introduced in the particle equation since only the filtered fluid velocity is available; this approximation adds to the *modeling* error which is intrinsic to the subgrid scale (SGS) modeling for the fluid phase.[10] Similar to what is done for the flow field, a way to model the effects of the SGS velocity fluctuations in the particle equations of motion could be identified for those situations in which subgrid and modeling errors affect the predicting capabilities of LES.[9]

Among previous LES applications to gas-solid turbulent flows,[7,11] the fluid SGS velocity fluctuations were neglected under the assumption that the particle response time was large compared to the smallest time scale resolved in the LES.[11] For well-resolved LES, this assumption holds to capture satisfactorily the statistics of particle velocity.[7,10,11] However, it was later demonstrated that LES without any SGS model for particles gives a certain degree of inaccuracy in the prediction of particle accumulation at the wall. We refer, in particular, to the results obtained by Kuerten and Vreman[10] and by Kuerten[9] for turbulent dispersion of heavy particles in channel flow. They have shown that, due to both subgrid and modeling errors, LES underestimates the tendency of particles to move toward the wall by the effect of turbulence (turbophoretic effect[12]). To circumvent this prob-

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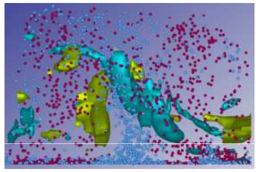
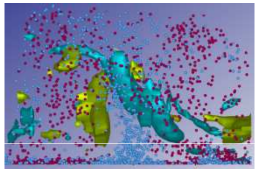
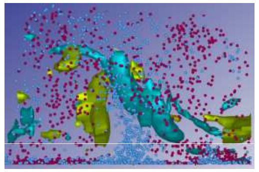


Vortices and vorticity…(visualization)

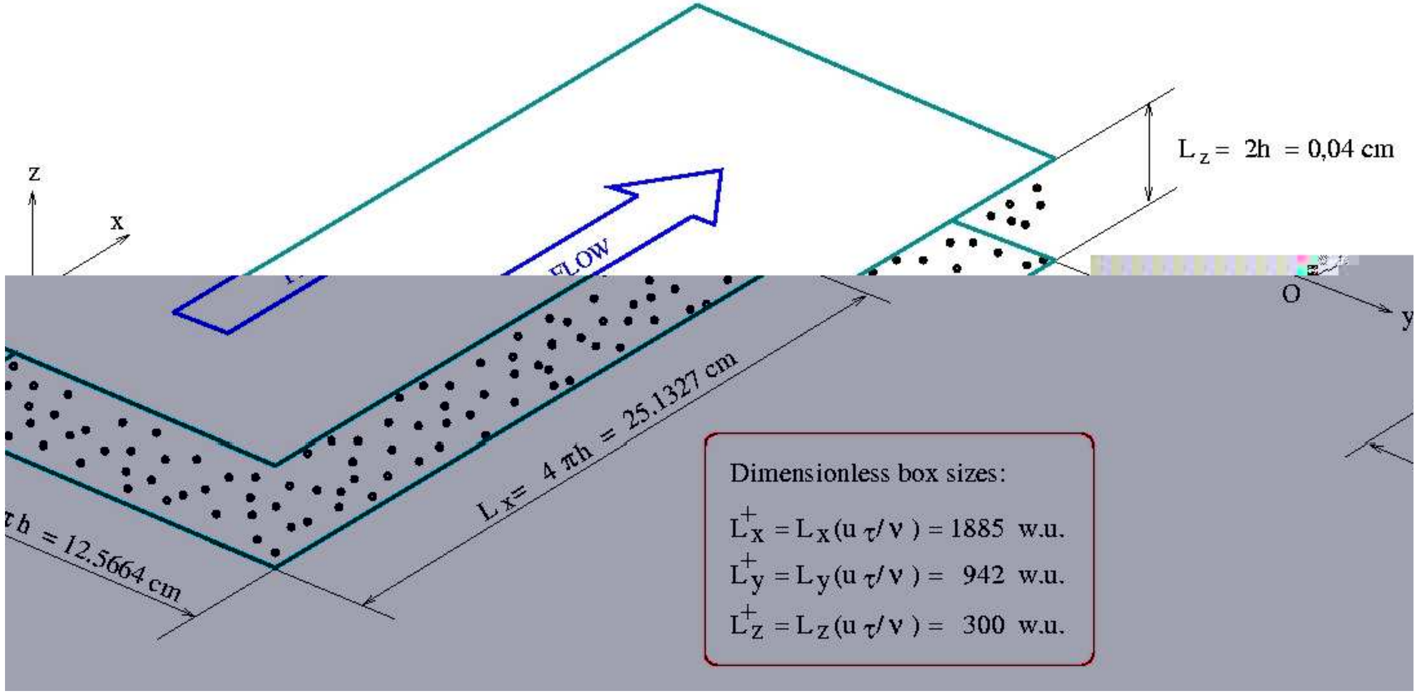


Vorticity

- **Examples of vorticity calculation: Blackboard**



Focus on Particle deposition at a wall



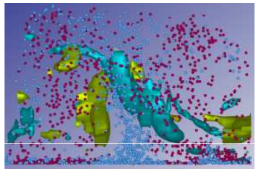
Dimensionless box sizes:

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

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

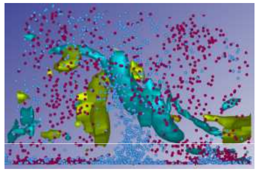
$L_z^+ = L_z(u_\tau/\nu) = 300$ w.u.

- **Supose we want to estimate particle deposition at a wall.**



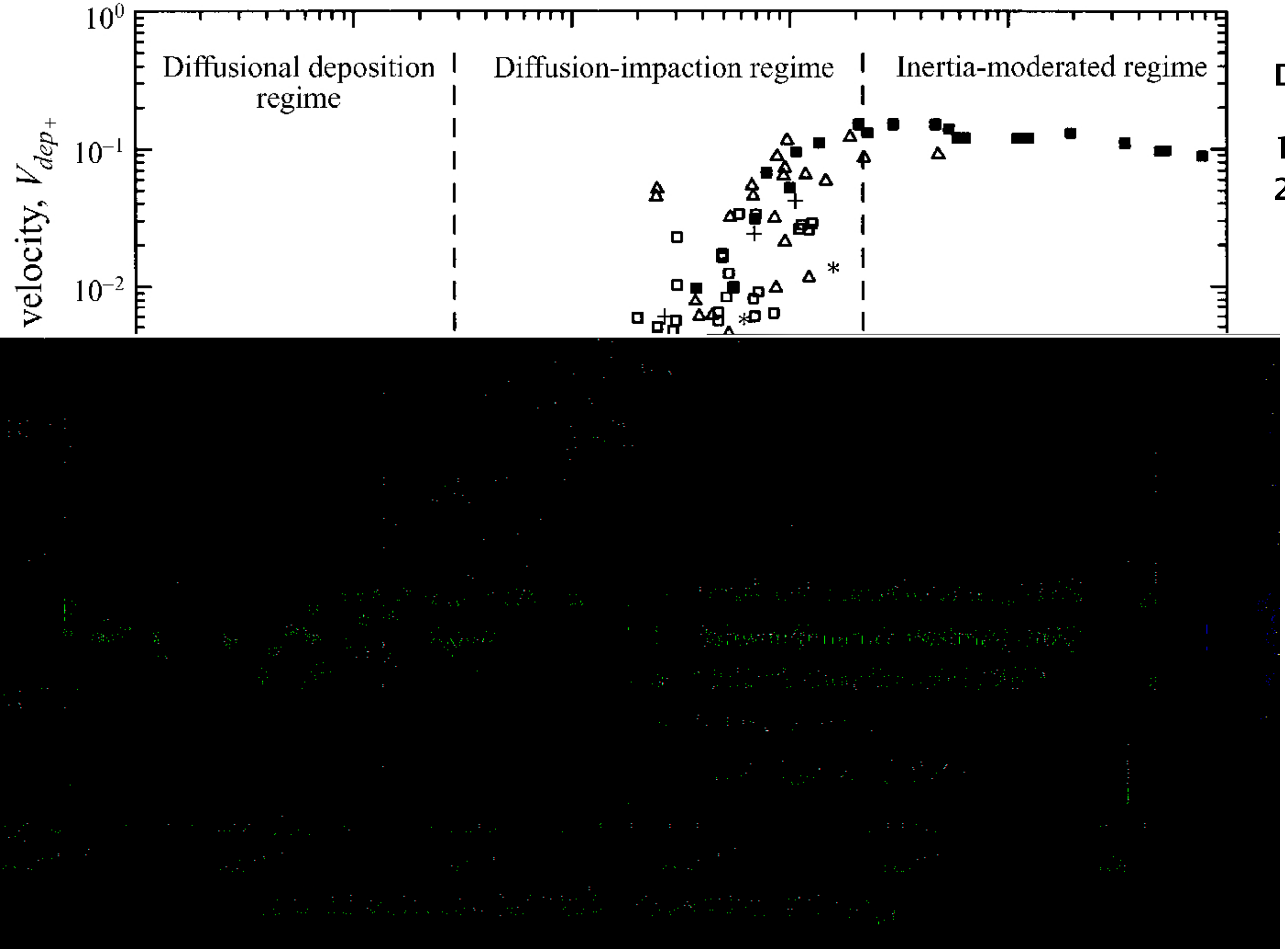
Turbulence Wall Scales

- **Blackboard calculations**



Focus on Particle deposition at a wall

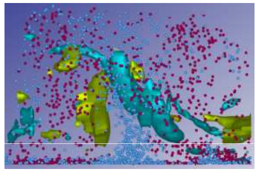
- **We can use existing databases and correlations:**



Define:

1.Wall deposition Velocity

2. Wall scaled τ_p



Turbulence Wall Scales

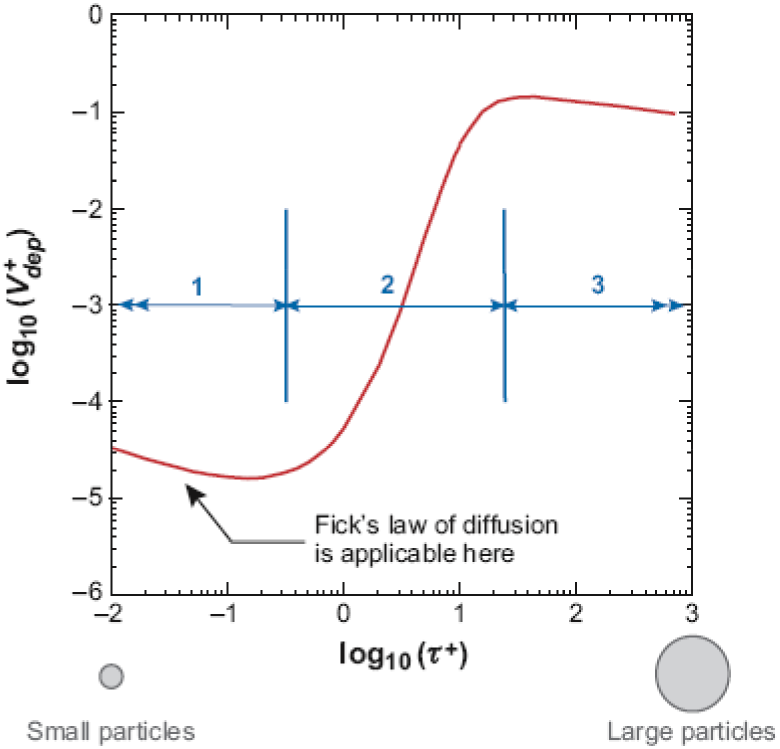
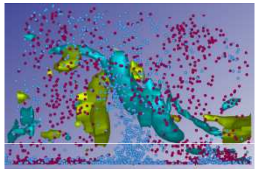


Figure 1

A typical variation in measured deposition rate with particle relaxation time in fully developed vertical pipe flow. Regime 1, turbulent diffusion; regime 2, turbulent diffusion-eddy impaction; regime 3, particle inertia moderated.



Turbulence Wall Scales

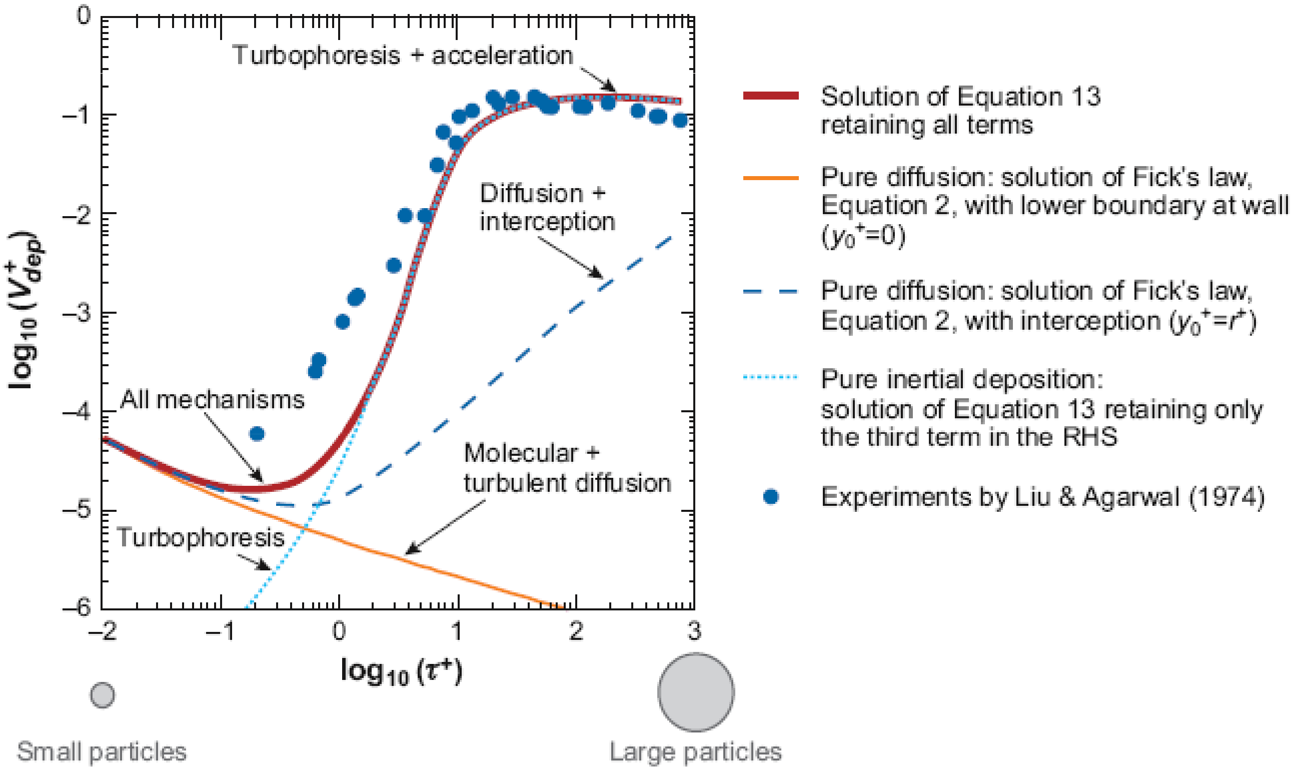
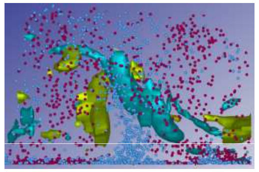


Figure 2

Computed deposition rate versus relaxation time (effects of pure diffusion, pure inertia, and interception): (*red line*) solution of Equation 13 retaining all terms; (*orange line*) pure diffusion, solution of Fick's law (Equation 2) with lower boundary at wall ($y_0^+ = 0$); (*dark blue dashed line*) pure diffusion, solution of Fick's law (Equation 2) with interception ($y_0^+ = r^+$); and (*light blue line*) pure inertial deposition, solution of Equation 13 retaining only the third term on the right-hand side (i.e., the convective flux term alone). Blue dots denote experiments by Liu & Agarwal (1974). For all computed curves, $k_s^+ = 0$, $\Delta T = 0$, and $\xi = 0$.



Particle Dynamics in the Wall layer

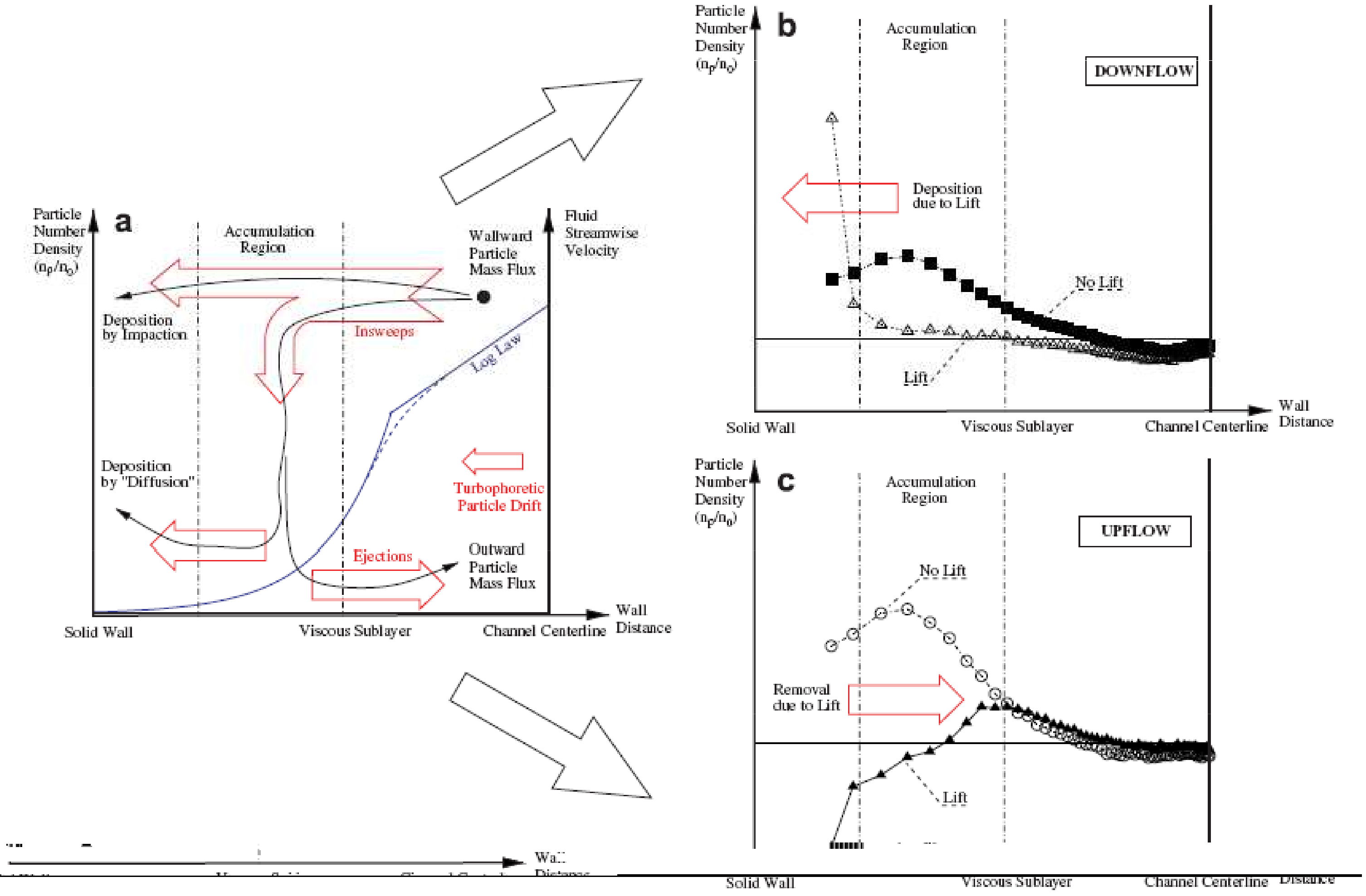
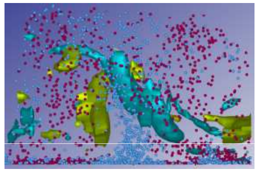


Fig. 14. Near-wall driving mechanisms, responsible for particle concentration build-up in the near-wall accumulation region (a) and effect of lift on particle concentration in the case of downflow (b) and in the case of upflow (c).



Vortex Identification

- If Vorticity is no good.. Then, what else?

Identification of Coherent Structures.0.

Intuitive definitions

---

1. Magnitude of the vorticity vector: $|\omega|$

Use of $|\omega|$ misleading when rotation due to pure shear and rotation due to actual swirling motion become comparable (e.g. wall-bounded flows).

2. Pressure

Pressure minima at vortex cores do not necessarily occur in unsteady inviscid 2D flows or in unsteady viscous 3D flows

In general, such methods:

i. do not prove to be Galilean invariant

ii. work if the vortical structure is characterized by a swirling motion associated with closed/spiral streamlines or pathlines, which is not always the case in highly unsteady flows

Identification of Coherent Structures.1.

D-criterion (Chong et al., 1990)

Vortex core = flow region of complex eigenvalues for the velocity gradient tensor, i.e. in flow regions where D>0. This is equivalent to having the antisymmetric part of the v.g.t. prevailing over the symmetric one.

The streamline rotation vector **Ω** is used for visualization purposes:

$$\mathbf{\Omega} = \mathrm{Im}(\lambda_c)\frac{\mathbf{e}_{\lambda_r}}{\left|\mathbf{e}_{\lambda_r}\right|}\frac{\mathbf{e}_{\lambda_r}\cdot\left[\mathrm{Re}(\mathbf{e}_{\lambda_c})\times\mathrm{Im}(\mathbf{e}_{\lambda_c})\right]}{\left|\mathbf{e}_{\lambda_r}\cdot\left[\mathrm{Re}(\mathbf{e}_{\lambda_c})\times\mathrm{Im}(\mathbf{e}_{\lambda_c})\right]\right|}$$

$\mathrm{Im}(\lambda_c) =$ imaginary part of eigenvalue λ_c

$\mathrm{Re}(e_{\lambda_c}), \mathrm{Im}(e_{\lambda_c}) =$ real/imaginary part of eigenvector $\mathbf{e}_{\lambda_c}$

Pros & cons:

+ the Δ-criterion bypasses non-Galilean invariance and unsteadiness
+ no CS can be found at the wall where Δ vanishes
-- unable to treat cases where the streamlines become locally closed or spiral, without the presence of truly vortical structure

Identification of Coherent Structures.2.

Q-criterion (Hunt et al., 1988)

Vortex core = connected region where Q>0 and the pressure is lower than the ambient value

$$Q > 0 \Rightarrow \omega^2 = \Omega_{ij}\Omega_{ij} > S^2 = S_{ij}S_{ij}$$

This method is equivalent to the Δ-criterion:if rotation predominates over strain than the antisymmetric part of the v.g.t. predominates over the symmetric one

Pros & cons:

+ insensitiveness to mean shear & large-scale variations of pressure
  (channel flow, Kelvin-Helmoltz instabilities in mixing layers)
+ does not lead to the selection of a particular privileged direction,
  which is considered the vortex axis
-- setting of the threshold for visualization of vortex isosurface is arbitrary

Identification of Coherent Structures.3

l_2-criterion (Jeong & Hussain, 1995)

Gradient of
NS Eqns
(symm. part)

$$\cancel{\frac{D}{Dt}S_{ij}} \cancel{- \nu S_{ij/kk}} + \Omega_{ik}\Omega_{kj} + S_{ik}S_{kj} = -\frac{1}{\rho}p_{ij}$$

Unsteady straining

Viscous effects

Ω

S

Hessian of pressure

Vortex core = connected region where p_{ij} has 2 positive eigenvalues *i.e.* Ω^2+**S**^{2} has 2 negative eigenvalues (local pressure minimum due to vortical motion on the eigenvector plane associated with the negative eigenvalues)

$$\lambda_1 \geq \lambda_2 \geq \lambda_3 \Rightarrow \lambda_2 < 0$$

Pros & cons:

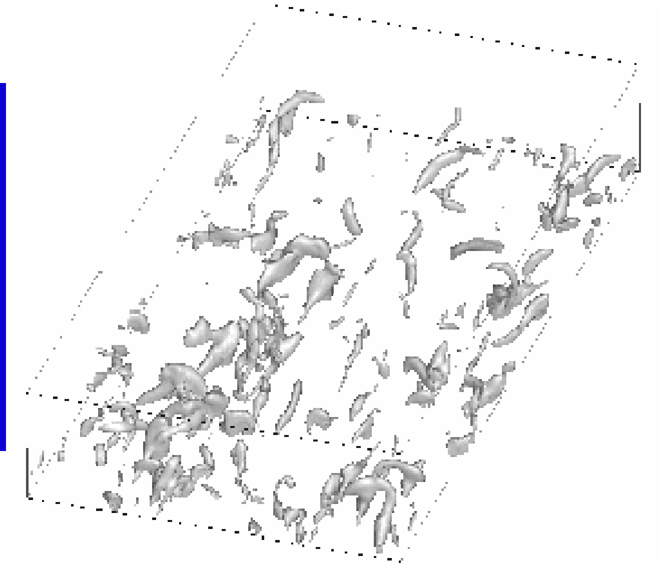
\+ improves pressure minima criterion by overcoming unsteady straining & viscous effects

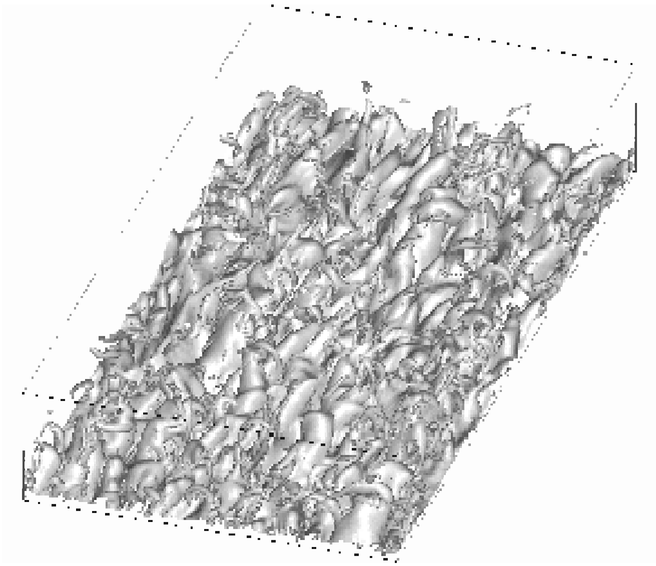
\+ no CS can be found at the wall where Ω^2+**S**^{2} vanishes

-- selects a privileged direction (the direction of the eigenvector associated with the largest eigenvalue of Ω^2+**S**^{2}) as vortex axis.

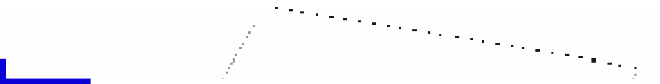
Identification of Coherent Structures.4. (TBL)

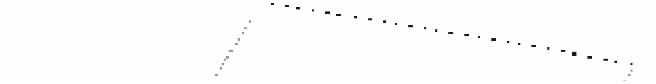
Pressure





Vorticity





Identification of Coherent Structures.6

Bibliography (suggested readings)

Flow topology

Rouson, D. & Eaton, J. (2001)

Chacin & Cantwell, (2000)

Chong, M.S., Perry, A.E. & Cantwell, B.J. (1990)

Ω-criterion

Chong, M.S., Perry, A.E. & Cantwell, B.J. (1990) *Phys. Fluids*, **2**, 765

Q-criterion

Hunt, J.C.R., Wray, A.A. & Moin, P. (1988) *Report CTR-S88*

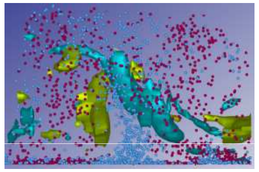
λ_2-criterion

Jeong, J. & Hussain, F. (1995) *J. Fluid Mech.*, v. **285**, p. 69

Review of identification criteria

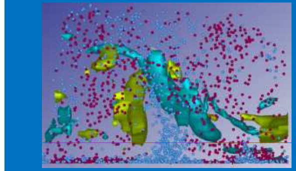
Dubief, Y., Delcayre, F. (2000) *J. Turbulence*

Cucitore, R., Quadrio, M. & Baron, A. (1999) *Eur. J. Mech. B*, v. **18**, p. 261.



- Identification of Vortices and Coherent Motions;

  >> Examples in Archetypal Flows



Flow Topology.1.

Velocity Gradient Tensor = Rate-of-Rotation + Rate-of-Strain

$$\frac{\partial u_i}{\partial x_j} \equiv u_{i,j} \equiv \nabla \mathrm{u} = \Omega_{\mathrm{ij}} + S_{\mathrm{ij}} \begin{cases} S_{ij} = \dfrac{1}{2}\left(\dfrac{\partial u_i}{\partial x_j} + \dfrac{\partial u_j}{\partial x_i}\right) = \dfrac{1}{2}\left(u_{i,j} + u_{j,i}\right) \\[2ex] \Omega_{ij} = \dfrac{1}{2}\left(\dfrac{\partial u_i}{\partial x_j} - \dfrac{\partial u_j}{\partial x_i}\right) = \dfrac{1}{2}\left(u_{i,j} - u_{j,i}\right) \end{cases}$$

Invariants

$$P = -tr\left[\nabla \mathrm{u}\right] = -S_{ii}$$

$$Q = \frac{1}{2}\left(\Omega_{ij}\Omega_{ij} - S_{ij}S_{ij}\right)$$

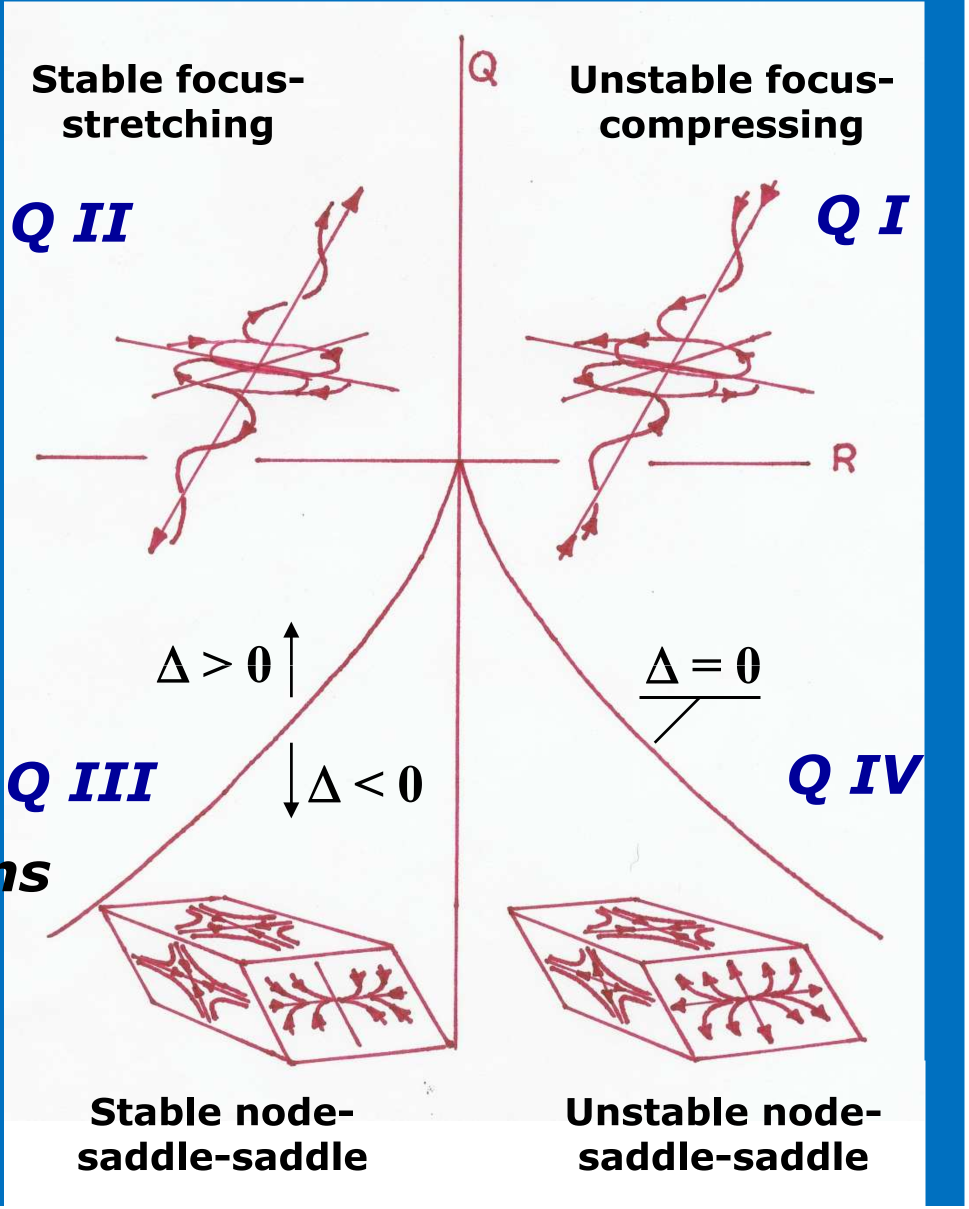
$$R = \det\left[\nabla \mathrm{u}\right]$$

$$\boxed{\Delta = \frac{Q^3}{27} + \frac{R^2}{4}}$$

Flow Topology.2.

$$Q > 0 \Rightarrow \Omega_{ij}\Omega_{ij} > S_{ij}S_{ij}$$

Rotation Rate > Strain Rate



Q I, QII = Vortical Flow Regions

Q III, QIV = Convergence Regions

Part II

Application of Structure Identification

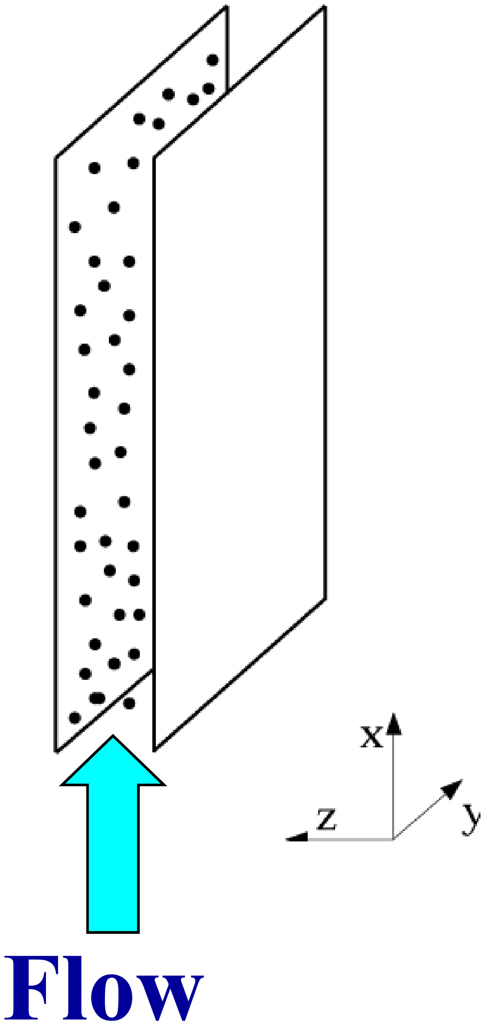
1. **Coherent Structures Dynamics in Turbulent Boundary Layer**

   \>> Turbulence Regeneration Cycle: Physical Explanation of Reynolds Stresses.

2. **Coherent Structures Dynamics in Confined Jet**

   >> Generation of pressure minima at vortex cores do not necessarily occur in

Coherent Structures Dynamics in Turbulent Boundary Layer
Computational Methodology: Eulerian Flow Field



Pseudo-spectral DNS of time-dependent turbulent Poiseuille flow in a channel.

Grid: 64 x 64 x 65 nodes
1885 x 942 x 150 w.u.

Fluid: air

$$\rho = 1.3\,\mathrm{Kg/m^3}$$

$$\nu = 1.57 \cdot 10^{-5}\,\mathrm{m^2/s}$$

<u>=1.65 m/s

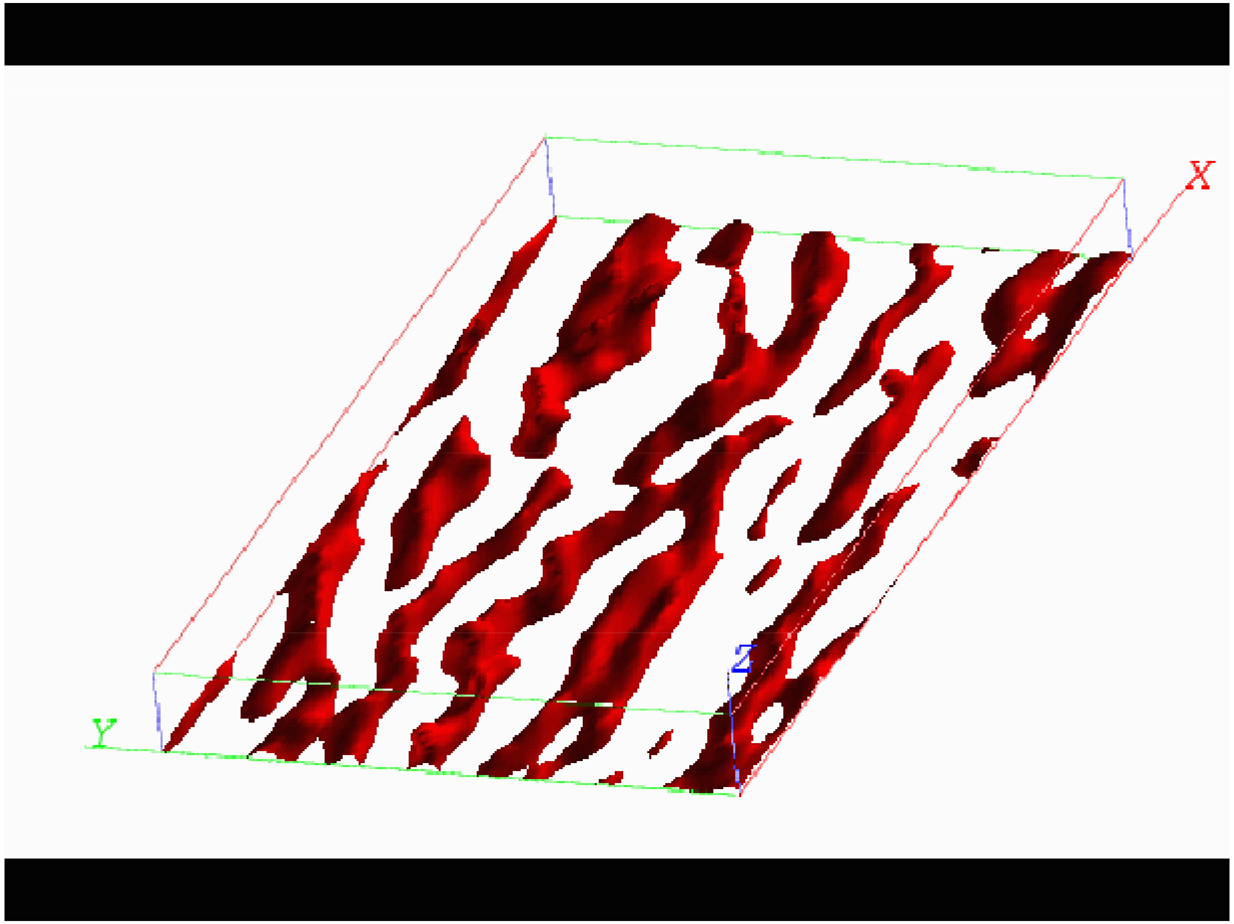
$$\mathrm{Re} = \frac{<u>h}{\nu} = 2110$$

u_τ=0.011775 m/s

$$\mathrm{Re}_\tau = \frac{u_\tau h}{\nu} = 150$$

Part II

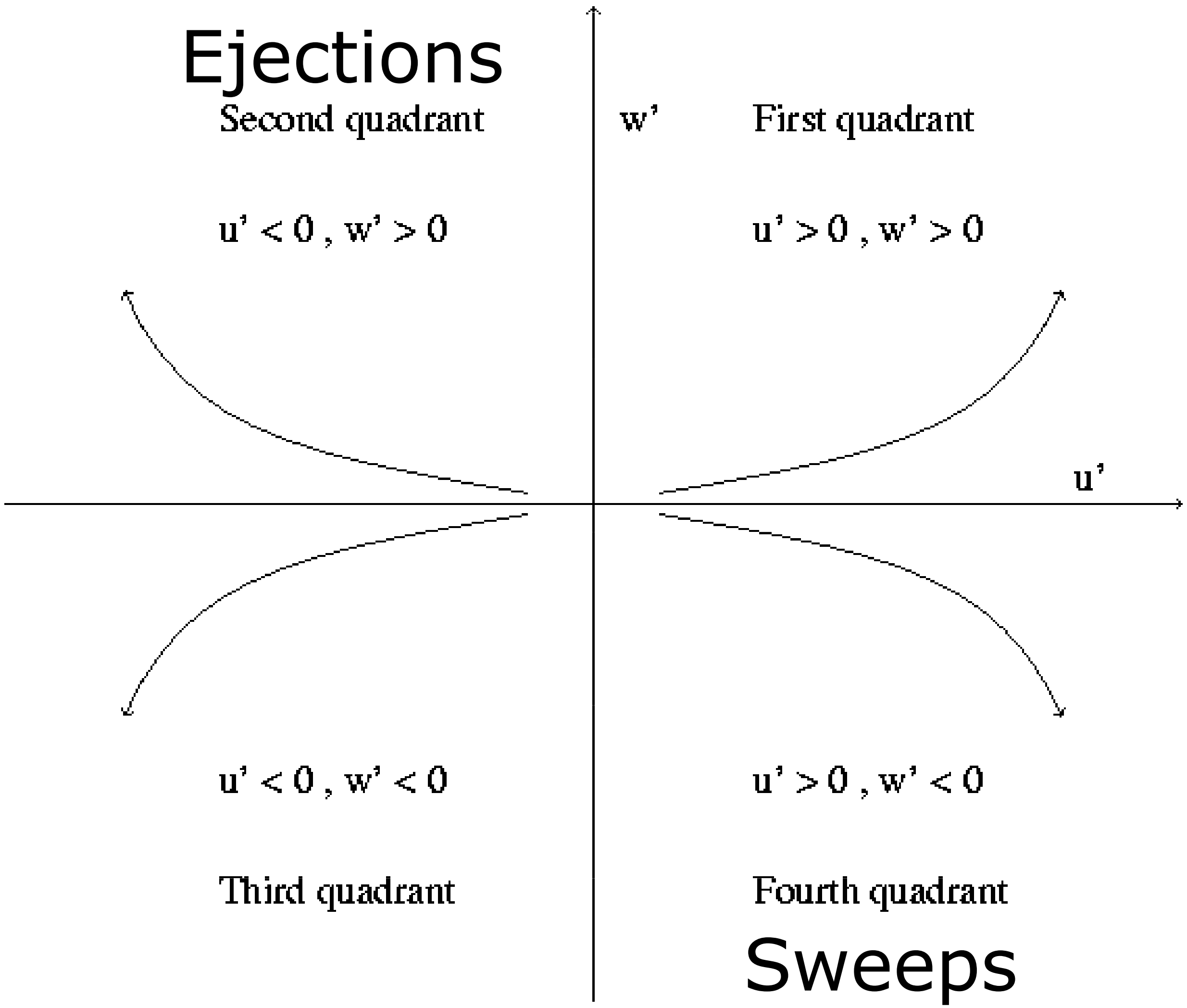
Turbulent Structures at the wall.1
Dynamics of the Low Speed Streaks



Red: Low-Speed
Streamwise Streaks

Part II

Turbulent Structures at the wall.3.
Reynolds Stresses

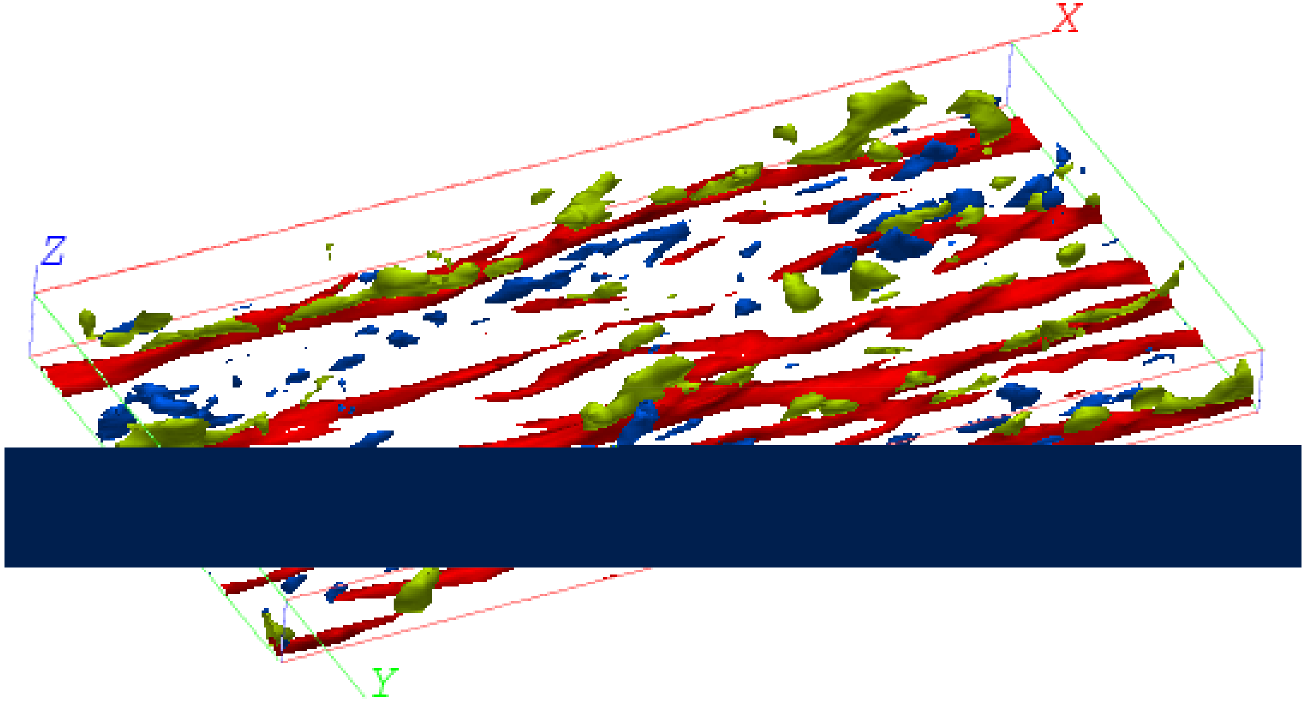


Ejections

Sweeps

Part II

Turbulent transfer at the wall .4.
Sweeps, ejections and Low-speed streaks

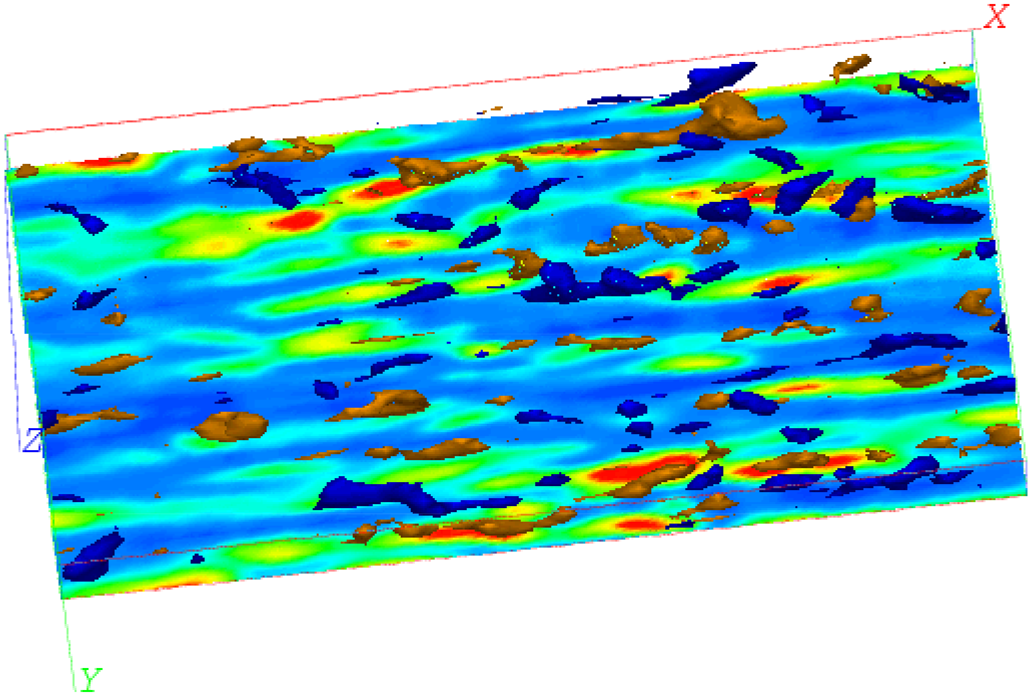


Red: Low-speed Streak

Blue: Ejection Gold: Sweep

Part II

Turbulent transfer at the wall .5.
Sweeps, ejections and wall shear stress



Red: high τ_w

Blue: low τ_w

Gold: Sweep

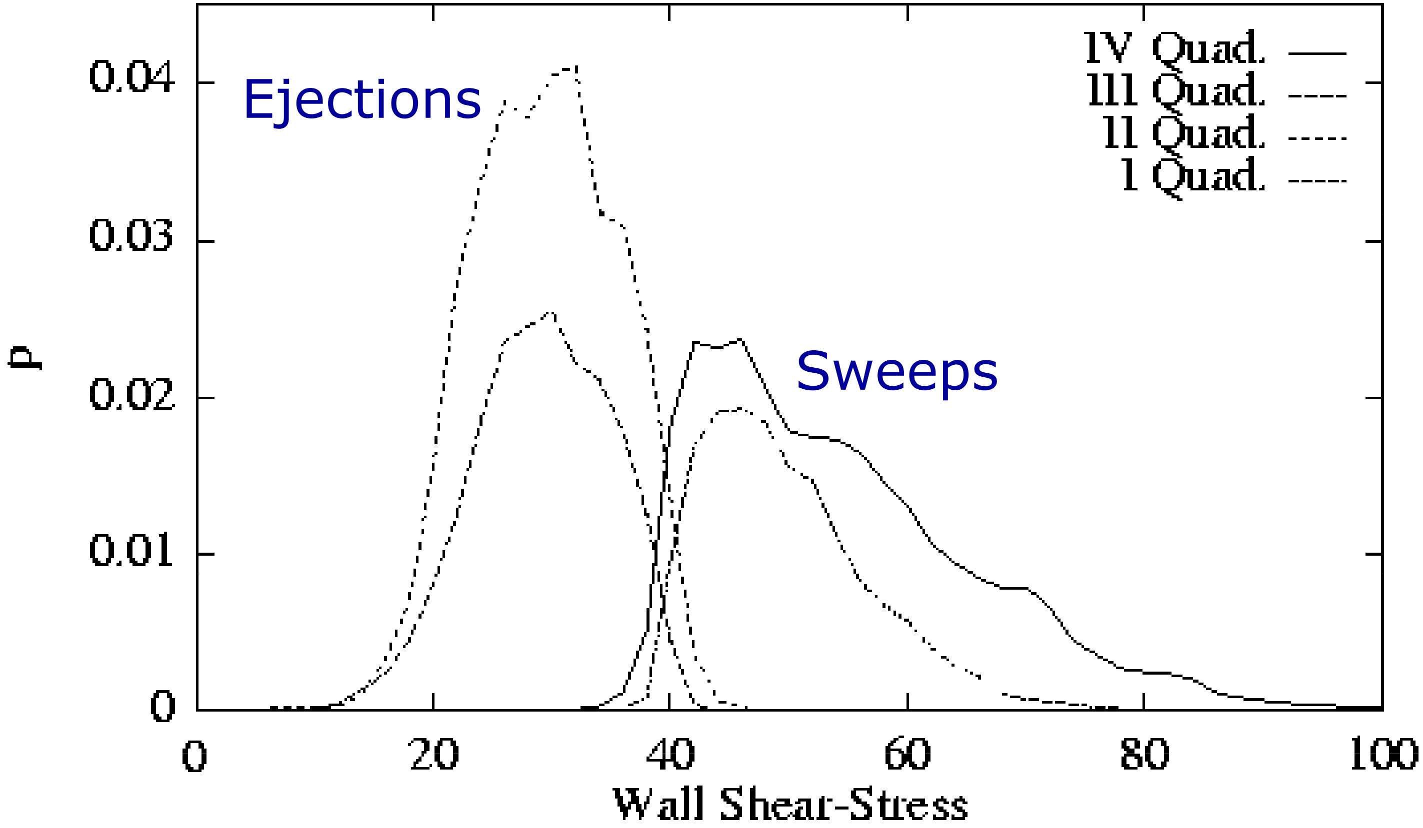
Blue: Ejection

Part II

Turbulent transfer at the wall .6.
Sweeps, ejections and Wall Shear Stress

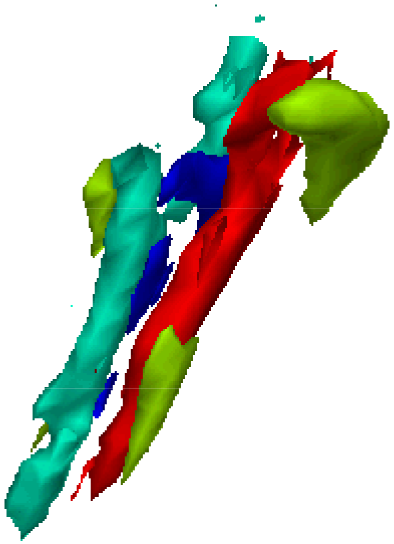
Ejections correlate with
Low Wall Shear

Sweeps correlate with
High Wall Shear



Part II

Turbulent transfer at the wall .7.
Sweeps, ejections and streamwise vortices



Red: Clockwise Streamwise Vortex

Pale Blue: Counter Clockwise Streamwise Vortex

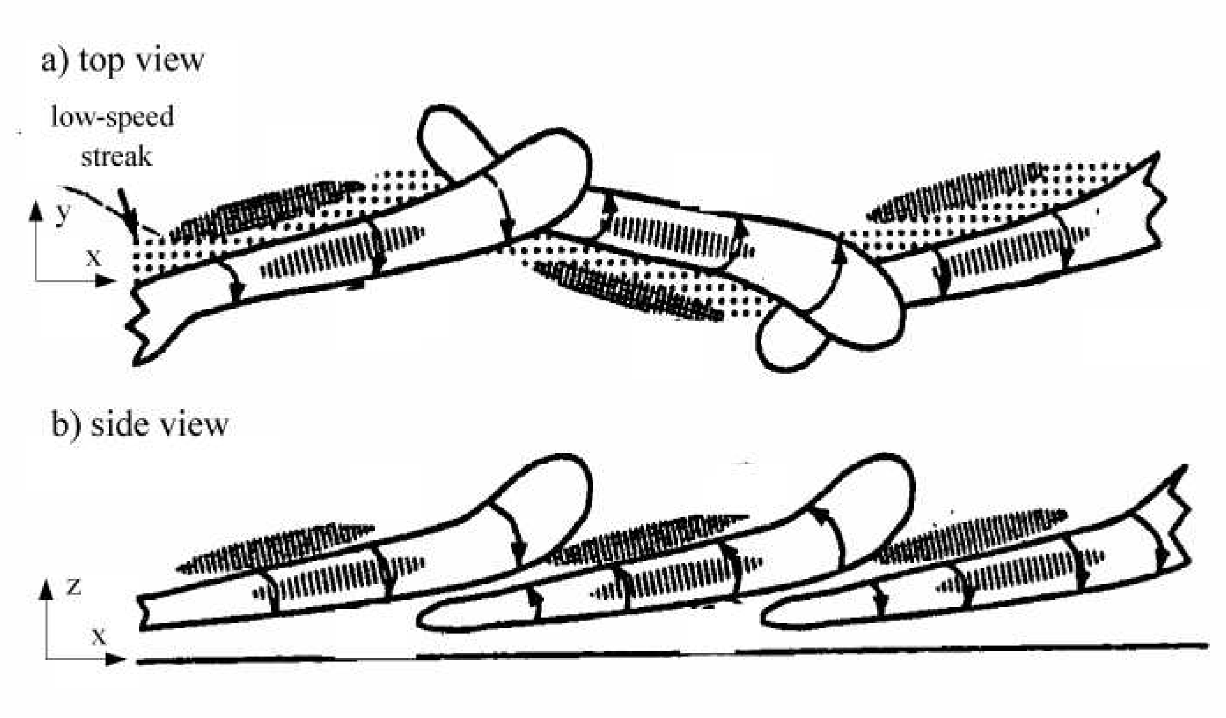
Gold: Sweep

Blue: Ejection

Turbulent transfer at the wall .8.

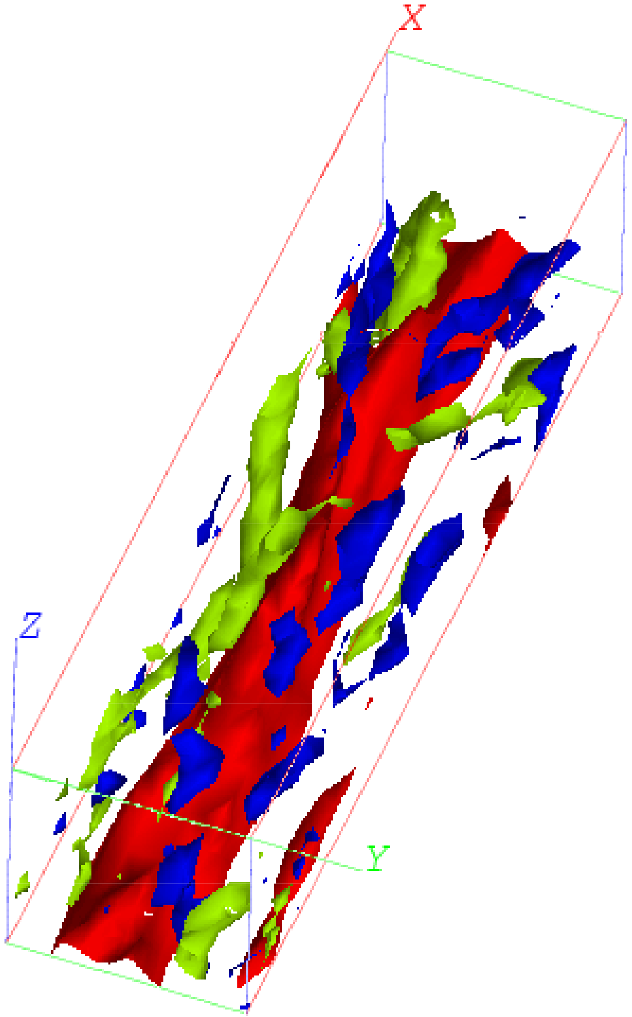
Observations:

- Only 25% of Quasi Streamwise Vortices are Paired
- 75 % are single and Staggered along the Low Speed Streak (Fazle Hussain)



Part II

Turbulent transfer at the wall .9. Sweeps, ejections and streamwise vortices



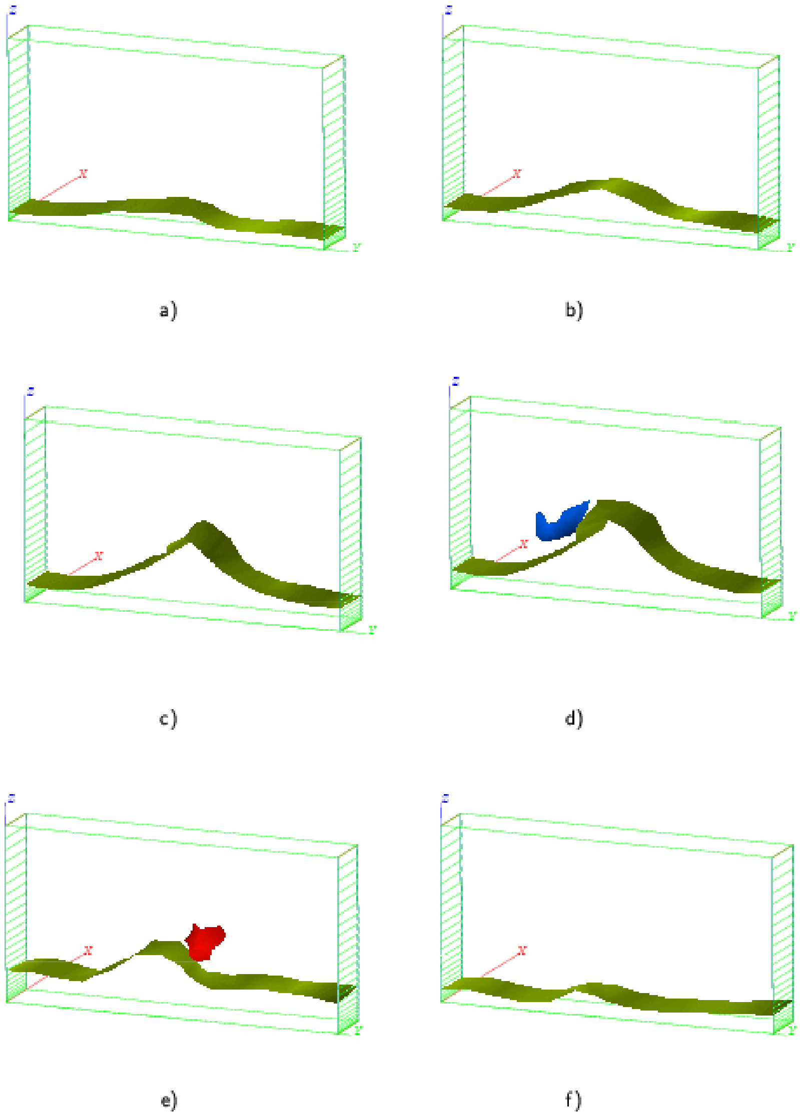
Red: Low Speed Streak

Blue: Clockwise Streamwise Vortex

Green: Counter-Clockwise Streamwise Vortex

Part II

Turbulent transfer at the wall .11.
Low-speed streaks and streamwise vortices



a) b) c) d) e) f)

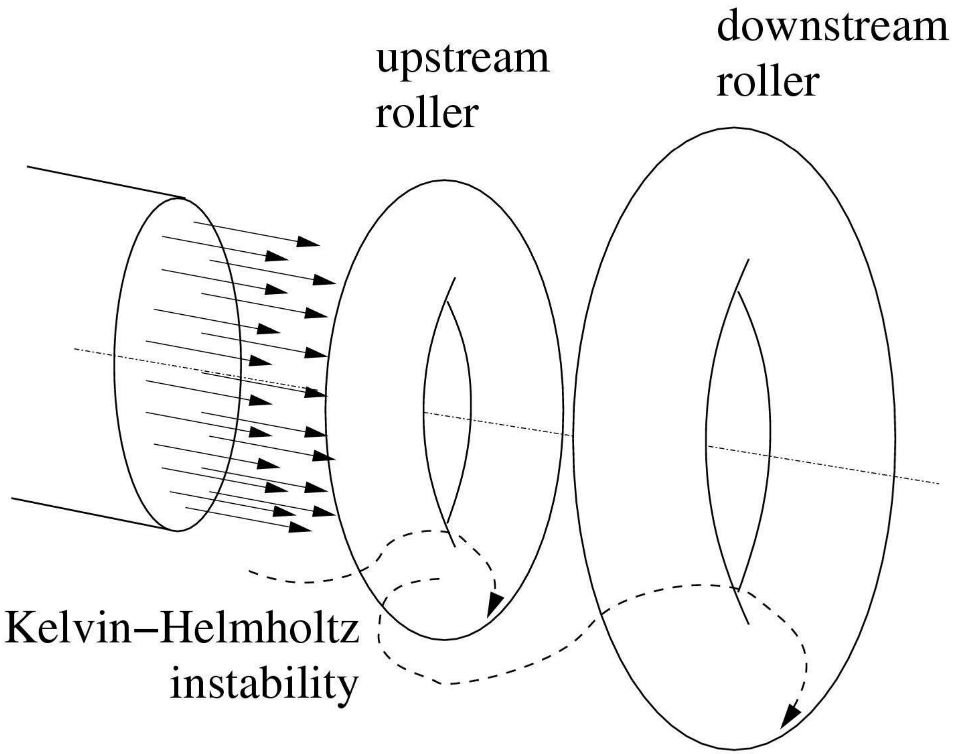
Green: Low Speed Streak

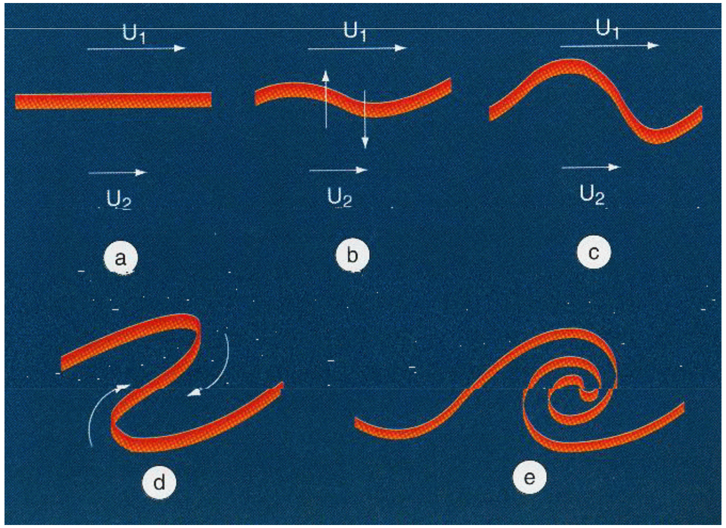
Red: Clockwise Streamwise Vortex

Green: Counter-Clockwise Streamwise Vortex

Part II

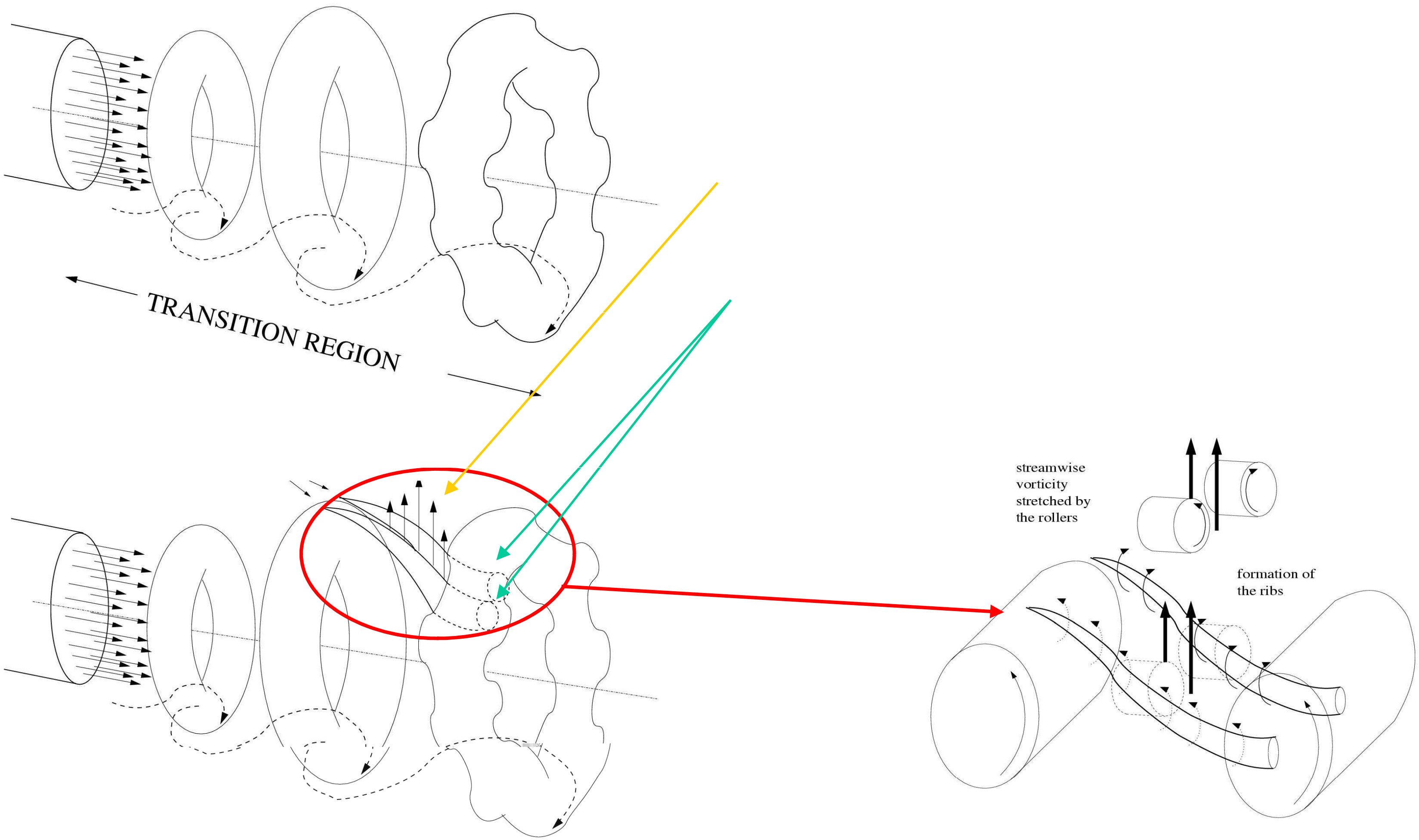
Flow Structure in a Bounded Jet. 1
Generation dynamics





Part II

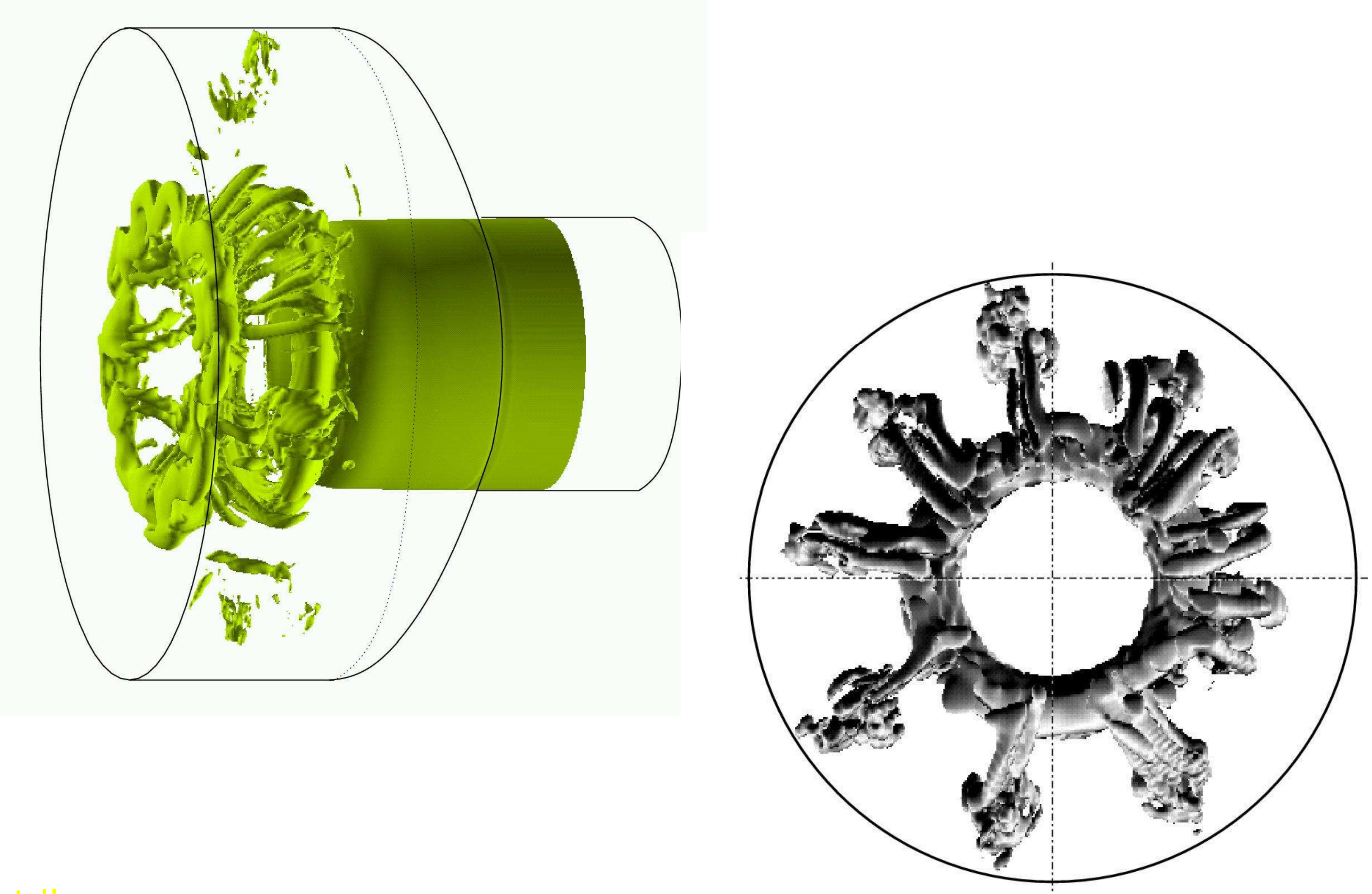
Flow Structure in a Bounded Jet. 2
Generation dynamics



RIB FORMATION MECHANISM
(Yule, 1978)

Part II

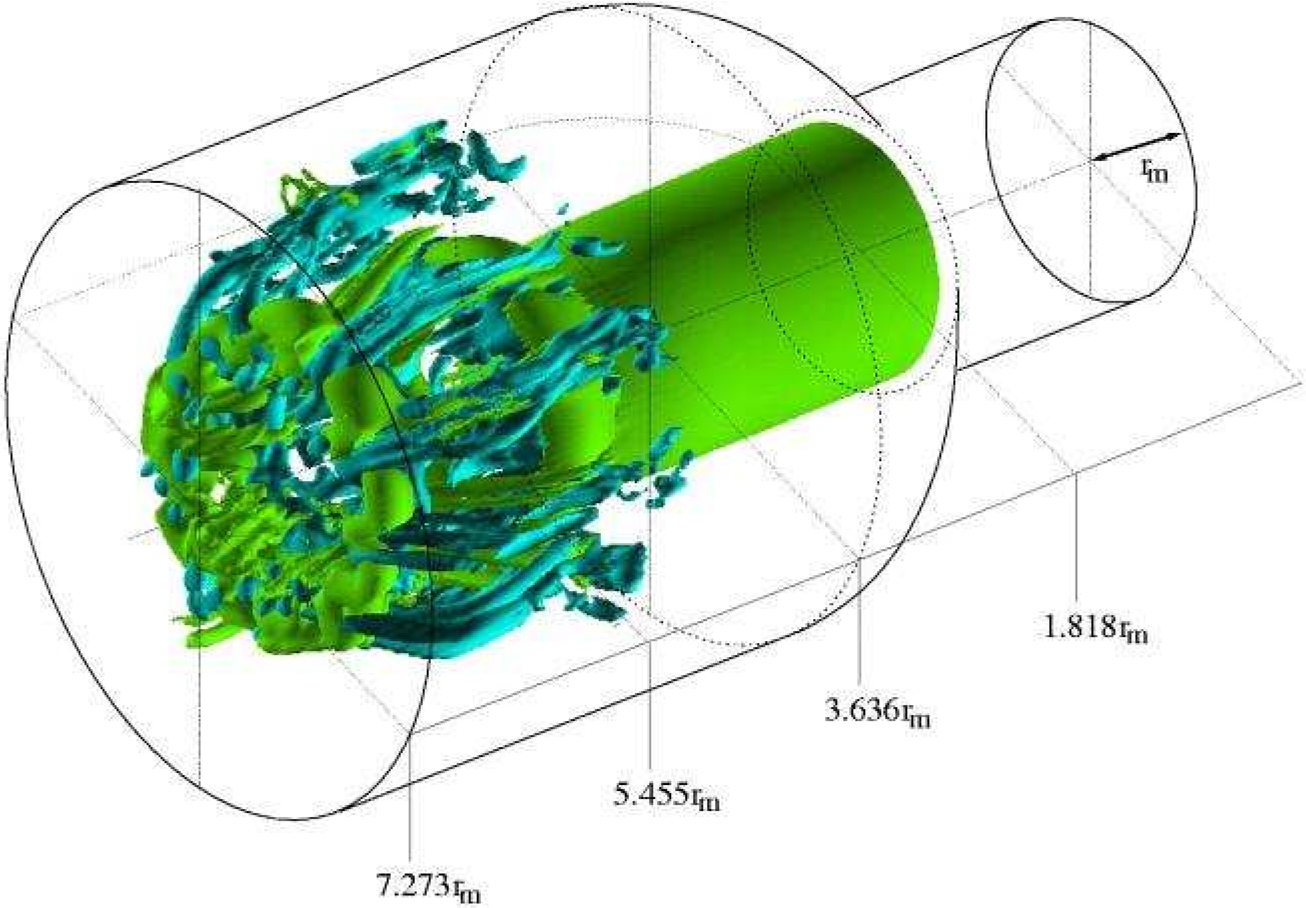
Flow Structure in a Bounded Jet. 3
Generation dynamics



Part II

Flow Structure in a Bounded Jet. 4
Generation dynamics

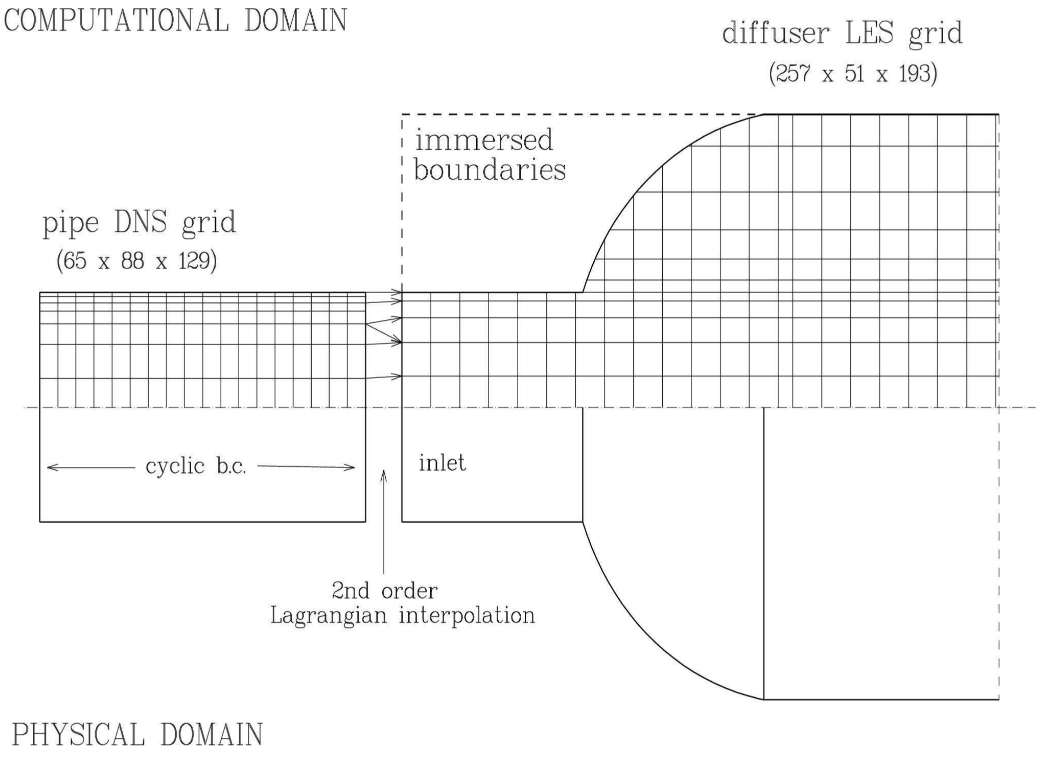
Green isosurface: vorticity **Blue isosurface: Q**



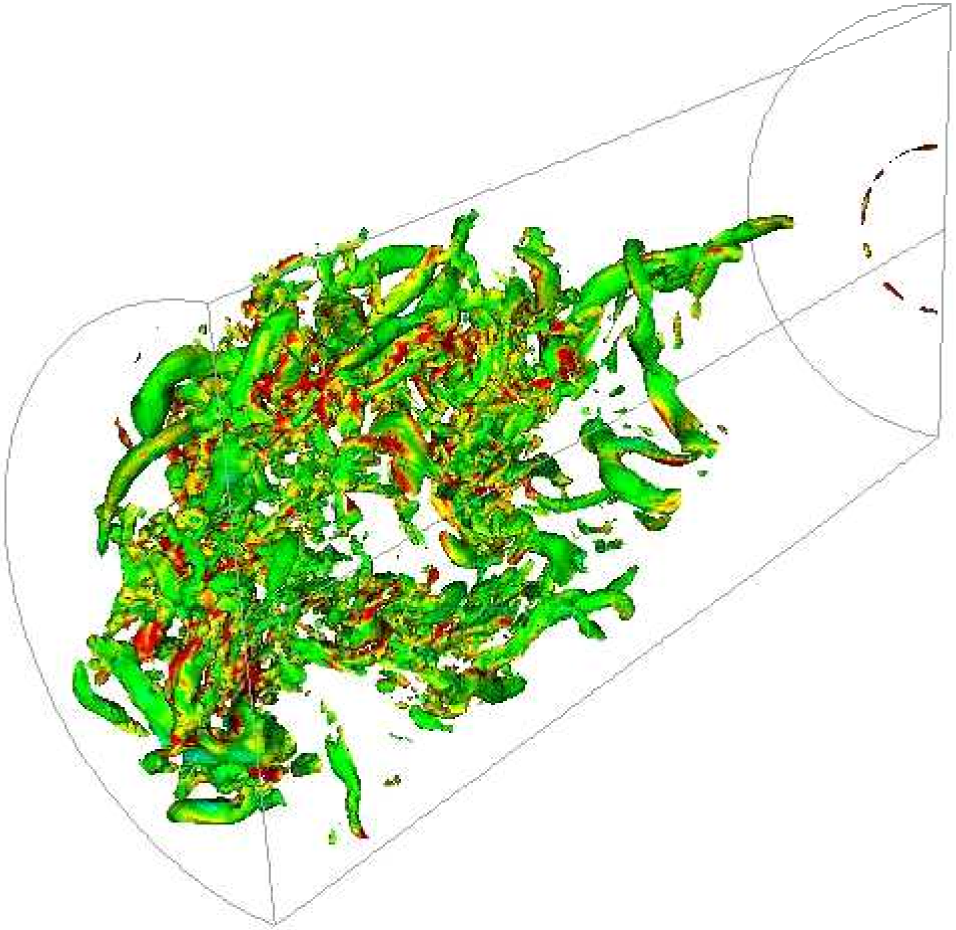
Part II

Flow Structure in a Bounded Jet. 5
Generation dynamics…But what if we modify initial conditions?

- Two parallel simulations:
- Turbulent pipe DNS
- LES of a large-angle diffuser
- DNS velocity field interpolated and supplied to LES inlet.
- Complex shape walls modeled through the immersed-boundaries (Fadlun et al., 2000)

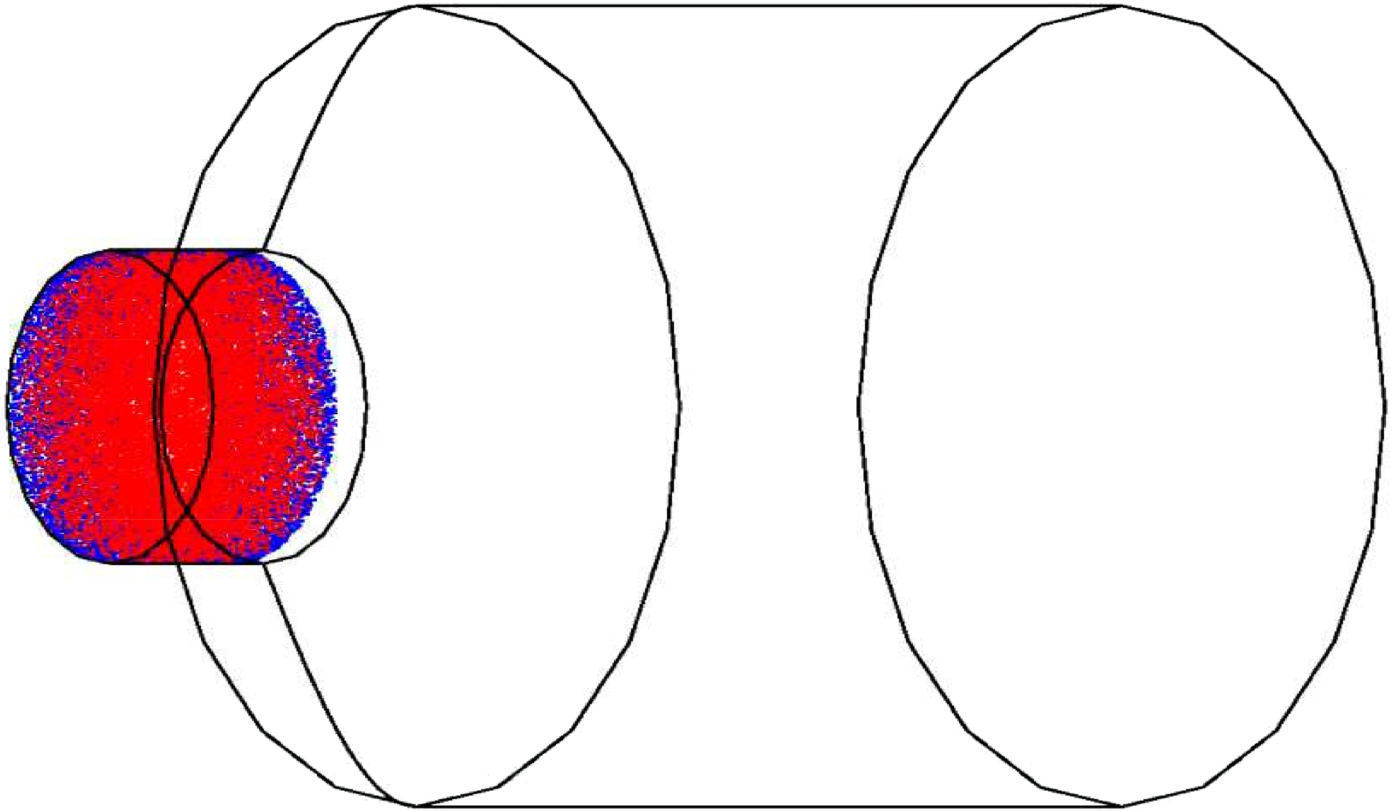


Flow Structure in a Bounded Jet. 4
Generation dynamics

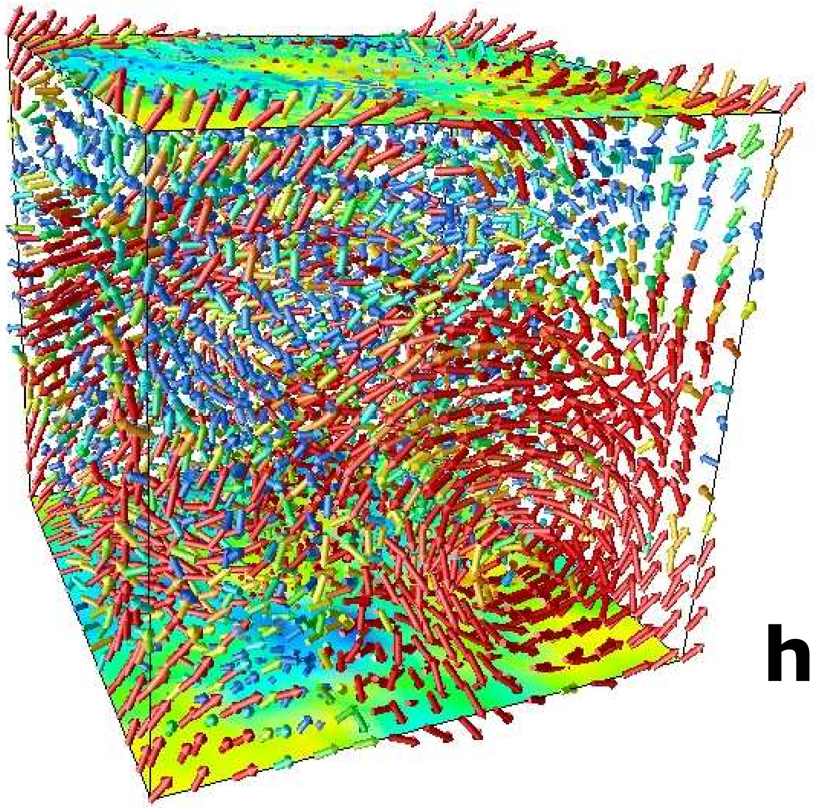


vorticity magnitude
on Q isosurface

Flow Structure in a Bounded Jet. 5
Particle Dispersion



Computational Fluid Dynamics database



Free CFD database, kindly hosted by Cineca supercomputing center (Bologna, Italy).

Over than 1 Tbyte DNS fluid-dynamics data available on line at:

http://cfd.cineca.it/cfd