Development and validation of a new LES turbulence model for wall-bounded flows

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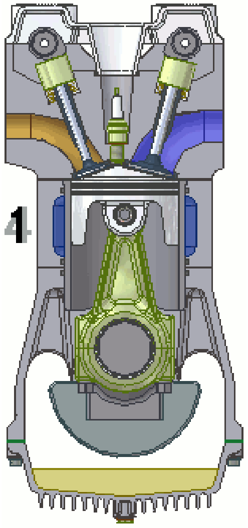
LES4ICE conference – 18/11/2010

Context and objectives (1/2)

- Combustion in IC engine
  - Type of fuel
  - Fuel/air ratio
  - Type of mixing
    - stratified
    - homogeneous
  - Combustion efficiency

→ Depend on the turbulent intensity



If flows in combustion chambers were laminar we would probably have “only” electric cars...

.... and unfortunately no LES4ICE conference.

Context and objectives (2/2)

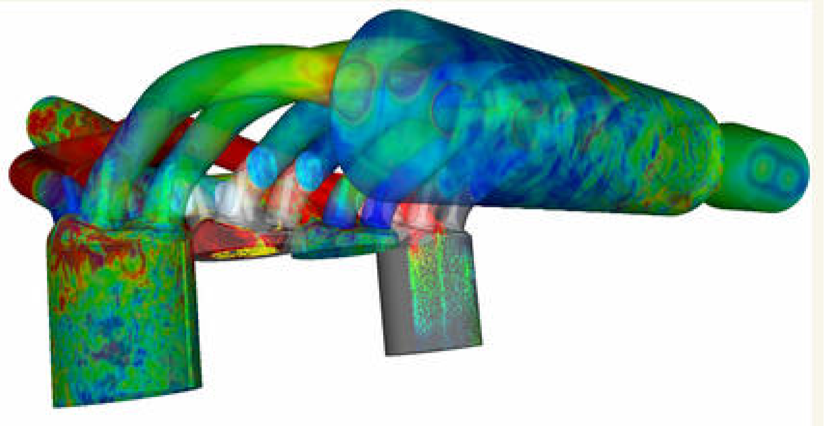
- Flows in a complex geometry
  - Fully turbulent regions

    Dissipate the right amount of energy
  - Transient regions

    Accurately predict the transition delay
  - Near wall regions/shear regions

    Weak contribution of the turbulence
  - Laminar regions

    No subgrid scale contribution expected



Develop or improve a subgrid scale model in order to take into account all those regions in a complex configuration

OUTLINE

- LES formalism and subgrid scale viscosity
- Dynamic Smagorinsky model
- Proposal of the Sigma model and a global strategy for the dynamic constant evaluation
- Proposal of a more advanced experimental test case
- Perspectives

LES formalism and subgrid-scale viscosity (1/2)

- LES formalism: Large scales are directly resolved and the most universal small scales are modeled

- Filtered NS equation

$$\rho\frac{\partial\overline{u_i}}{\partial t}+\rho\frac{\partial\overline{u_i}\,\overline{u_j}}{\partial x_j}=-\frac{\partial\bar{p}}{\partial x_i}+\frac{\partial\overline{\tau_{ij}}}{\partial x_j}-\frac{\partial\tau_{ij}^{sgs}}{\partial x_j}\longrightarrow\tau_{ij}^{sgs}=\rho\overline{u_i u_j}-\rho\overline{u_i}\,\overline{u_j}$$

- Functional modeling approach

$$\tau_{ij}^{sgs}-\frac{1}{3}\tau_{ii}^{sgs}=-2\rho\vartheta^{sgs}\overline{S_{ij}}$$

LES formalism and subgrid-scale viscosity (2/2)

$$\boxed{\nu^{sgs} = C_{op}^{2}\Delta^{2}D_{op}}$$

- Subgrid scale viscosity properties
  - Reproduce the dissipative effect of the small scales
  - Zero for laminar flows and fully resolved computations
  - Zero at solid boundaries/shear regions with a y^3 asymptotic behavior

Dynamic Smagorinsky model (1/3)

$$\boxed{\nu^{sgs} = C_S^2 \Delta^2 D_S}$$

- Smagorinsky time scale J. Smagorinsky Mon. Weather Rev. 91, 1963

$$\boxed{D_s = \sqrt{2 S_{ij} S_{ij}}}$$

- Dynamic constant with Lilly correction M. germano Phys. Fluids 3(7) 1991

D. K. Lilly Phys. Fluids 4(3) 1992

$$\boxed{C_s^2 = \frac{< L_{ij} M_{ij} >_h}{< M_{ij} M_{ij} >_h}}$$

< >h : Averaging over homogeneous direction

Lij : Leonard term

Mij: Differential operator between the initial filter and the test filter

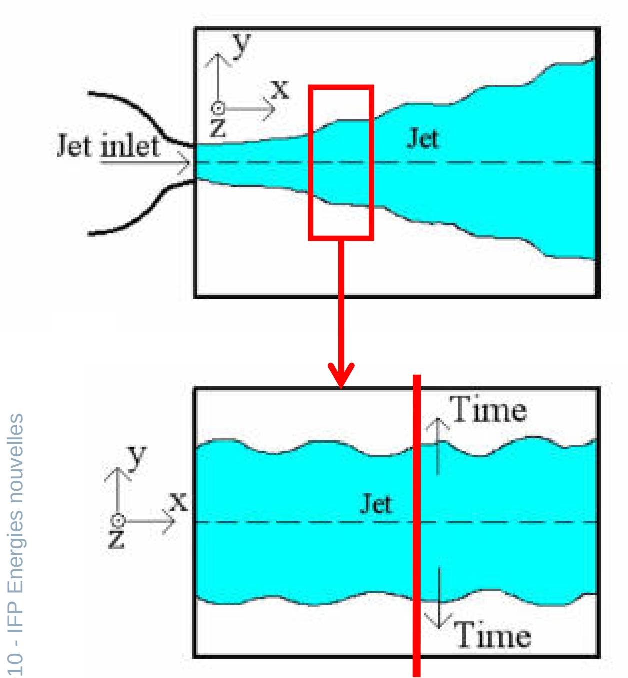
Dynamic Smagorinsky model (2/3)

- Advantages of the dynamic Smagorinsky model
  - Overcomes the drawbacks of the Smagorinsky model
  - Adapts the viscosity to the mesh refinement, the numeric and the turbulence intensity
- Drawback
  - Difficult to extend the model to complex geometries where homogeneous directions are almost impossible to identify
- The common alternative consists to use the model in its local form and to clipp all the negative values

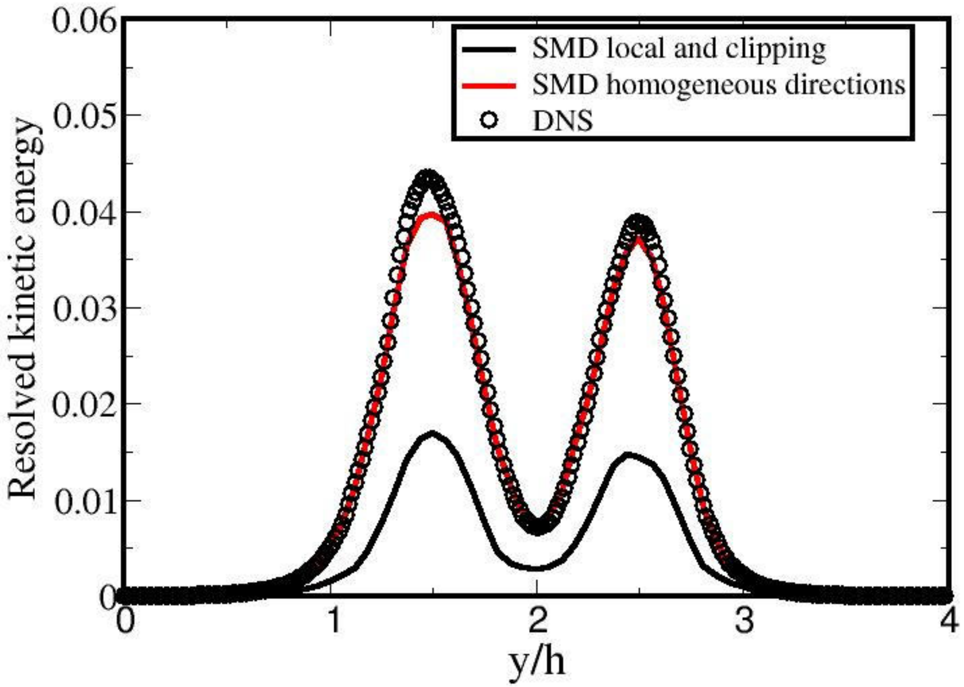
$$C_s^2 = \frac{< L_{ij}M_{ij} >_h}{< M_{ij}M_{ij} >_h} \qquad \longrightarrow \qquad C_s^2 = \frac{< L_{ij}M_{ij} >_l^+}{< M_{ij}M_{ij} >_l}$$

Dynamic Smagorinsky model (3/3)

- Consequences of the local clipping
  - Test case periodic jet performed by G. Ballarac (LEGI)



da Silva & Pereira, PoF, 08



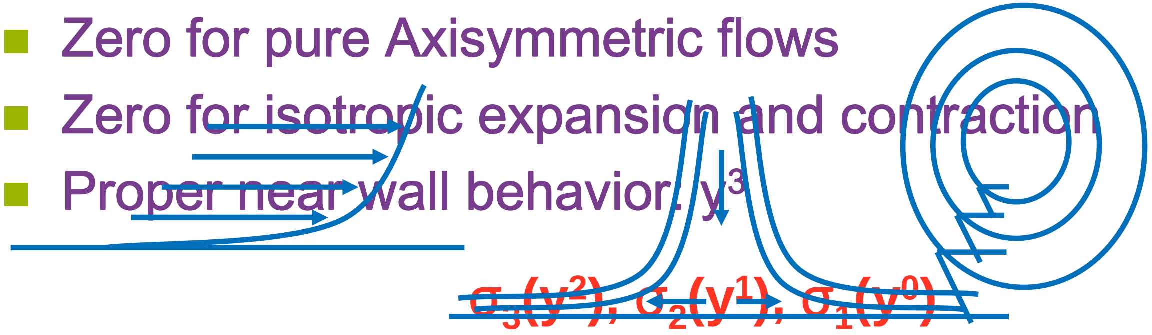
Proposal of the sigma model (1/3)

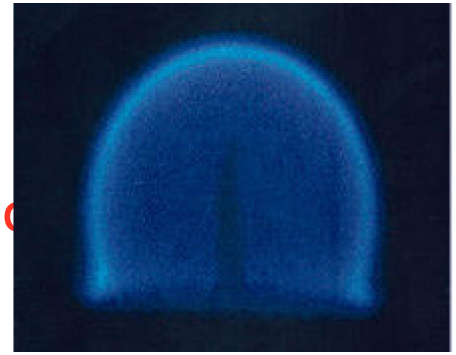
$$\boxed{\nu^{sgs} = C_\sigma^2 \Delta^2 D_\sigma}$$

$\sigma_1 \geq \sigma_2 \geq \sigma_3$ singular values of g_{ij}

$$\boxed{D_\sigma = \frac{\sigma_3(\sigma_1-\sigma_2)(\sigma_2-\sigma_3)}{\sigma_1^2}}$$

- Properties of the sigma time scale
  - Zero for any 2D/2Components flows
  - Zero for pure Axisymmetric flows
  - Zero for isotropic expansion and contraction
  - Proper near wall behavior: y^3





$\sigma_1 = \sigma_2 = \sigma_3$

H. Baya Toda, O. Cabrit, G. Balarac, S. Bose, J. Lee, H. Choi and F. Nicoud
CTR, Proceedings of the Summer Program, Stanford University, 2010

Proposal of the sigma model (2/3)

- Static Sigma model : $C_\sigma = 1.5$
- Standard global procedure: volume weighted averaging

$$C_\sigma^2 = \frac{\langle\langle L_{ij} M_{ij} \rangle\rangle_{voli}}{\langle\langle M_{ij} M_{ij} \rangle\rangle_{voli}}$$

$\langle\langle\ \rangle\rangle_{voli}$: volume weighted averaging

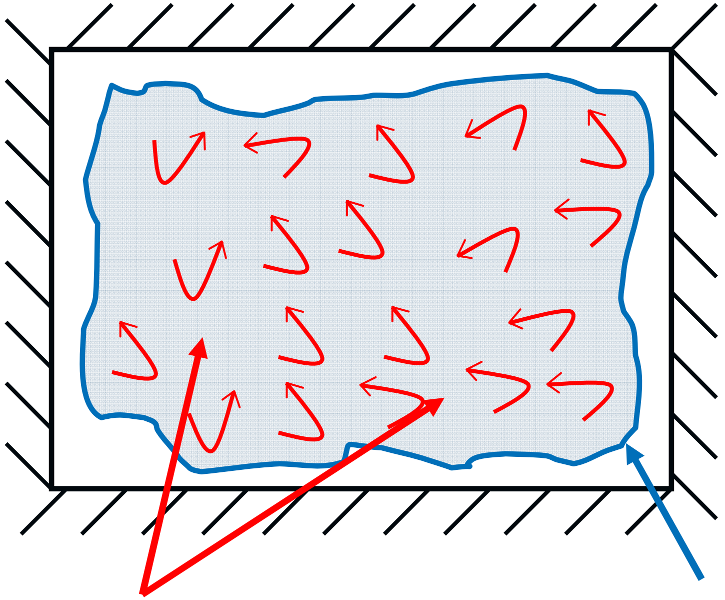
C_σ is homogeneous in space and varies only in time

N. Park, S. Lee, J. Lee, and H. Choi. Phys. Fluids, 18, 2006.

Proposal of the sigma model (3/3)

- Modified global procedure to eliminate regions where viscous effects (shear regions/solid boundaries) dominate: volume and SVS weighted averaging

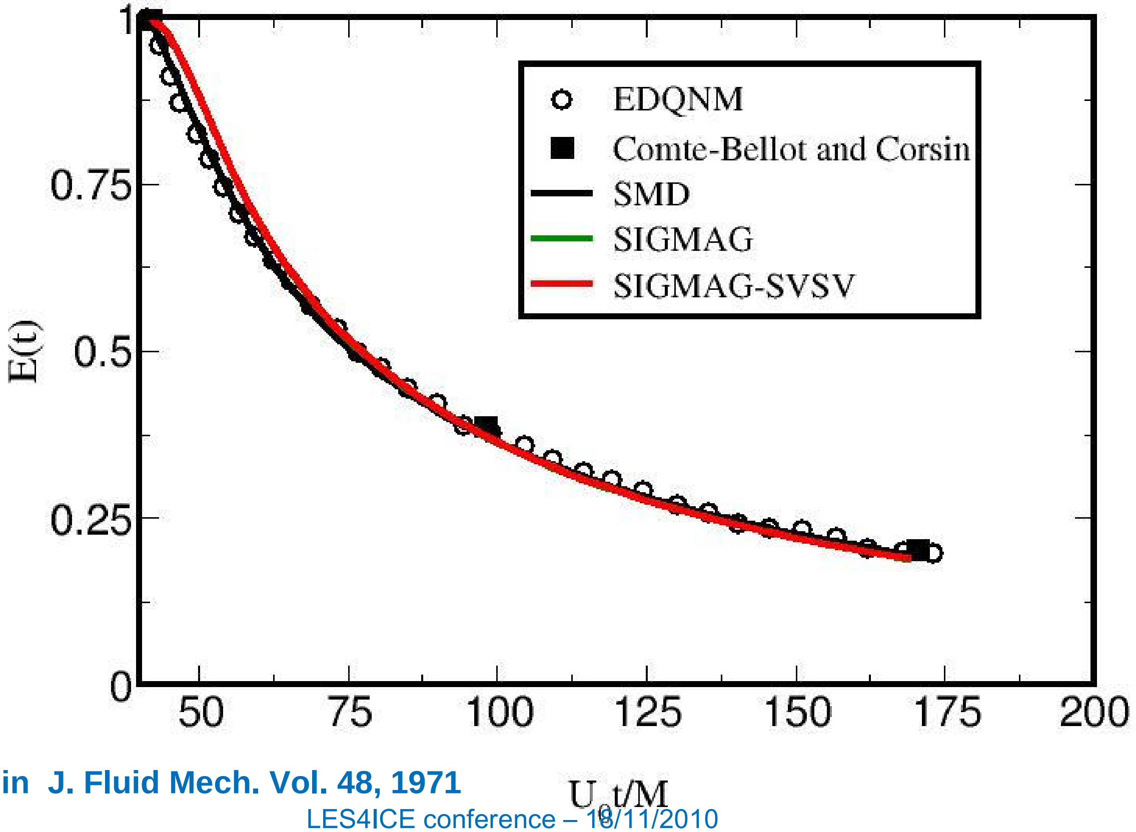
$$C^2_{\sigma\_SVS} = \frac{<< L_{ij}M_{ij} >>_{volisvs}}{<< M_{ij}M_{ij} >>_{volisvs}}$$



H. Baya Toda, K. Truffin, and F. Nicoud.
ECCOMAS, Lisbon, Portugal, 14-17 June 2010

Validation of the sigma model (1/2)

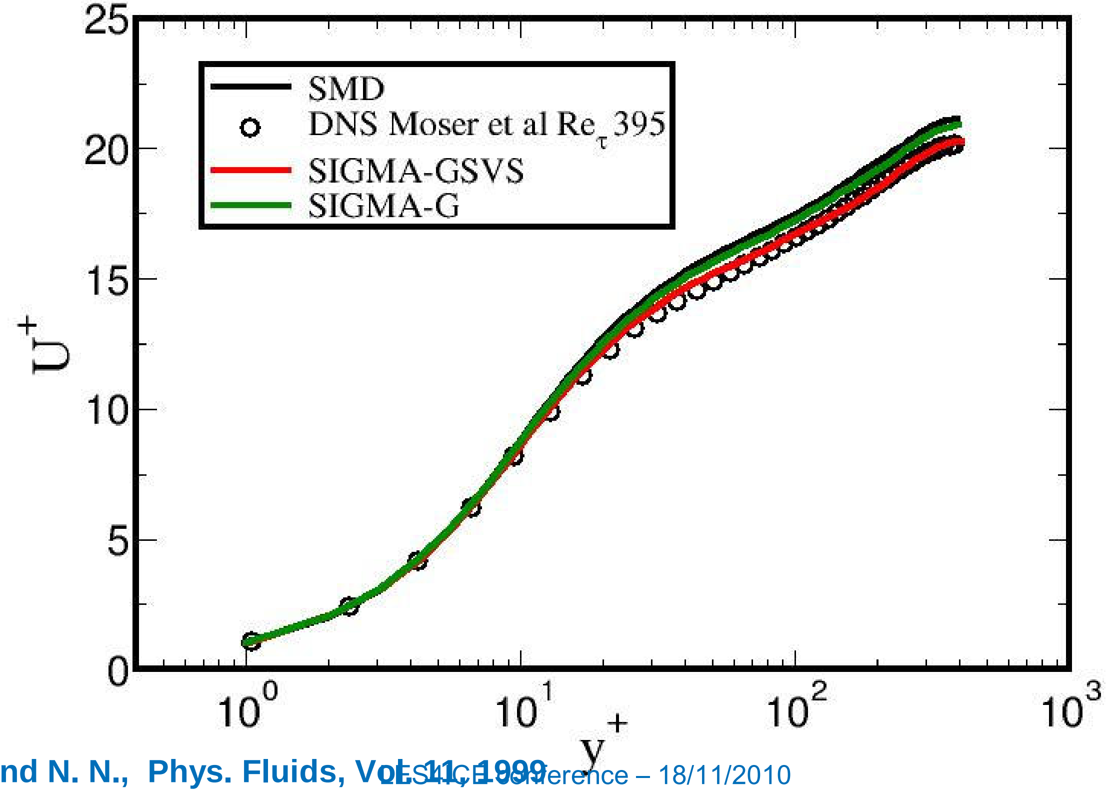
- Academic test case
  - Homogeneous Isotropic Turbulence of Comte-Bellot and Corsin



G. Comte-Bellot and S. Corsin J. Fluid Mech. Vol. 48, 1971

Validation of the sigma model (2/2)

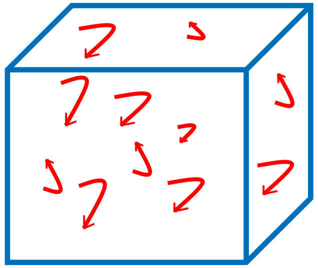
- Academic test case
  - Turbulent channel of Moser et al.



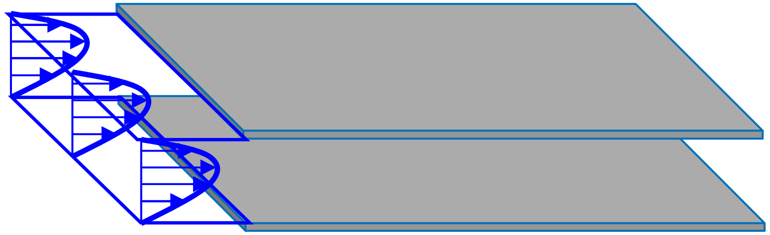
R. D. Moser, J. Kim and N. N., Phys. Fluids, Vol. 11, 1999

Proposal of an advanced test case (1/6)

- Target application: IC engine



HIT



Turbulent channel

Vortex formation

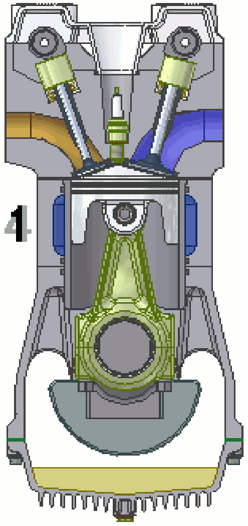
Convection

Impingement on cold solid boundaries

?

Heat Transfer

Turbulent environnement



Proposal of an advanced test case: Hot Impinging Jet in Cross Flow (2/6)

LES constraints

- **Small dimensions ratio**

realistic but computable dimensions

- **Homogeneous turbulent cross flow**

convergent, honeycomb and grill

- **Unsteady computation**

fast opening injector

- **Low Mach number flow 0.2**

accurate control of the pressure and temperature

Diagnostics constraints

- **PIV, LIF, LIP**

Optical access in the streamwise and spanwise directions of the cross flow

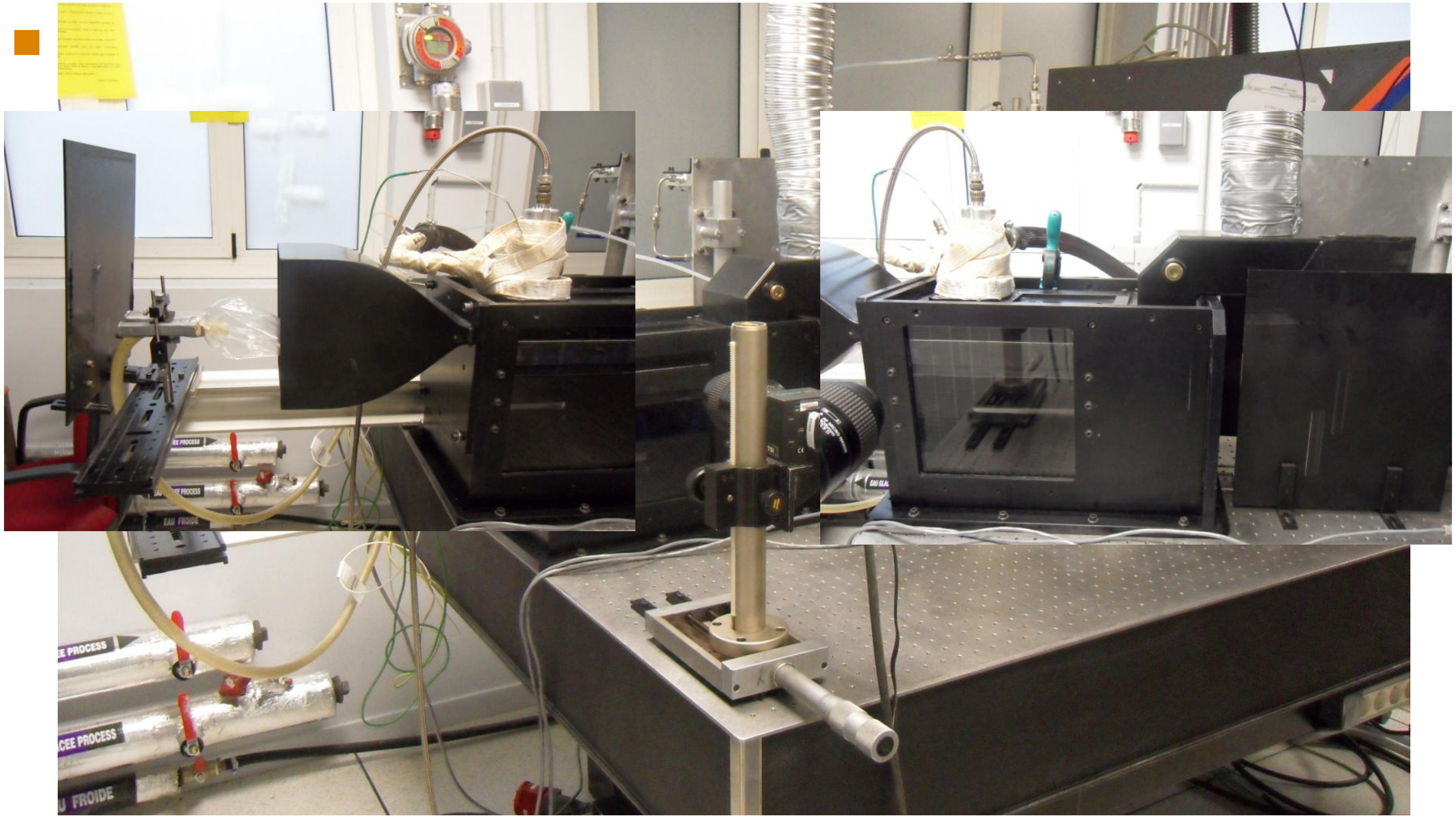
- **Seeding system**

seeding system for PIV and LIF measurement

- **Heat flux measurement**

solid boundary with a low conductivity in order to increase the wall temperature

Proposal of an advanced test case (3/6)

- 

Proposal of an advanced test case (4/6)

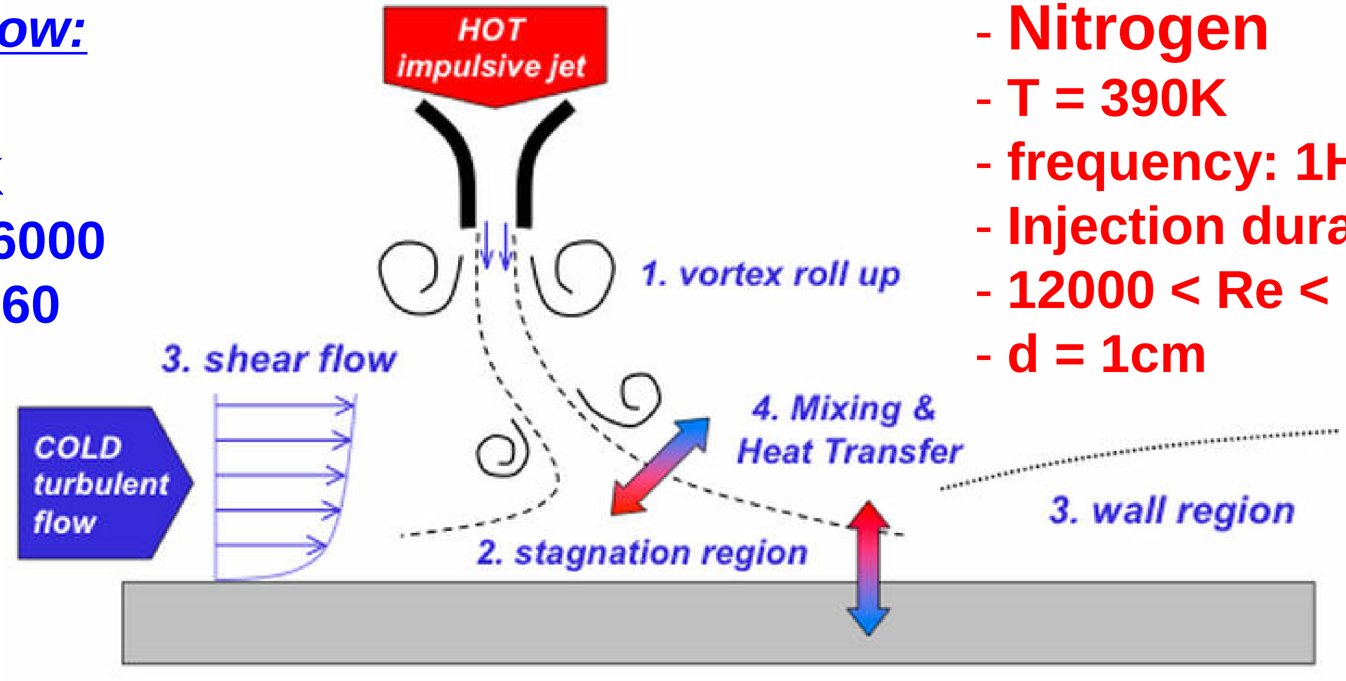
- Unsteady hot impinging jet in a cross flow

Pulsed Jet:

- **Nitrogen**
- **T = 390K**
- **frequency: 1Hz**
- **Injection duration 10 ms**
- **12000 < Re < 60000**
- **d = 1cm**

Cross flow:

- **Air**
- **T=300K**
- **$Re_{b,}$~ 16000**
- **Re_{τ} ~ 260**
- **h = 2d**

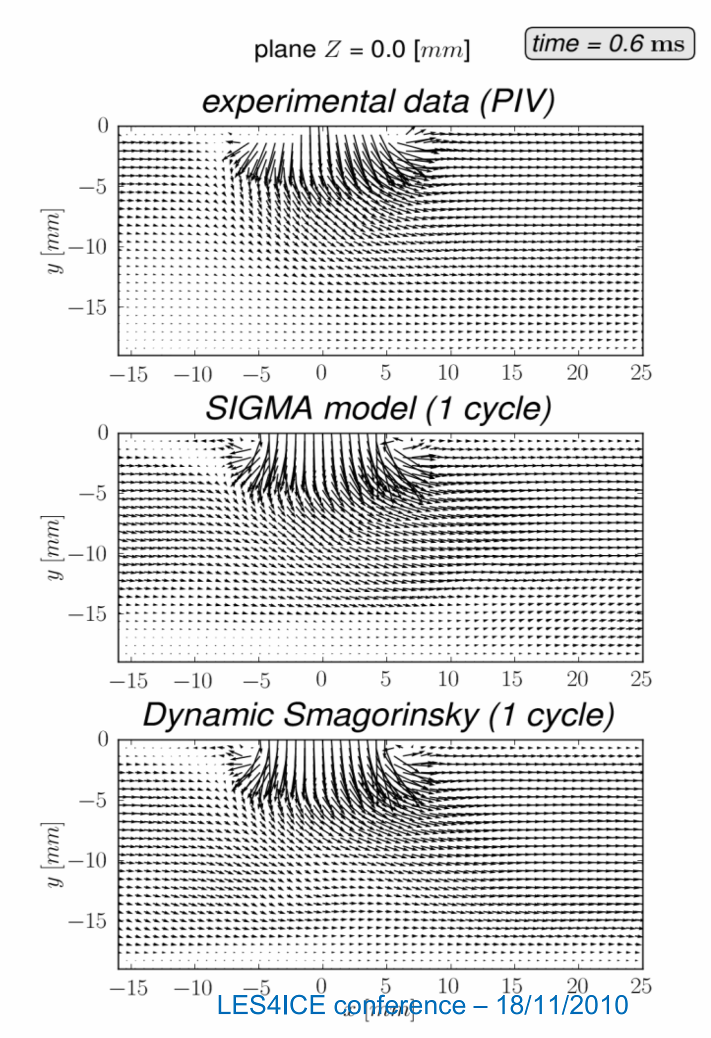


First comparisons PIV and CFD results

PIV

SIGMA

SMD

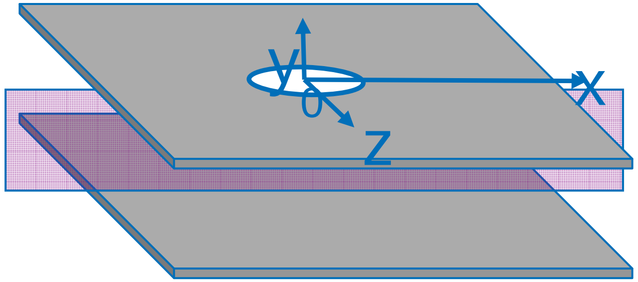


plane Z = 0.0 $[mm]$ time = 0.6 ms

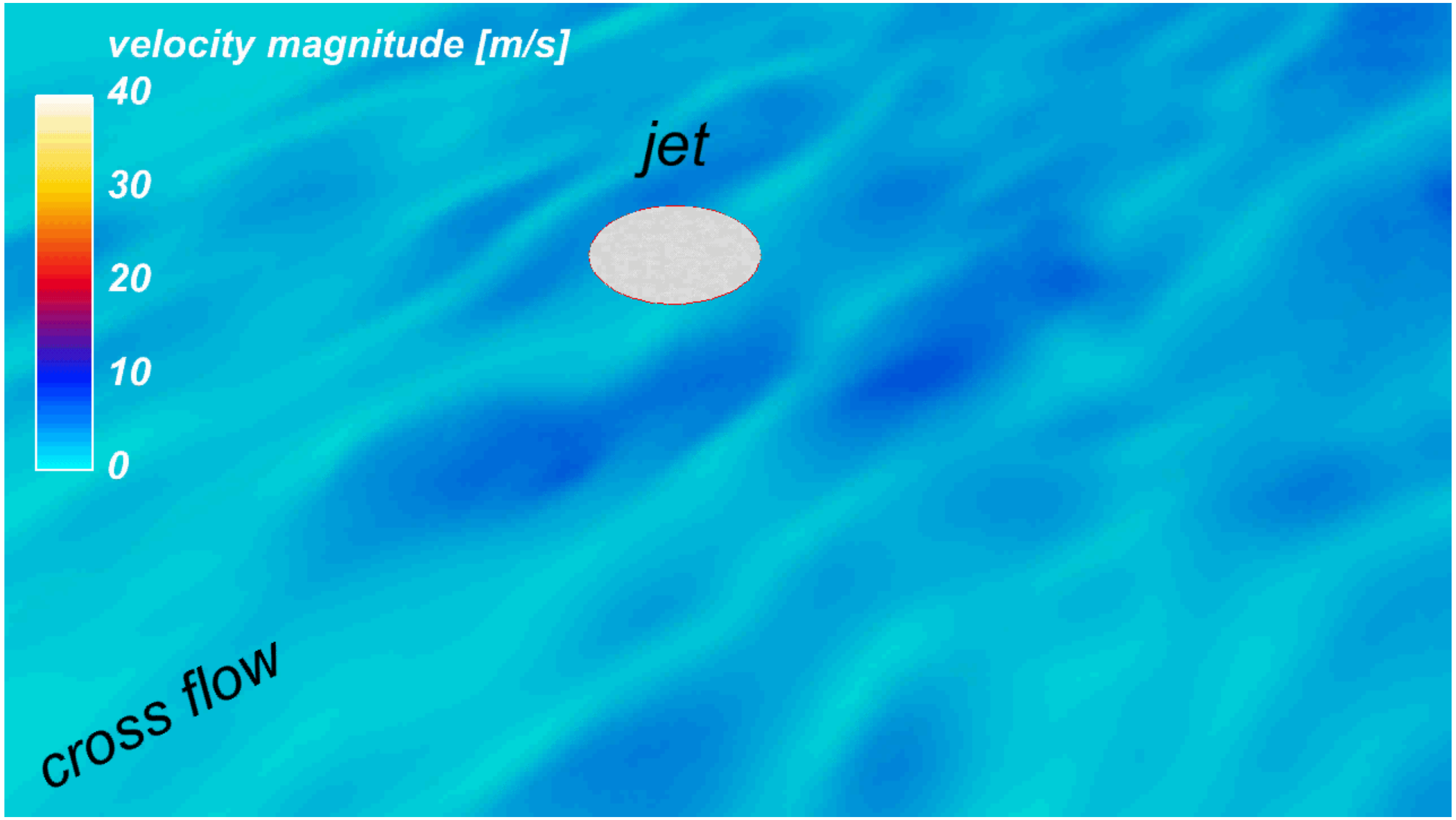
experimental data (PIV)

SIGMA model (1 cycle)

Dynamic Smagorinsky (1 cycle)



Proposal of an advanced test case (6/6)



Perpectives

- SGS conductivity based on the sigma operator
- LIF measurement on the experimental test case
  - Mixture (air-nitrogen) temperature measurement
- Advanced comparisons between the different SGS models (viscosity and conductivity) predictions and the PIV and LIF measurements
- Acknowledgments to :
  - Olivier Cabrit (Post-doc at Cerfacs)
  - G. Balarac (LEGI Grenobles)
  - Damien Peyresaubes (former IFP E.n.) and Jerome Cherel

Useful properties

g_{ij} is the velocity gradient tensor

pure shear

$$g_{ij} = \begin{pmatrix} 0 & \pm 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

solid rotation

$$g_{ij} = \begin{pmatrix} 0 & \pm 1 & 0 \\ \mp 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

isotropic contraction/dilatation

$$g_{ij} = \begin{pmatrix} \pm 1 & 0 & 0 \\ 0 & \pm 1 & 0 \\ 0 & 0 & \pm 1 \end{pmatrix}$$

axysimmetric contraction/dilatation

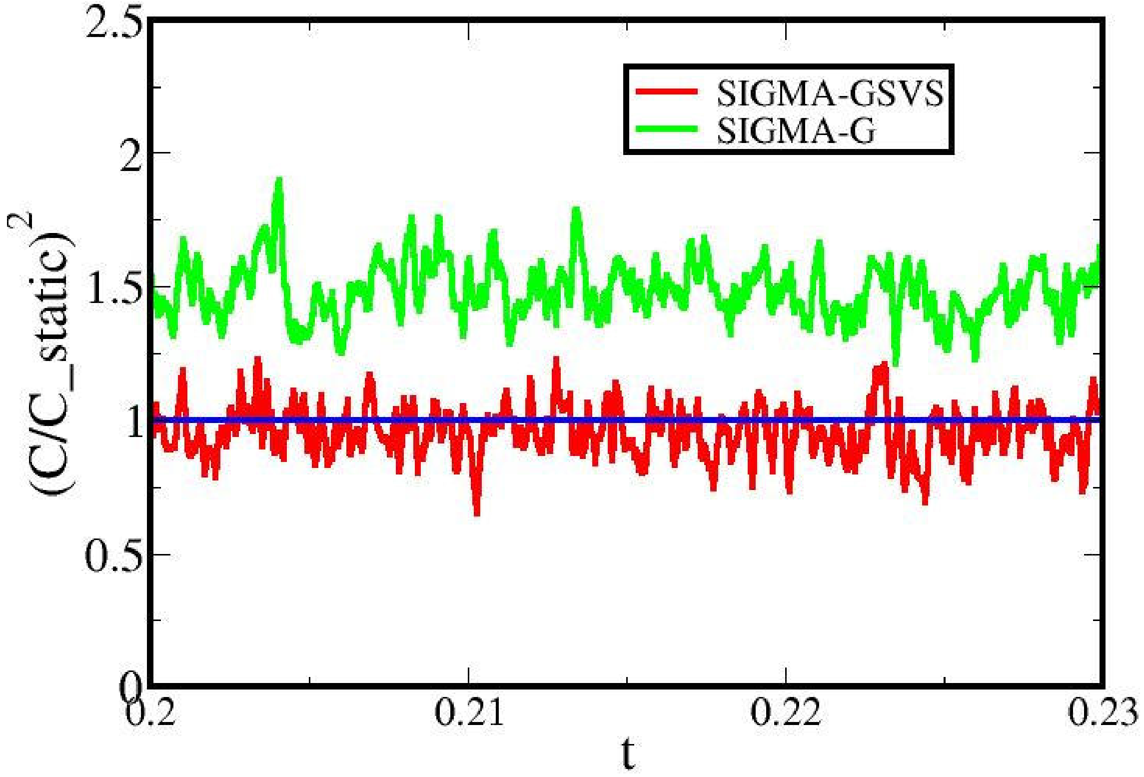
$$g_{ij} = \begin{pmatrix} \pm 2 & 0 & 0 \\ 0 & \mp 1 & 0 \\ 0 & 0 & \mp 1 \end{pmatrix}$$

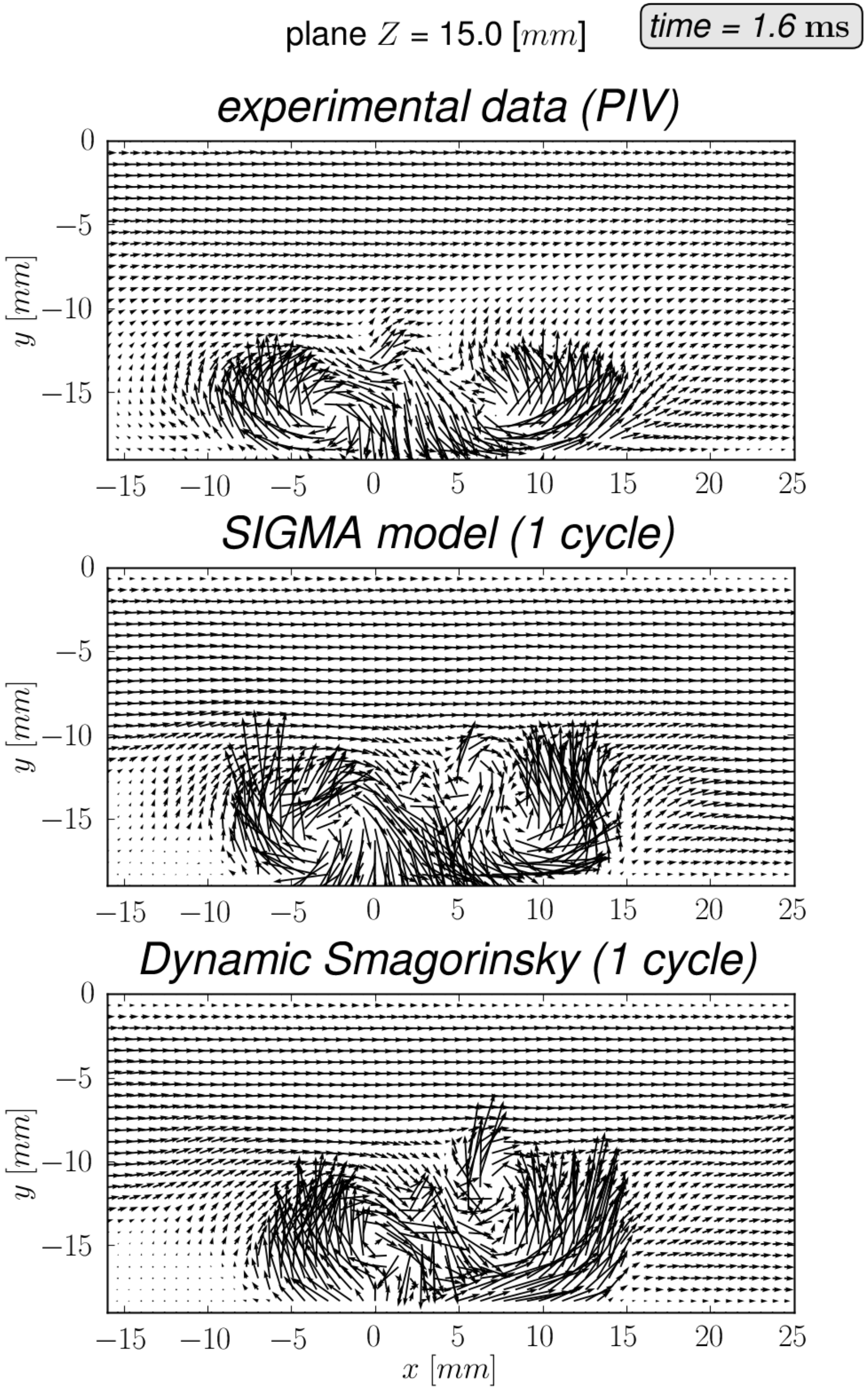
APPENDIX 1

- Characteristics of the periodic jet performed by G. Ballarac

APPENDIX 2

- Time evolution of the constants for the turbulent channel test case




plane Z = 15.0 $[mm]$
time = 1.6 ms
experimental data (PIV)
SIGMA model (1 cycle)
Dynamic Smagorinsky (1 cycle)
$y\ [mm]$
0
−5
−10
−15
−15
−10
−5
0
5
10
15
20
25
$x\ [mm]$

APPENDIX 4

- Characteristics of the computation of the JICF
  - Numerical scheme

    Lax-Wendroff :
  - Number of nodes
  - LES models

    Dynamic Smagorinsky and static Sigma