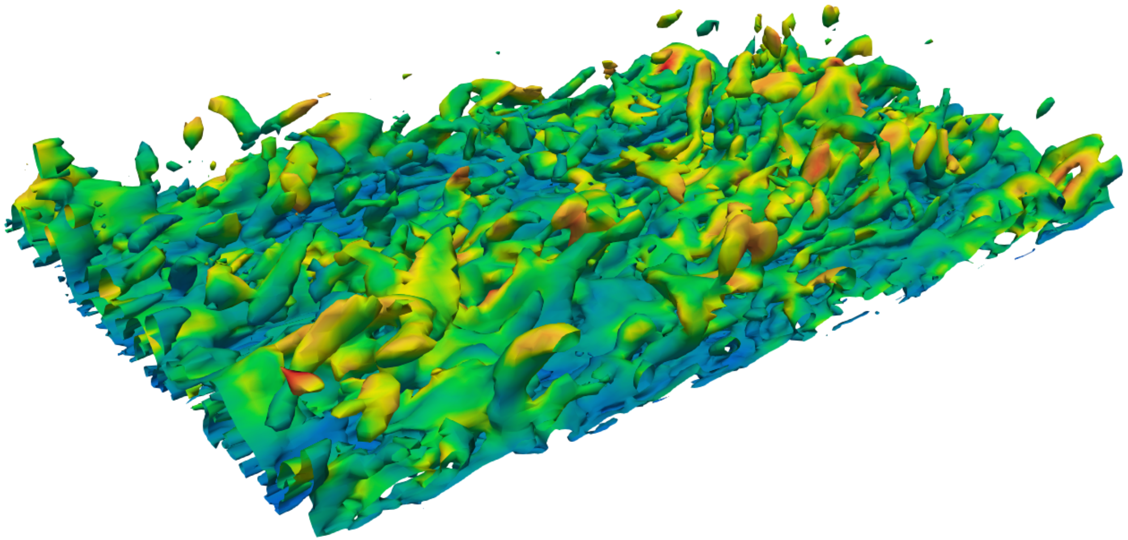
Turbulence models assessment using finite-volume and high-order methods for aeronautical applications

Bernat Font*, Fabio Naddei, Oriol Lehmkuhl



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Next generation of industrial aerodynamic simulation code
EuroHPC Joint Undertaking

Discretization methods, turbulence models, and mesh types, affect convergence

Spatial discretization methods:

- Finite Difference
- Finite Volume
- Finite Element
- Discontinuous Galerkin

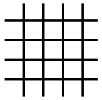
....

LES turbulence closures:

- Smagorinsky
- Dynamic Smagorinsky
- WALE (wall-adapting local eddy-viscosity)
- Vreman

...

Mesh



- There is no obvious choice to match discretization method and turbulence model.
- Turbulence models usually are case- (and mesh-) dependent too.

$$\tau_{ij}^a = -2\nu_{\mathrm{SFS}}\bar{S}_{ij}$$

$$\phi = \langle\phi\rangle + \phi'$$

The integral length scale approximation (ILSA) model

The filter width $\triangle$ depends on an estimated integral scale, and not on the local cell size.
The integral scale is calculated with temporal-averaged quantities.

$$\nu_{\mathrm{SFS}} = (C_k L_{\mathrm{est}})^2 \left|\bar{S}\right| \qquad \triangle = C_\triangle L_{\mathrm{est}} \qquad L_{\mathrm{est}} = \frac{\langle\mathcal{K}_{\mathrm{res}}\rangle^{3/2}}{\langle\varepsilon_{\mathrm{tot}}\rangle}$$

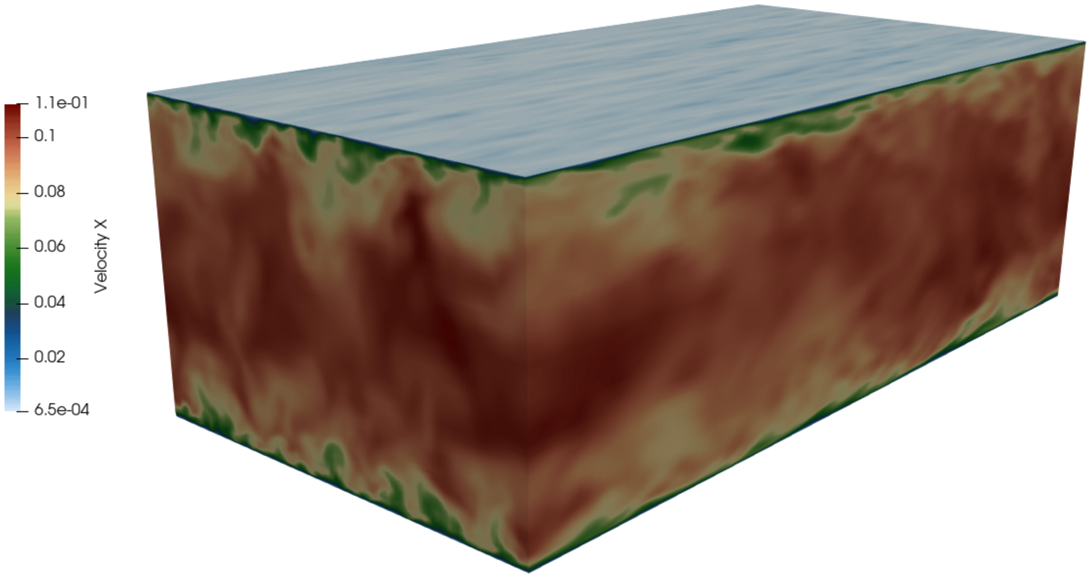
C_k is determined via s_τ, ILSA's single parameter which encapsulates the amount of turbulent kinetic energy aimed to be modelled.

$$s_\tau = \left[\frac{\langle\tau_{ij}^a\tau_{ij}^a\rangle}{\langle(\tau_{mn}^a + R_{mn}^a)(\tau_{mn}^a + R_{mn}^a)\rangle}\right]^{1/2} \qquad \mathcal{X}_1[1-(1/s_\tau)^2]C_k^4 - \mathcal{X}_2 C_k^2 + \mathcal{X}_3 = 0$$

- Because mesh independence, ILSA yields grid converged results for a range of s_τ .
- Suitable for h-adaptivity, and p-adaptivity in high-order methods.

1. A. Rouhi, and U. Piomelli, 2016. Phys. Rev. Fluids 1, 044401.
2. O. Lehmkuhl, U Piomelli, and G Houzeaux, 2019. Int. J. Heat and Fluid Flow.

Turbulent channel flow at $Re_\tau = 950$



Geometry: $6h \times 2h \times 3h$

$Ma = 0.08$

BC: Top & bottom walls: no-slip.
Others: periodic.

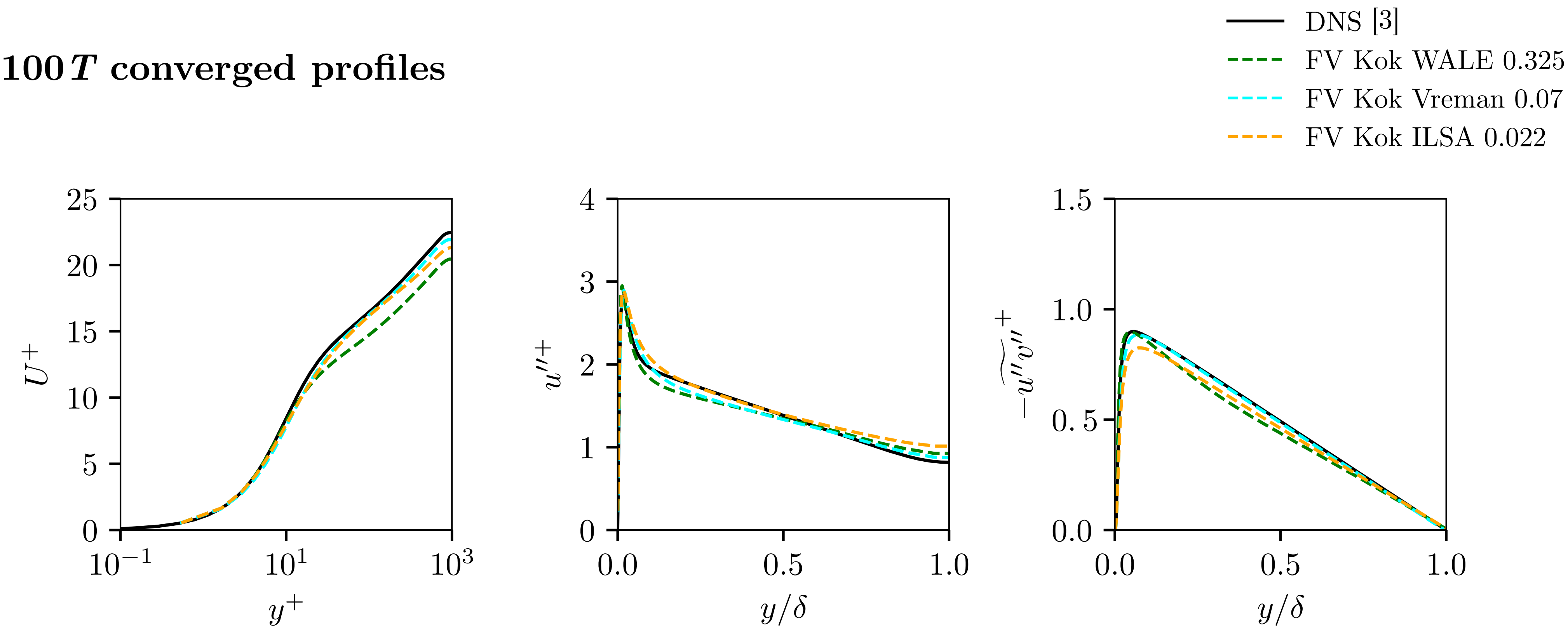
IC: Perturbed analytical solution.

Statistics averaged for $100\,T$.

Mesh: $96 \times 98 \times 96$
$y^+ = 1$

Numerical methods: **Finite volume**, Kok convective scheme, Runge-Kutta 4th order.

$100\,T$ converged profiles

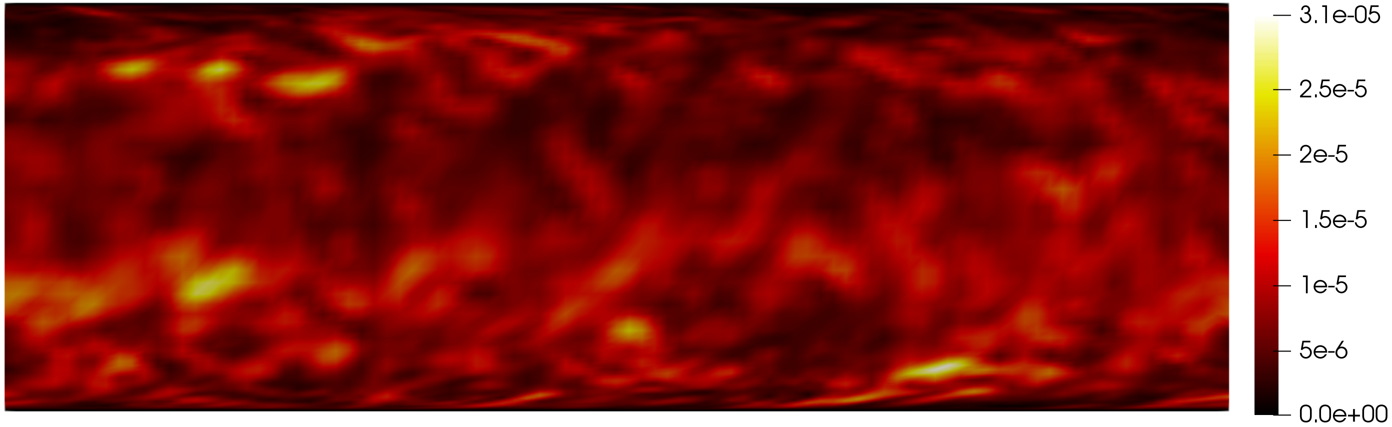


- All models have been tested with their default constants.
- ILSA and Vreman models yield similar results, while WALE displays a larger discrepancy.

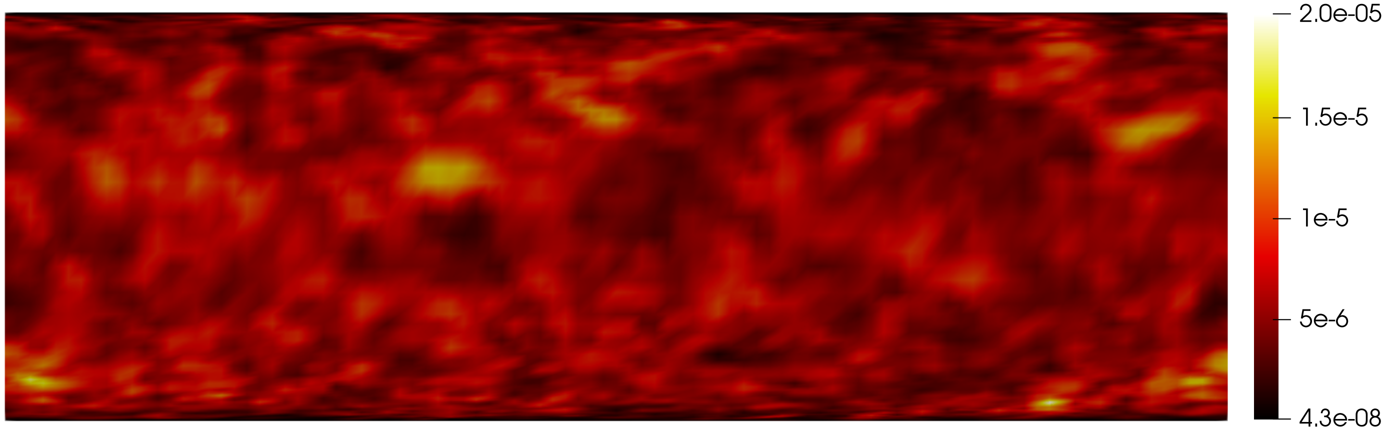
3. Hoyas & Jimenez, 2008. Phys. Fluids 20, 101511

The ILSA SGS viscosity follows physical structures despicte mesh anisotropy

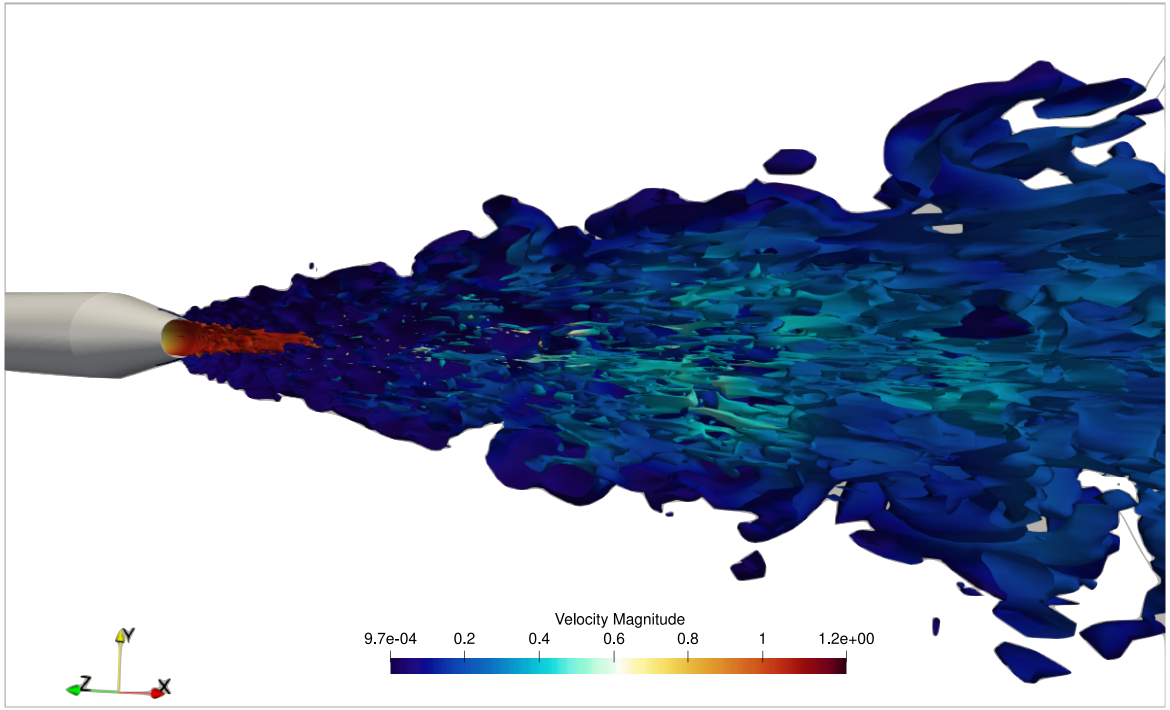
ILSA
$s_\tau = 0.022$



Vreman
$c \approx 2.5C_s^2 = 0.07$



Jet exhaust aerodynamics and noise (JEAN)* test case



Case kindly provided by Dr. S. Pezzano @ CERFACS

$Re = 10^6$

$Ma = 0.9$

IC: RANS-SA using FV + p staging

Mesh: 138M DOFs (2.1M Hex64)

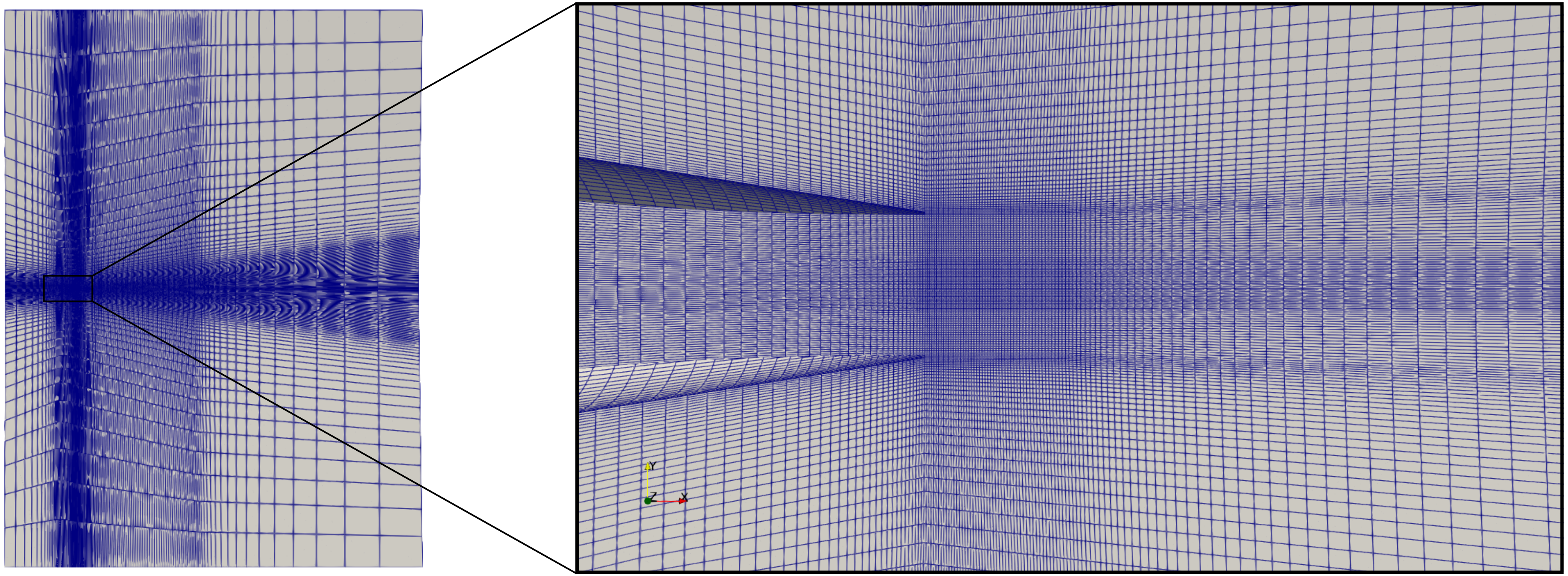
Numerical methods:

Discontinuous Galerkin spectral element method (**DGSEM**) with p=3

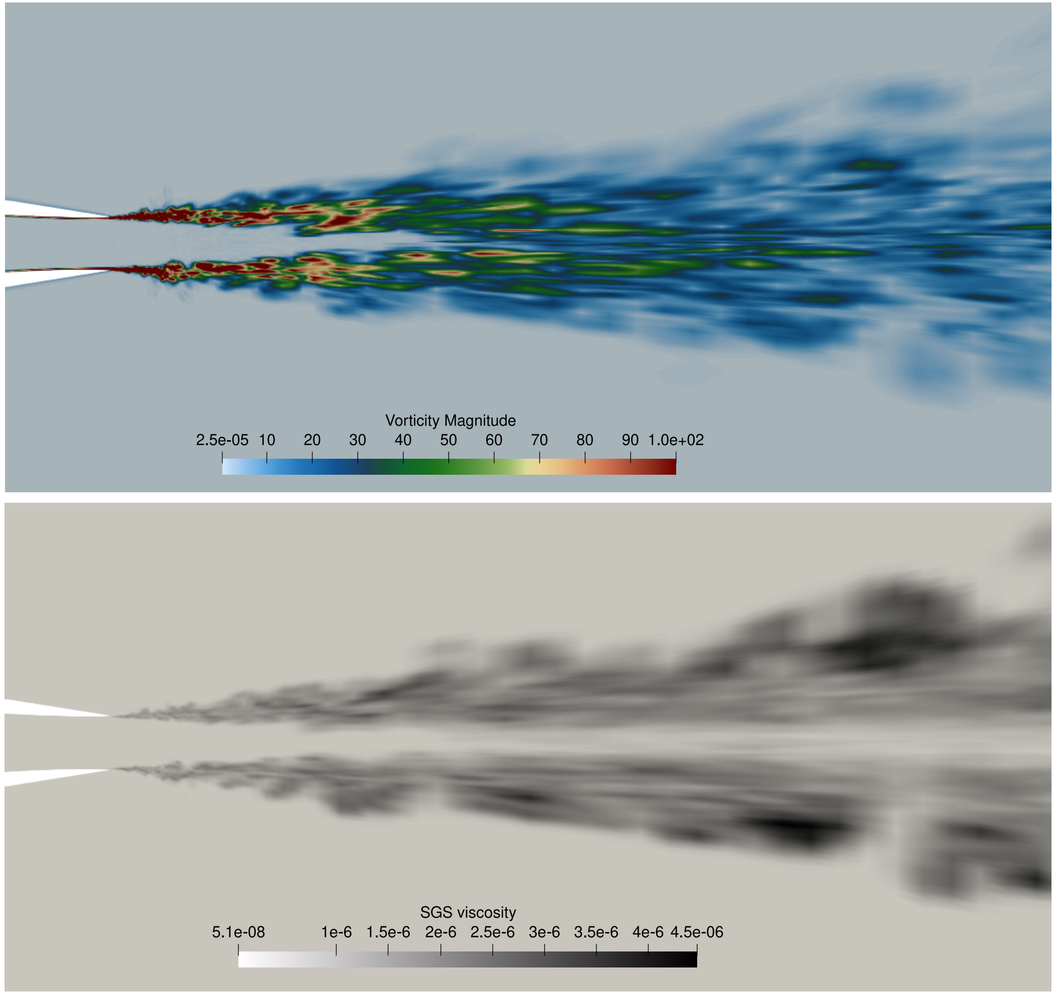
SLAU2 convective scheme
Runge-Kutta 3rd order time scheme

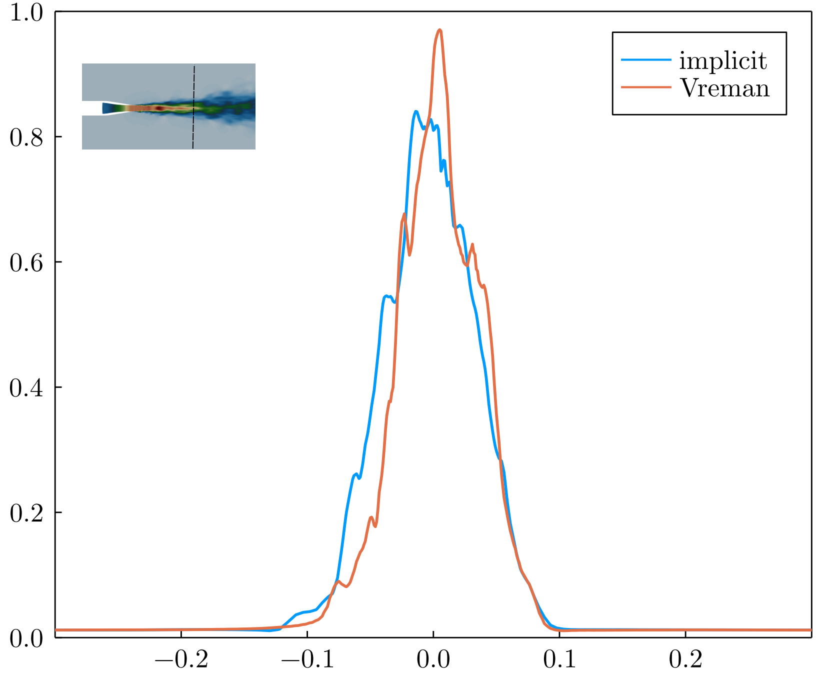
* https://cordis.europa.eu/project/id/G4RD-CT-2000-00313

A highly anisotropic mesh can be challenging for turbulence models



The Vreman model is desactivated in the center of the channel





Summary

Channel test case

- The WALE, Vreman, and ILSA LES models have been assessed.
- Vreman and ILSA achieved better results than WALE.
- The ILSA eddy viscosity follows the flow structures, contrary to the WALE model.

JEAN nozzle test case

- The Vreman model has been compared with an implicit LES solution.
- The Vreman model gets desactivated at the centerline of the jet in the downstream region because of the highly anisotropic mesh.
- The jet profile appears more accelerated when using the Vreman model in comparison with iLES.

Future work

- Run the chan test case with the ILSA model.
- Run the JEAN test case with the ILSA model.

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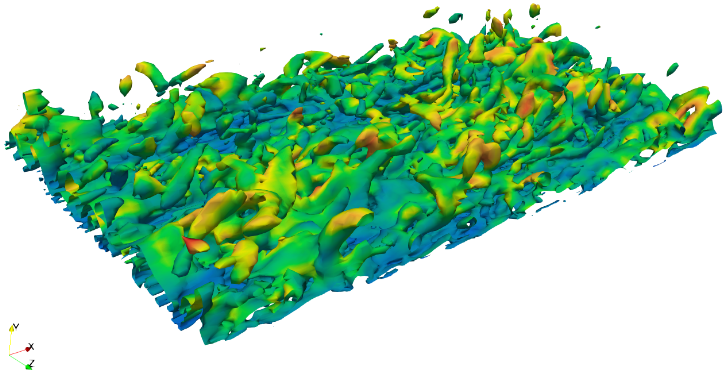

Thanks!

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