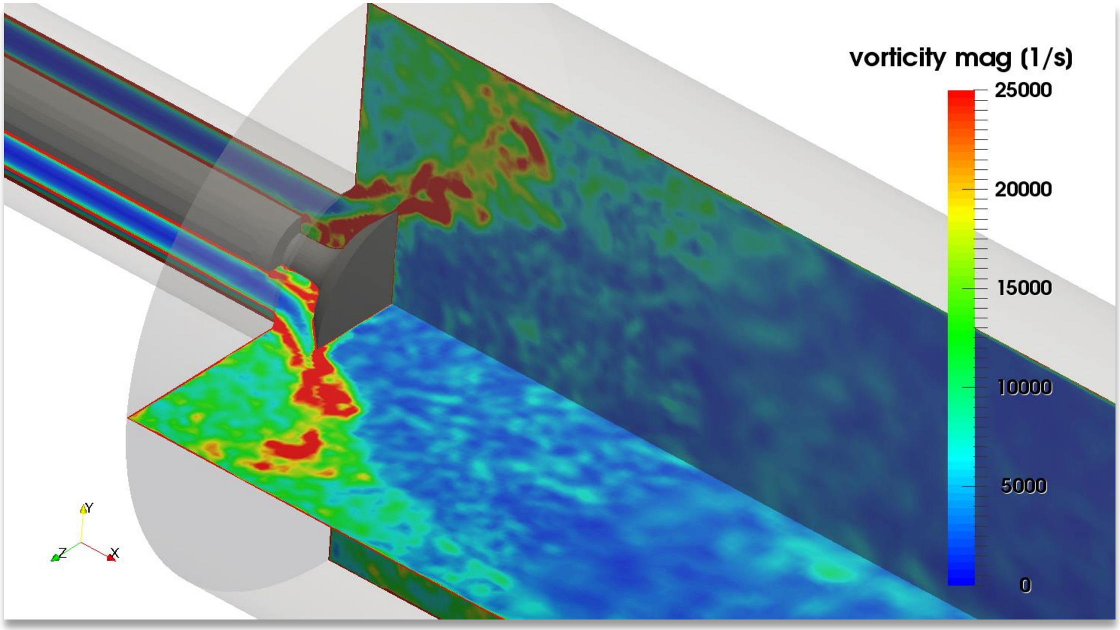
"DES Turbulence Modeling for ICE Flow Simulation in OpenFOAM®"



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OUTLINE

- ✓ <u>**Motivations**</u>
- ✓ Modeling
- ✓ Implementation/calibration
- ✓ Engine-like flow benchmarks
- ✓ Further developments
- ✓ Conclusions

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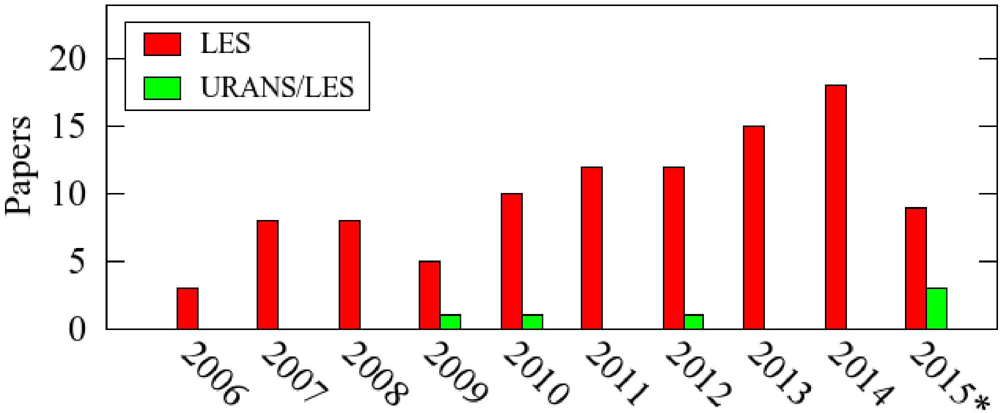
Why DES turbulence modeling?



Per-year number of published papers with relevant LES and URANS/LES ICE flow applications (source: www.scopus.com)
****Year 2015 data are provisional***

- **Increased popularity** of scale-resolving simulation methods
- Standard LES modeling allows to capture unsteady features such as **cycle-to-cycle variability**, but…

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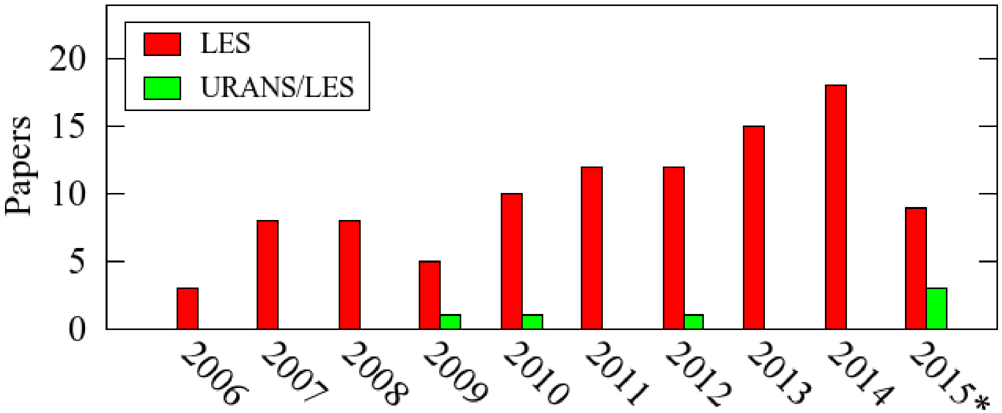

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- ❑**…time steps are much smaller** compared to URANS (even on realtively coarse grids)
- ❑**…multiple simulated cycles** are needed to extract reliable flow statistics

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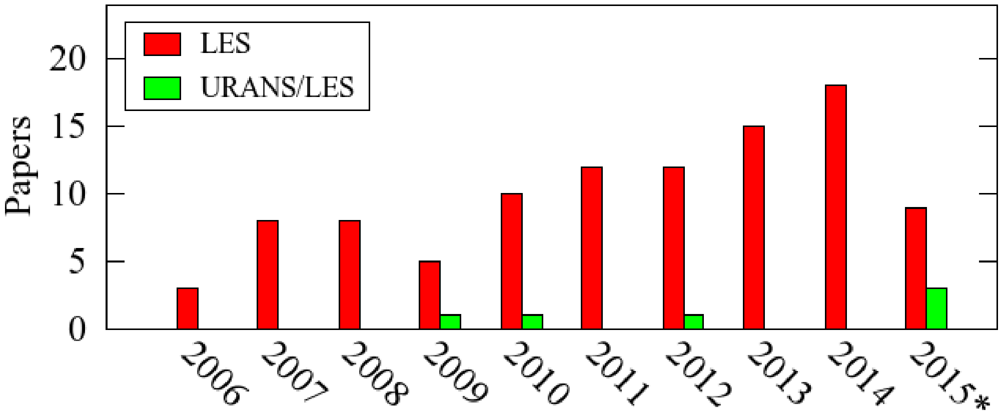

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A very large amount of cpu time required for a single cylinder flow characterization (unless some level of compromise is accepted)

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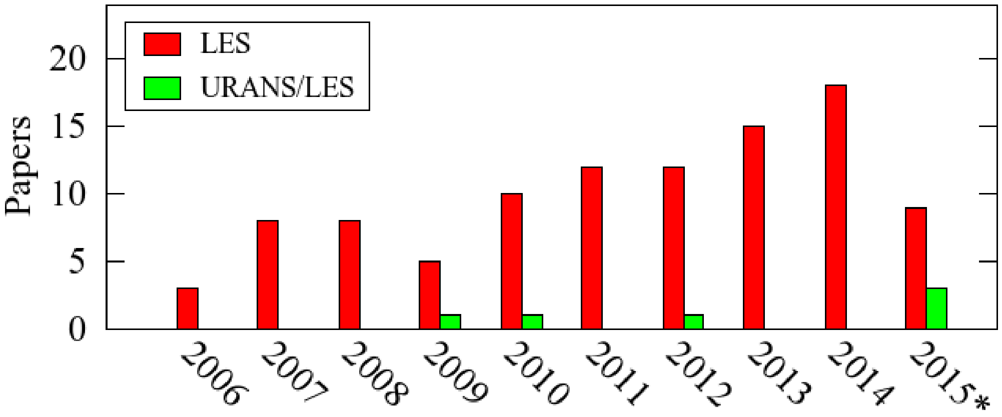

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- ❑**Hybrid URANS/LES methods** can be considered to mitigate some of the issues related to LES

- ❑**Detached Eddy Simulation (DES)** is the most mature hybrid technique, but**…**

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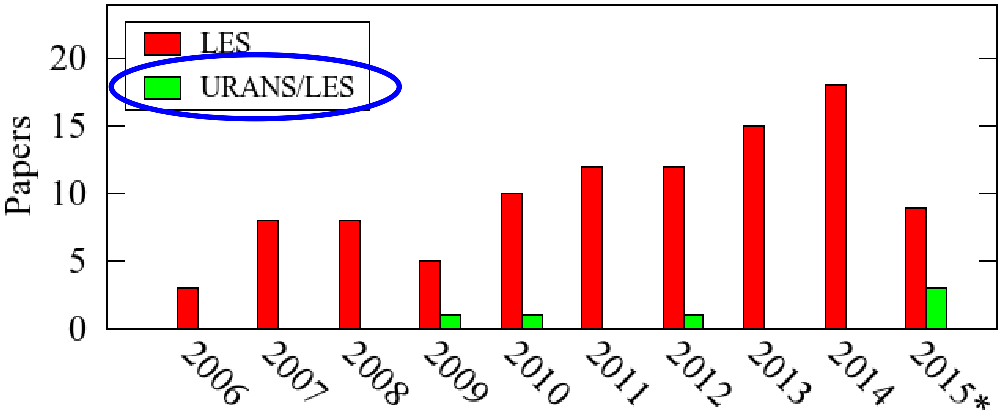

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- **Detached Eddy Simulation (DES)** is the most mature hybrid technique, but**…**
- **…**still **relatively unexplored** for ICE flow applications

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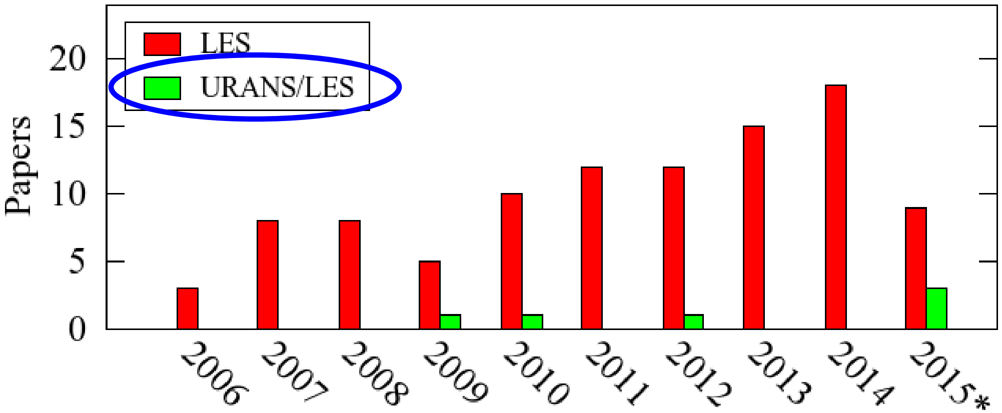

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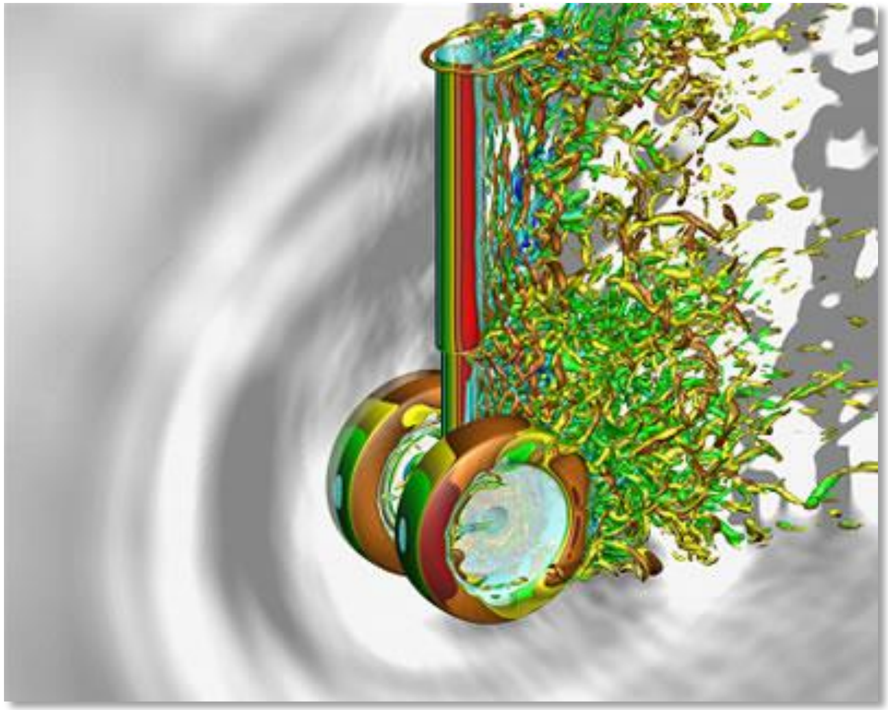
- ❑ **…**still **relatively unexplored** for ICE flow applications

❑ *Goals of our work:*

- ❖ ***Development of a two-equation DES turbulence simulation method for ICE-like flow predictions***
- ❖ ***Initial validation of the proposed methodology on well established flow benchmarks***
- ❖ ***Detection of improvement areas (based on the initial results)***

The DES principle



❑Steady, **attached zones** of the flow efficiently **simulated by RANS**

❑**LES triggering** in massive separation, by **length scales switching** in the eddy viscosity destruction mechanism (**from modeled to grid-dependent**)

❑All seamlessly managed by a **single modeling framework (RANS-based)**

❑Very good accuracy in massively separated external flows

❑Can be less efficient in internal complex flows (**validation/development needed**)

Starting point: improved RANS k-g model

Main features:

- Originally derived from the k-ω by **Kalitzin et al. (1996);** the ω-equation is reformulated in terms of the root-squared turbulent time scale g ($g = \sqrt{k/\varepsilon} = 1/\sqrt{\beta^* \omega}$).

- Straightforward wall bc (**g→0**) and linear near-wall scaling (**g~y$_n$**).

- **Modified by the authors including realizability constraints for the turbulent time scale τ**

Equations:

$$\frac{\partial (u_i g)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\nu + \frac{\nu_t}{\sigma_g}\right)\frac{\partial g}{\partial x_i}\right] - \frac{\alpha g^3}{2k\tau} P_k + \frac{\beta g}{2\beta^* \tau} - \left(\nu + \frac{\nu_t}{\sigma_g}\right)\frac{3g}{\tau}\left(\frac{\partial g}{\partial x_i}\frac{\partial g}{\partial x_i}\right) \quad (1)$$

$$\frac{\partial (u_i k)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + P_k - \frac{k}{\tau} \quad (2)$$

$$\nu_t = \beta^* k \tau \quad (3)$$

$$\tau = \min\left(g^2, \frac{a}{\beta^* \sqrt{6|S|^2}}\right) \quad ; \quad a \le 1 \quad (4)$$

DES reformulation

Basis:

❑Strelets (2001) showed that a two-equation model can be reduced to a DES model by implementing a “grid sensitive” length scale in the destruction term of the k-equation

Destruction term modification

$$\frac{\partial (u_i k)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + P_k - D$$

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- **The same approach has been followed in the present work**

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$$D_{RANS} = \frac{k^{3/2}}{l_{RANS}}; \quad l_{RANS} = k^{1/2} \cdot \tau$$

$$D_{DES} = \frac{k^{3/2}}{l_{DES}}; \quad l_{DES} = min\left(l_{RANS}, \quad C_{DES} \cdot \Delta\right)$$

$$\begin{cases} \Delta = f(grid) \\ C_{DES} = \mathcal{O}(1) \end{cases}$$

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Destruction term modification (2)

$$\frac{\partial (u_i k)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + P_k - D$$

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$$D_{DES} = F_{DES} \cdot D_{RANS}$$

$$F_{DES} = \max\left(l_{RANS} / (C_{DES} \cdot \Delta), \quad 1\right)$$

Final form

Application of the DDES concept

The concept:

- Avoid Modeled Stress Depletion (MSD) in grids with **ambiguous near-wall spacing** (*$C_{DES}\cdot\Delta$ < BL thickness*)

- Spalart et. al (2006) proposed the use of a **"delaying function"** to force the extention of the pure RANS region towards BL's outer edge

- **Adaptation of the delaying function** to the present formulation

DDES form of the destruction term:

$$D_{DDES} = F_{DDES} \cdot D_{RANS}$$

$$F_{DDES} = \max\left\{\phi_d\left[l_{RANS}/\left(C_{DES}\cdot\Delta\right)\right],\ 1\right\}$$

Final form (DDES)

$$\phi_d = 1 - \tanh\left[\left(k_d \cdot r_d\right)^3\right]$$

k_d = constant

r_d = function of flow quantities and wall distance

$$\phi_d \to 0 \ ; \ F_{DDES} \to 1$$ ***Forced RANS mode***

Overview

Why OpenFOAM® ?

- ❑**Open source** unstructured finite volume computational framework
- ❑**Hexa-dominant** automatic mesher (**SHM**) with **local volumetric refinement**

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Potentially attractive for hybrid RANS/LES

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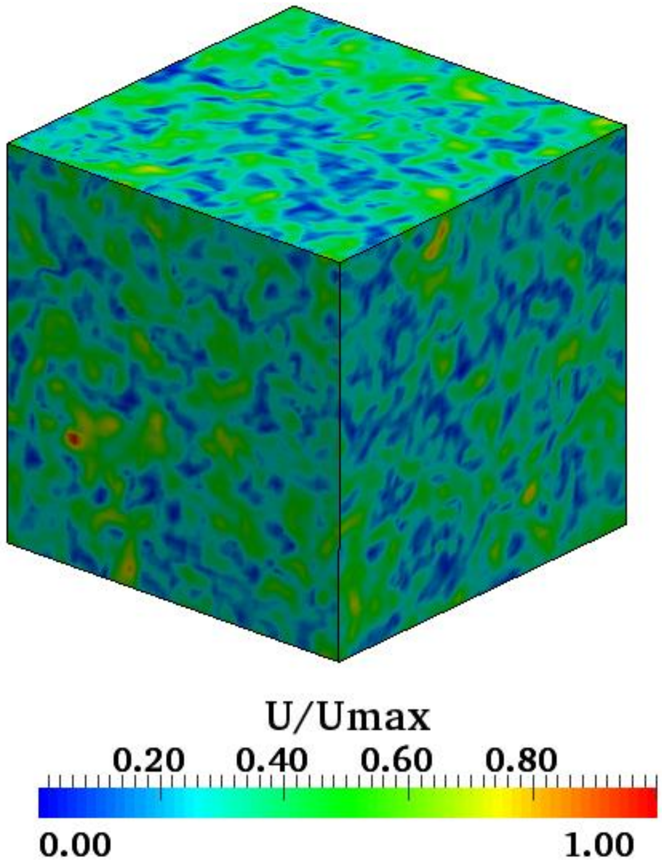
Potentially attractive for hybrid RANS/LES

Methodology calibration:

1. Numerical schemes choice
   - **Focus on convective transport in LES mode**

2. C_{DES} constant calibration
   - Checking model's consistency in LES mode ($l_{DES} \equiv C_{DES} \cdot \Delta$)
   - **Focus on the C_{DES} constant calibration**

Turbulence box: momentum convection schemes



- Standart test for DNS and SGS models
- Cubic domain with cyclic BCs in each direction; spatial discretization obtained with N^3 perfectly cubic cells (N=64)
- Flow field initialized with an incompressible divergence-free turbulent spectrum

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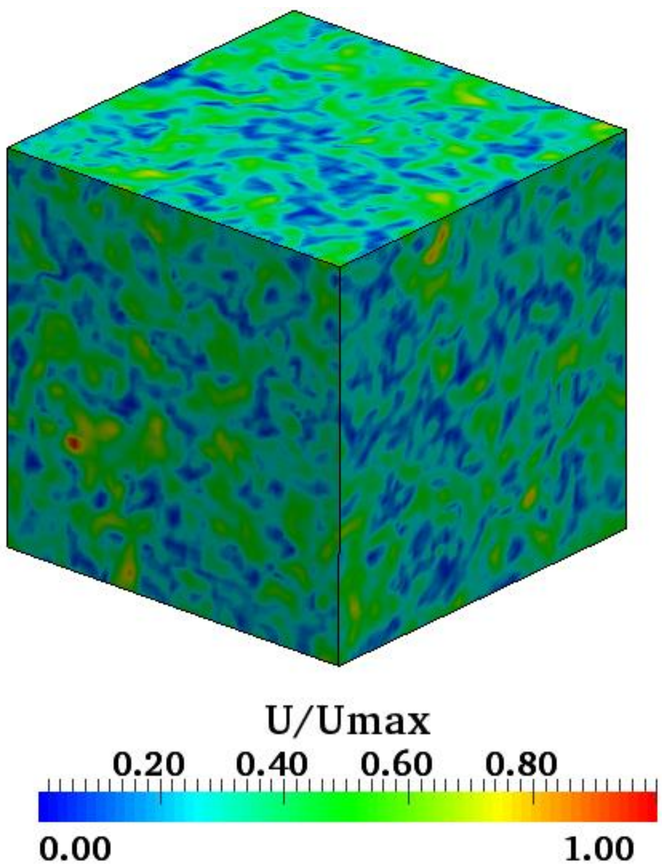
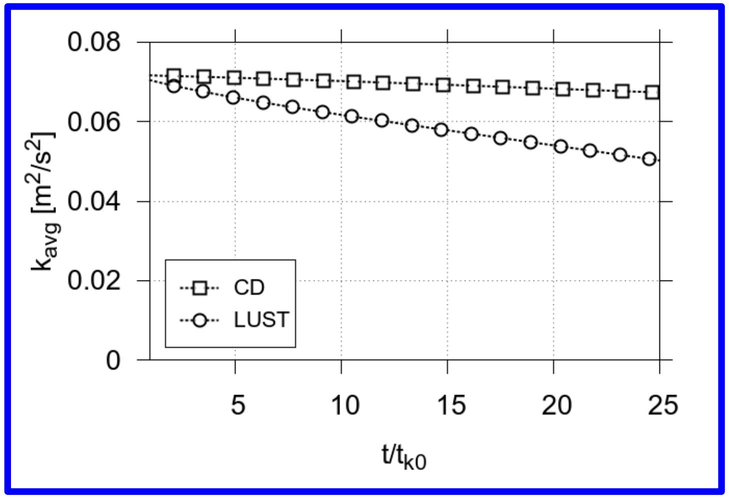
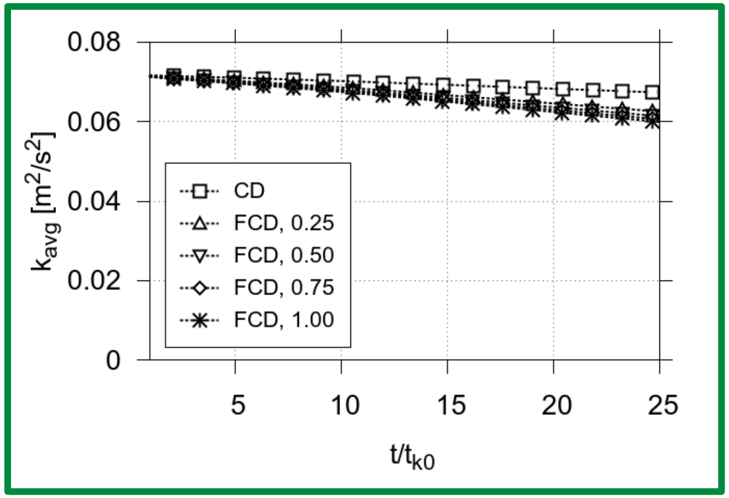


- Standart test for DNS and SGS models
- Cubic domain with cyclic BCs in each direction; spatial discretization obtained with N^3 perfectly cubic cells (N=64)
- Flow field initialized with an incompressible divergence-free turbulent spectrum
- To evaluate **convection schemes**, Euler equations are solved (**zero-viscosity, no SGS modeling**)
- **Three alternatives considered:**
  1. **Central Differencing (CD)**
  2. **Linear Upwind Stabilized Transport (LUST)**
  3. **Filtered Central Differencing (FCD)**

Turbulence box: momentum convection schemes





- Volume-averaged kinetic energy of the flow monitored through time
- **LUST is highly dissipative compared to CD**
- **FCD is in between, the amount of dissipation depending on the filtering parameter** $0<\varphi<1$

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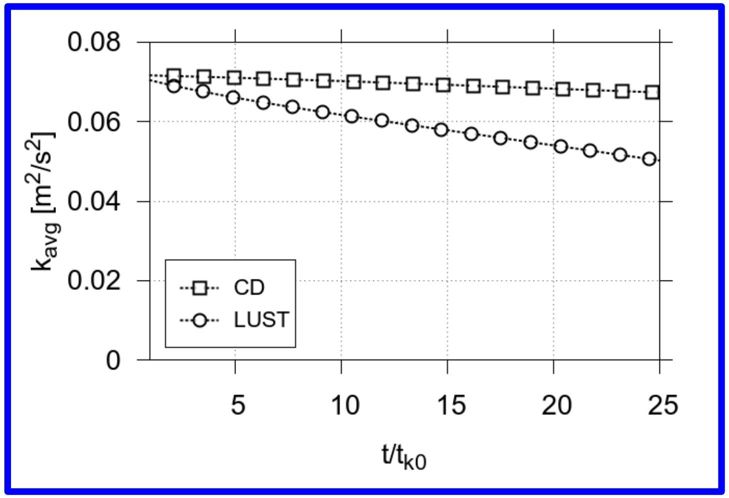

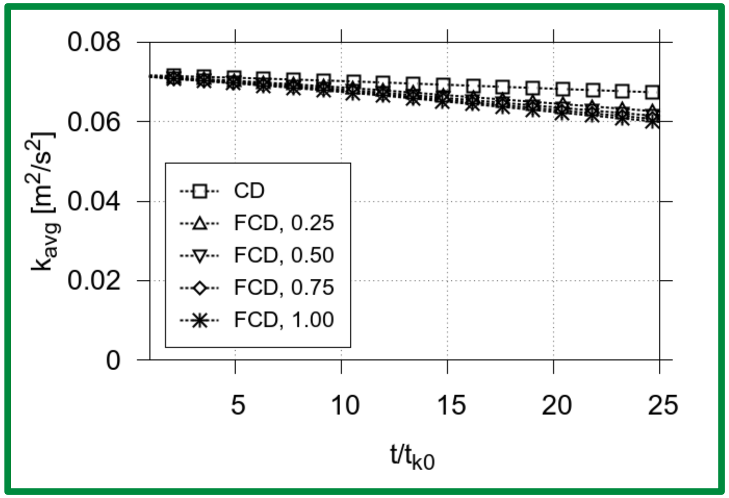

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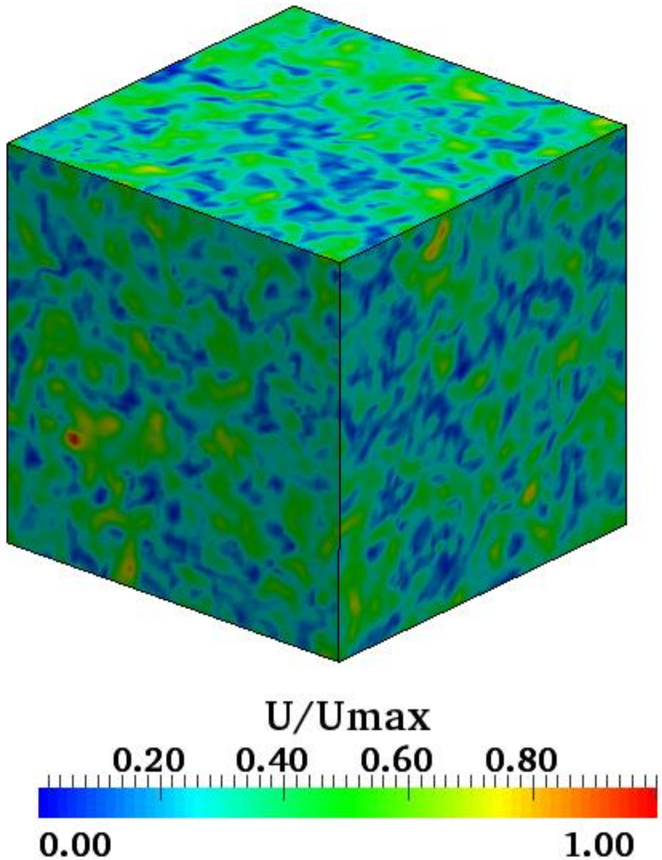
FCD with $\varphi = 0.25$ chosen as a compromise between energy conservation and stability

Turbulence box: C_{DES} calibration



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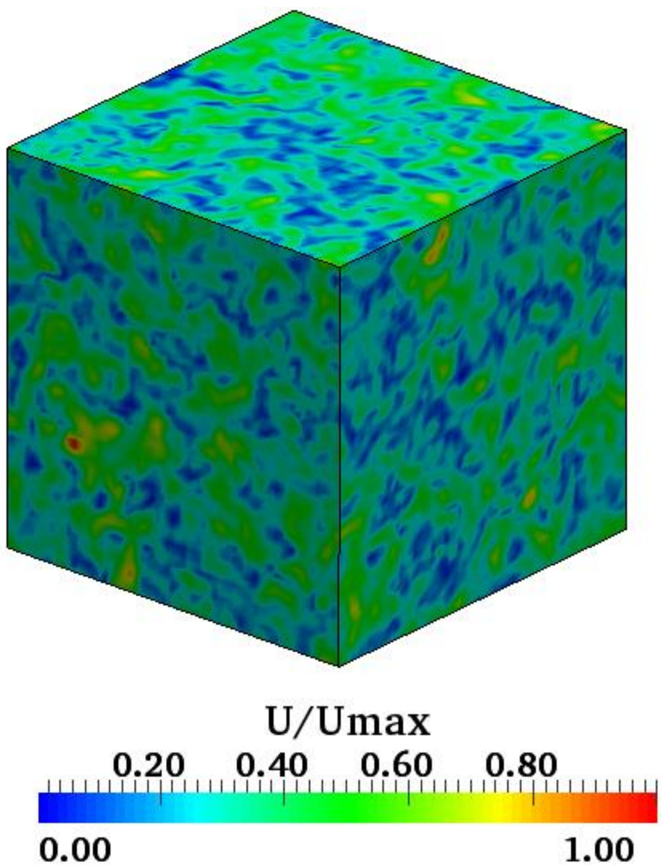
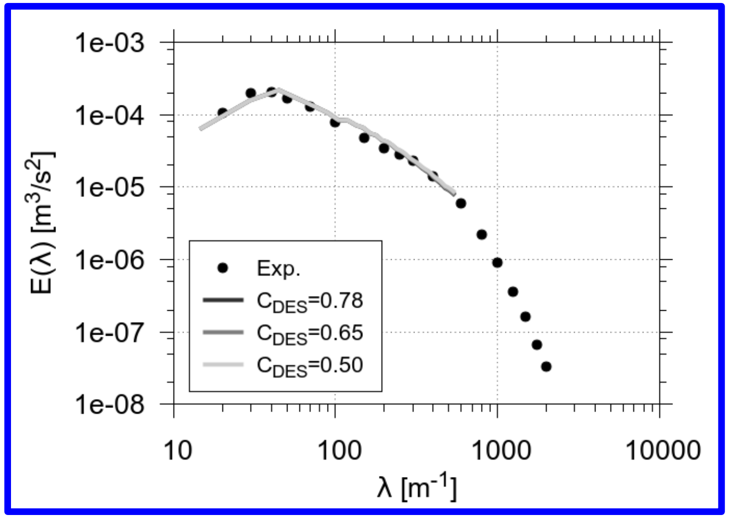
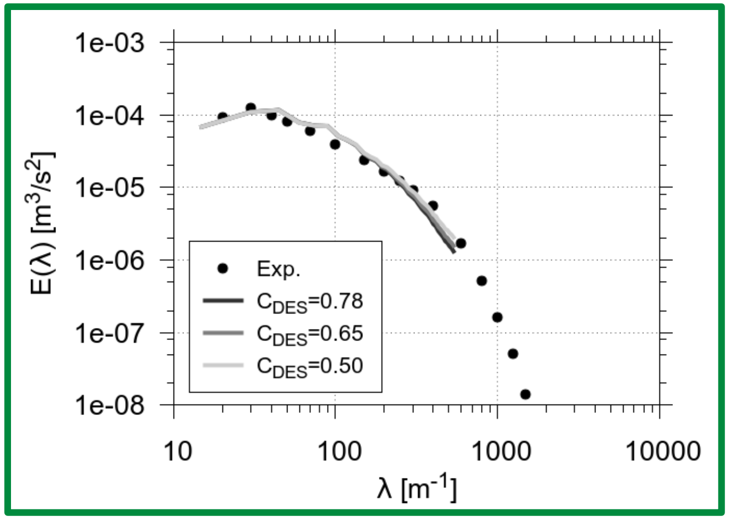


- Standart test for DNS and SGS models
- Cubic domain with cyclic BCs in each direction; spatial discretization obtained with N^3 perfectly cubic cells (N=64)
- Flow field initialized with an incompressible divergence-free turbulent spectrum
- Turbulence is left to **spontaneously decay** driven by the k-g pure LES model ($l_{DES} \equiv C_{DES} \cdot \Delta$)
- C_{DES} is decreased, starting from C_{DES} = 0.78 (k-ω SST DES standard value)
- **Energy spectra** evaluated at different simulation times

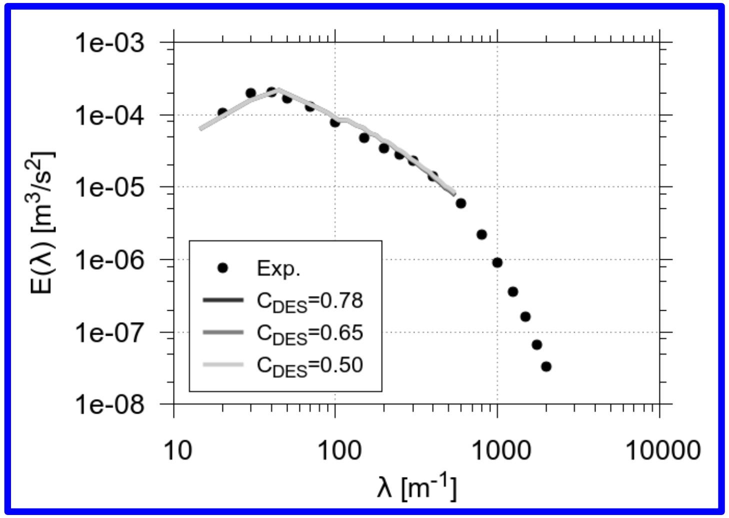
Turbulence box: C_{DES} calibration

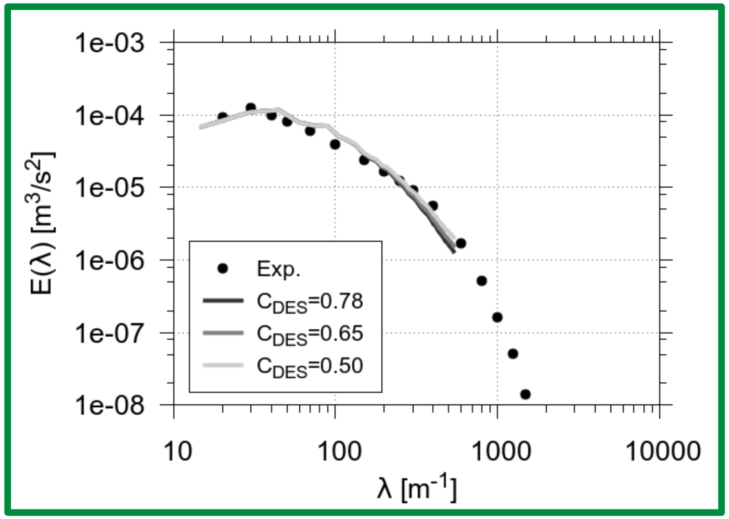




- 3D spectra compared to Comte-Bellot and Corrsin's experimental data
- **FCD 0.25** set for momentum convection, bounded NVD scheme for k and g
- **The initial energy decay is well described by the k-g LES model, regarldess of C_{DES}**
- **For longer decaying times C_{DES} = 0.5 is the best-matching option**

Turbulence box: C_{DES} calibration





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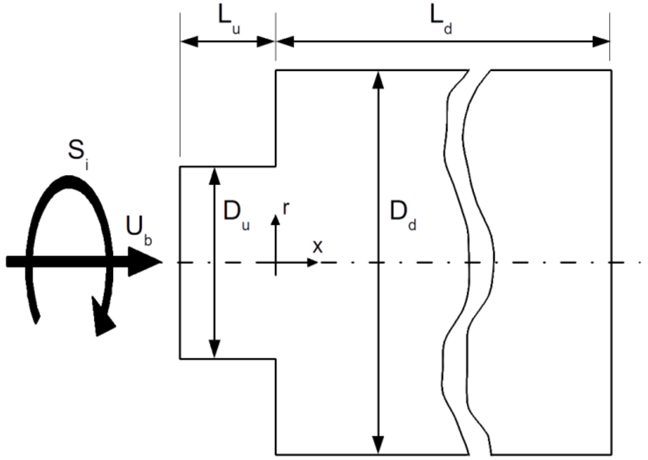
C_{DES} = 0.5 chosen as baseline value

Axisymmetric sudden expansion



Preliminary remarks (1):

- Sudden circular flow expansion with/without imposed swirling motion at the inlet (**Dellenback et al., 1988**)
- Two cases studied (**S_i = 0 and S_i = 0.6**), inlet bulk Reynolds number **$Re_b \approx 3 \cdot 10^4$**

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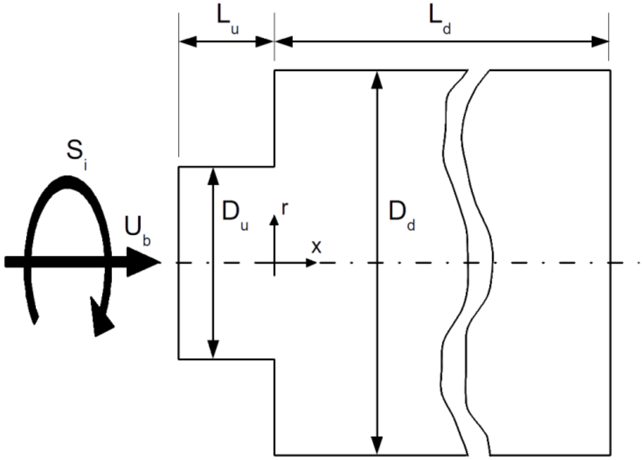

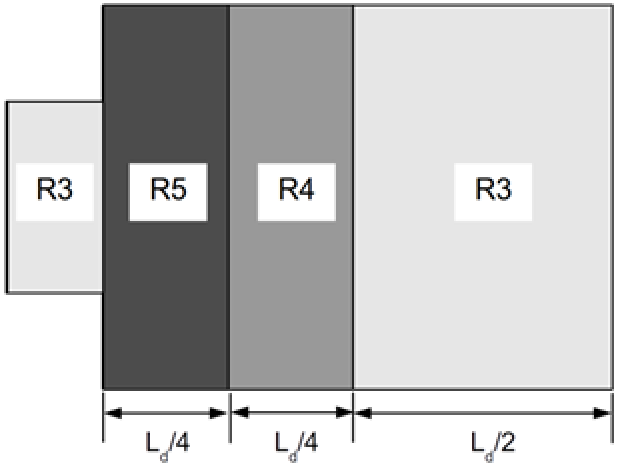

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- Unstructured hexa-dominant grid (**$5.78 \cdot 10^5$ cells**) with ad-hoc cell density distribution (**R0 = D_u, R5 = $D_u/2^5$**)

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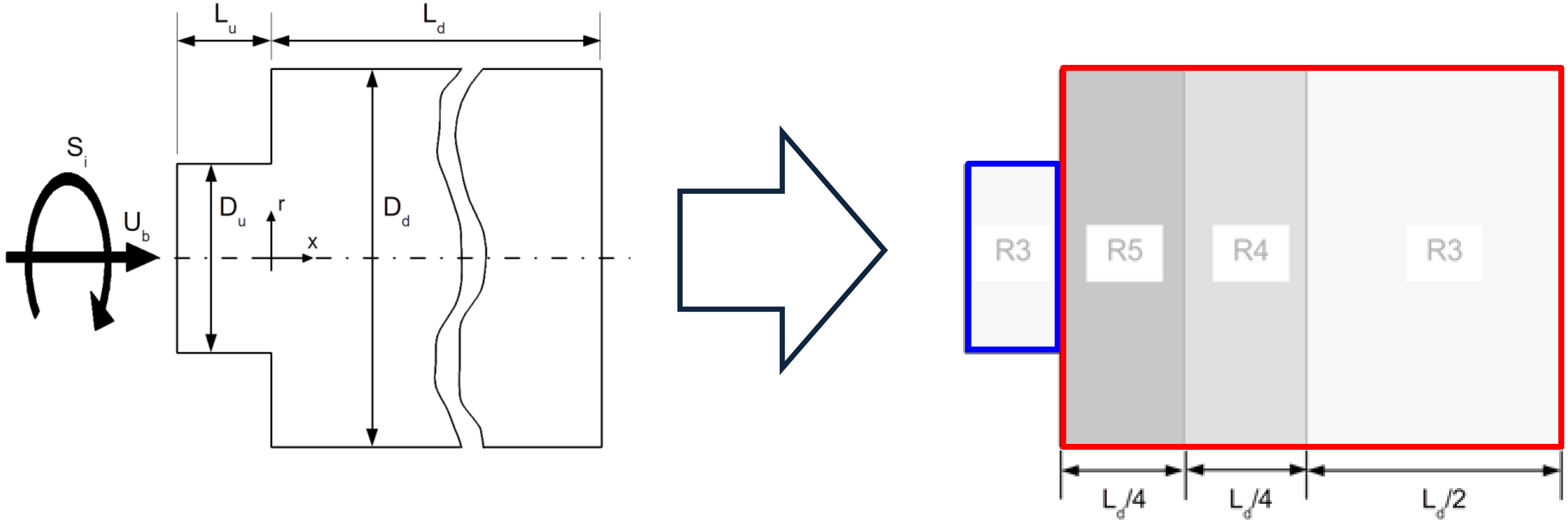
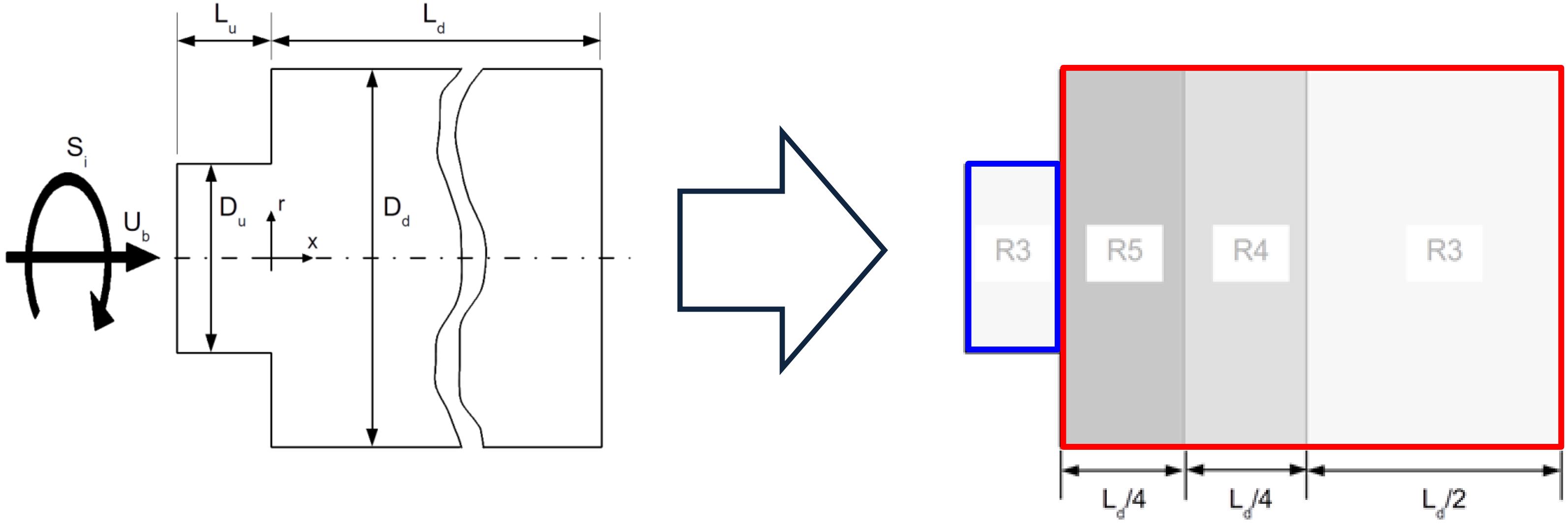


Preliminary remarks (2):

❑**Zonal numerical treatment** for momentum convection in DDES:

- **Linear Upwind (LU) scheme in the steady, attached upstream region**
- **FCD 0.25 in the separated flow region (implicit promotion of RANS/LES triggering)**

Axisymmetric sudden expansion



Preliminary remarks (3):

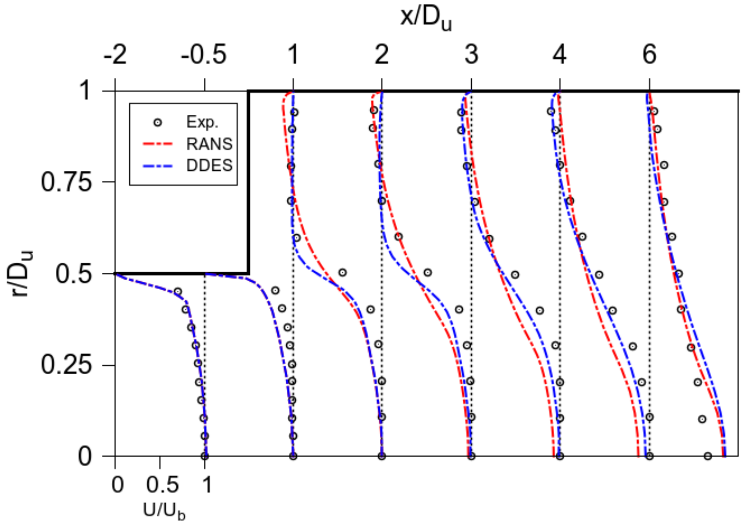
❑**DDES computational procedure:**

1. RANS solution to initialize the flow (experimental data mapped on inlet);
2. DDES run for **2 domain flow throughs** with statistics turned off;
3. DDES run for **10 flow throughs** with statistics on (mean values and fluctuations)
4. Post-separation turbulence statistics extracted from the resolved flow field time history

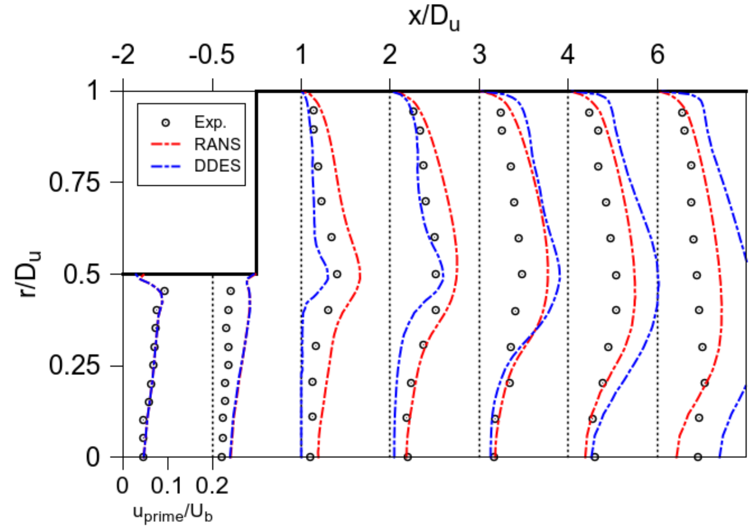
❑**Boundary conditions**: standard incompressible inflow/outflow, wall functions for k and momentum (y+ < 20)

Axisymmetric sudden expansion

Axial velocities



Axial velocity fluctuations



Results, $S_i = 0$:

Axisymmetric sudden expansion

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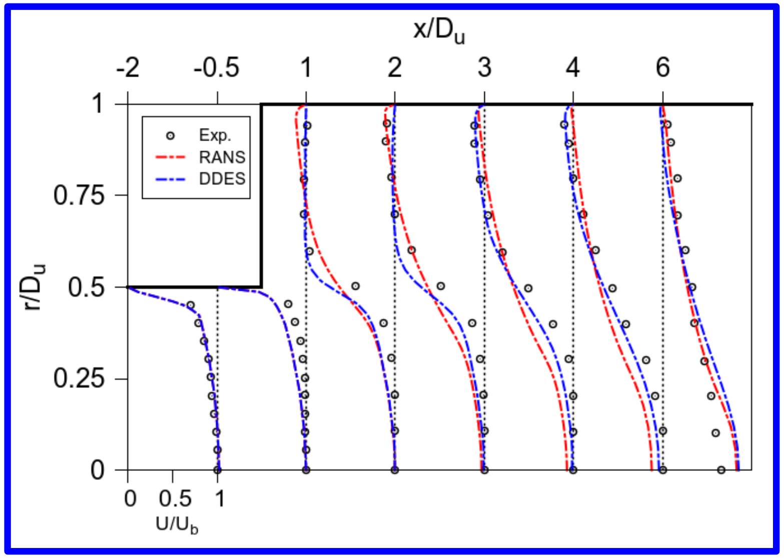

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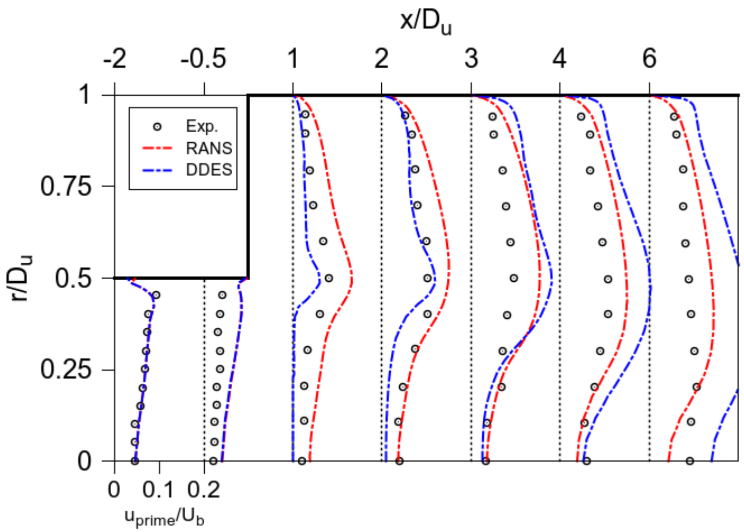

Results, $S_i = 0$:

❑**RANS produces overdiffusive shear layers, DDES mean velocity field is more consistent**

Axisymmetric sudden expansion

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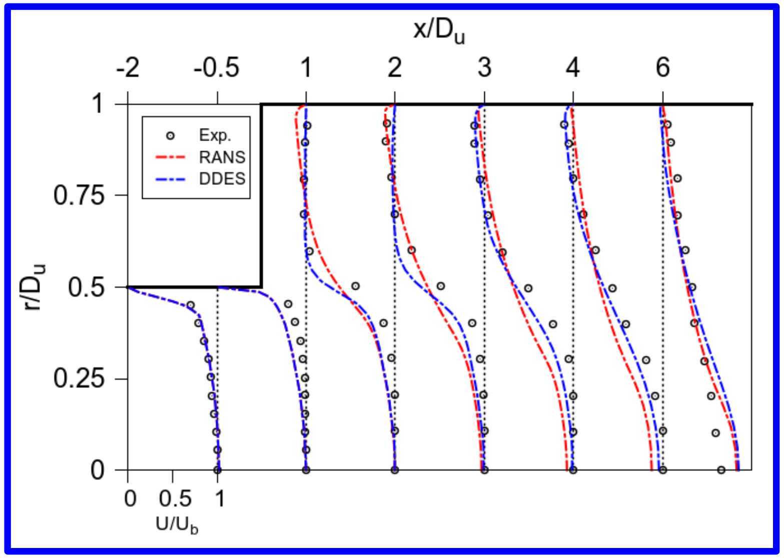

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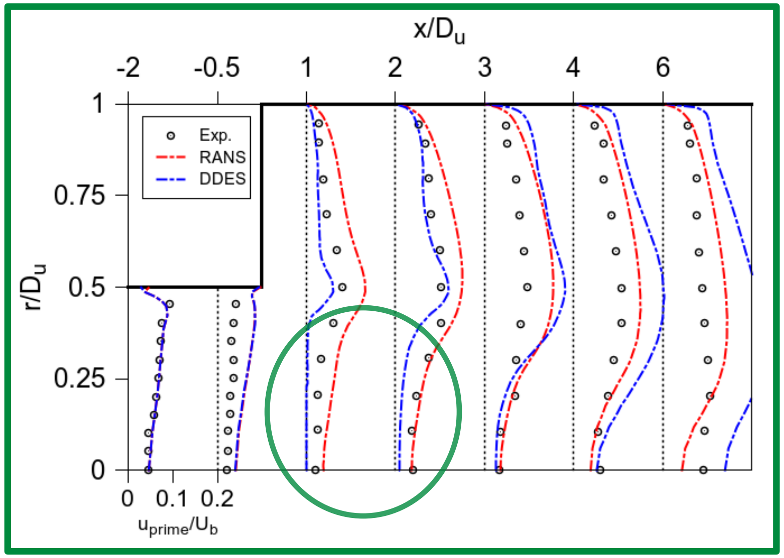
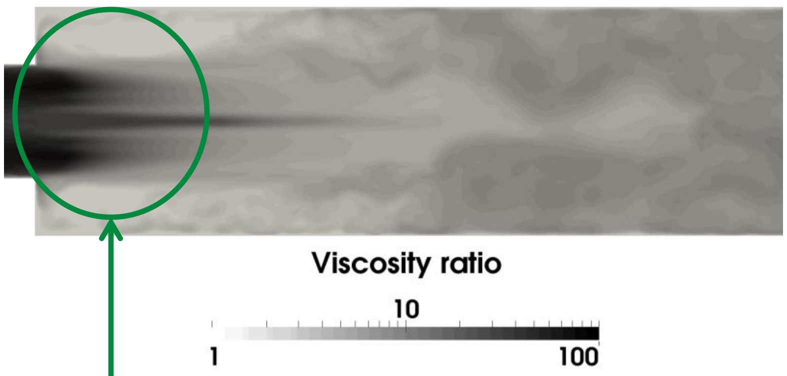


Results, $S_i = 0$:

- ❑RANS produces overdiffusive shear layers, DDES mean velocity field is more consistent
- ❑Lack of resolved turbulence content in the jet core region close to the expansion step

Axisymmetric sudden expansion

Instantaneous viscosity ratio



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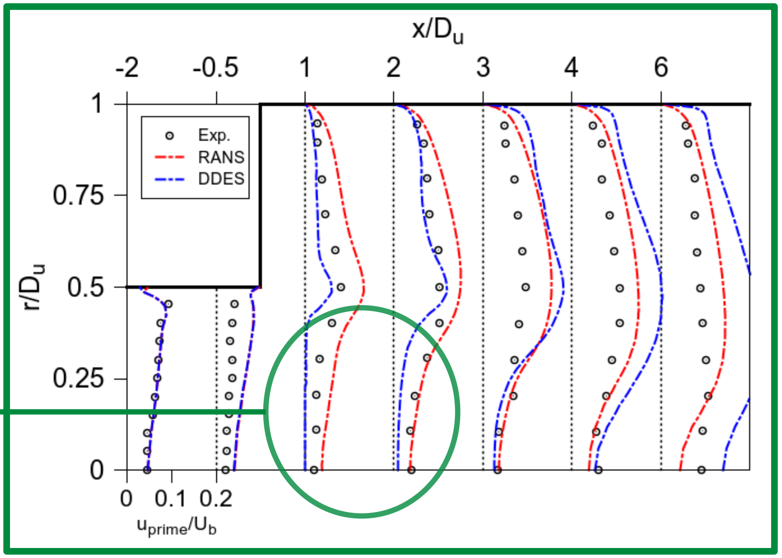
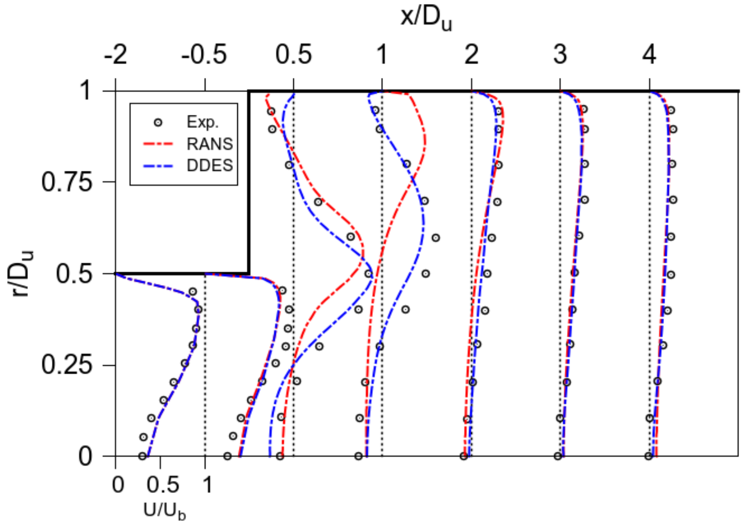


Results, $S_i = 0$:

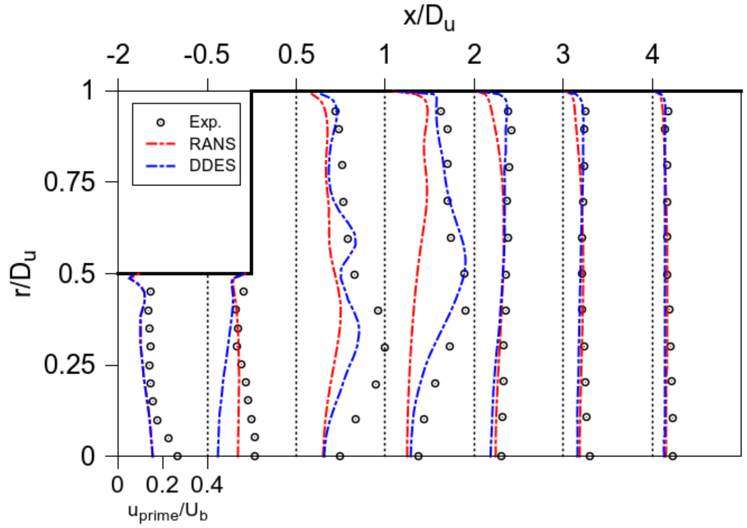
- ❑RANS-like behavior erroneously extended beyond the separation point
- ❑Lack of resolved turbulence content in the jet core region close to the expansion step

Axisymmetric sudden expansion

Axial velocities



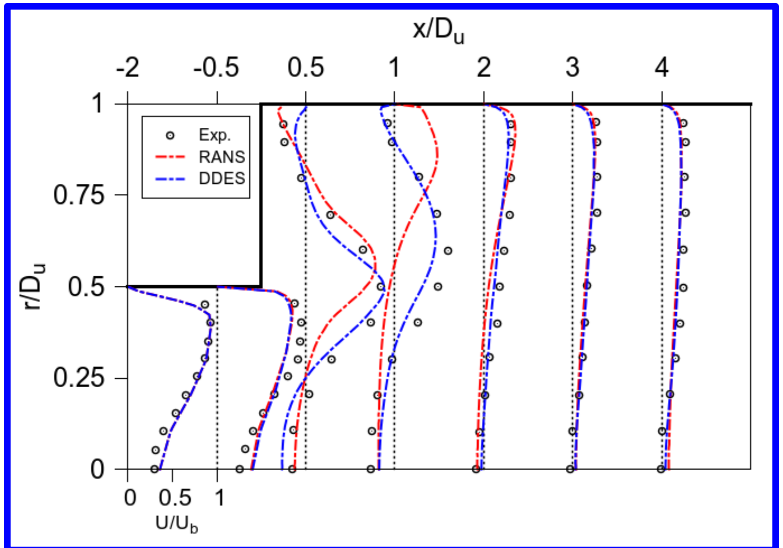
Axial velocity fluctuations



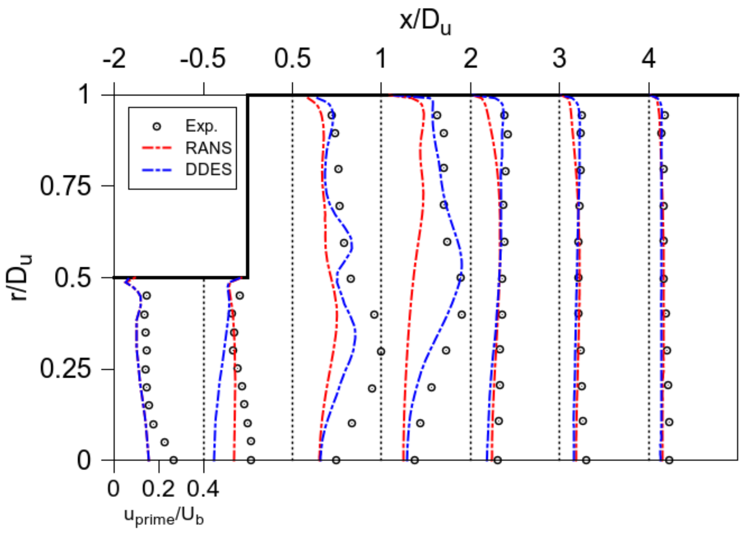
Results, $S_i = 0.6$:

Axisymmetric sudden expansion

Axial velocities



Axial velocity fluctuations

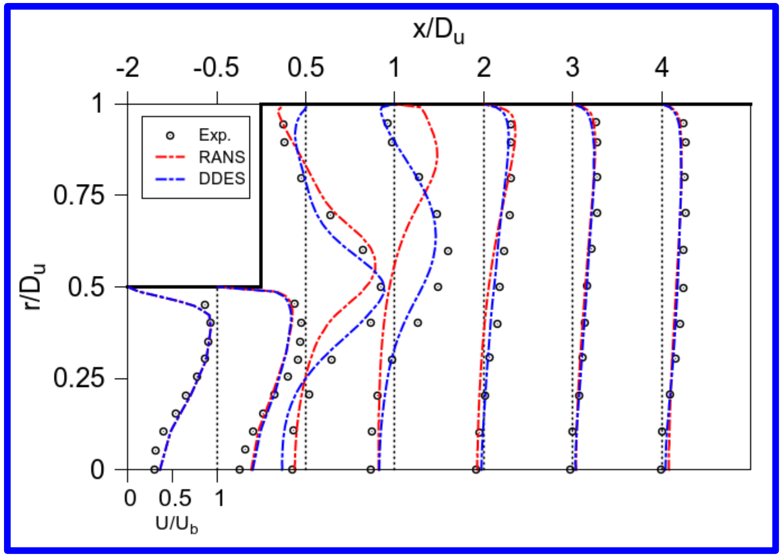


Results, S_i = 0.6:

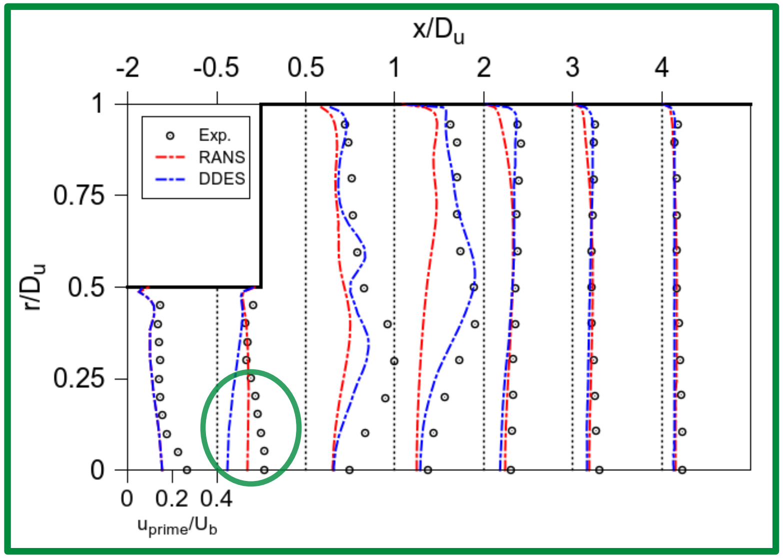
- RANS predicts a too fast radial flow spreading (early jet reattachment), DDES describes well the flow field both in the bulk and near-wall regions

Axisymmetric sudden expansion

Axial velocities



Axial velocity fluctuations



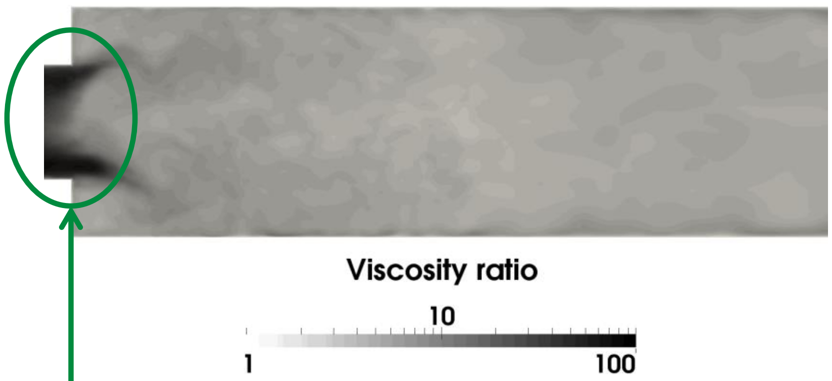
Results, $S_i = 0.6$:

❑**RANS predicts a too fast radial flow spreading (early jet reattachment), DDES describes well the flow field both in the bulk and near-wall regions**

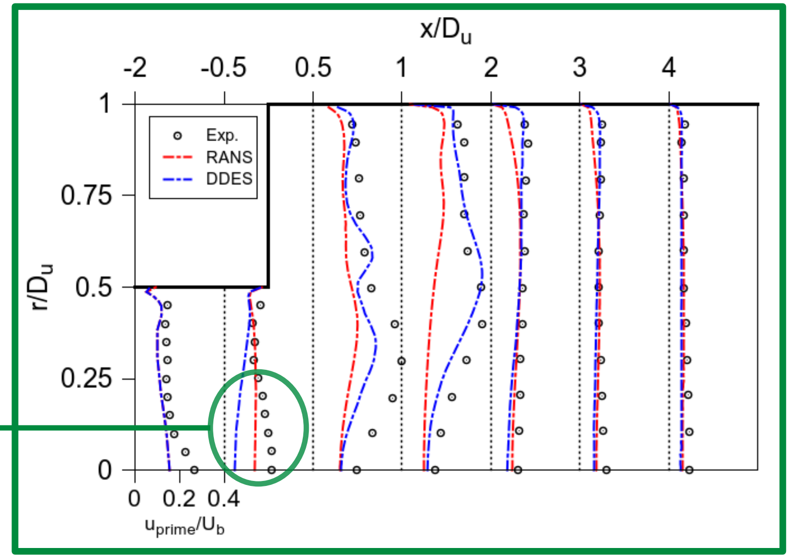
❑**Lack of modeled turbulence content before separation in DDES**

Axisymmetric sudden expansion

Instantaneous viscosity ratio



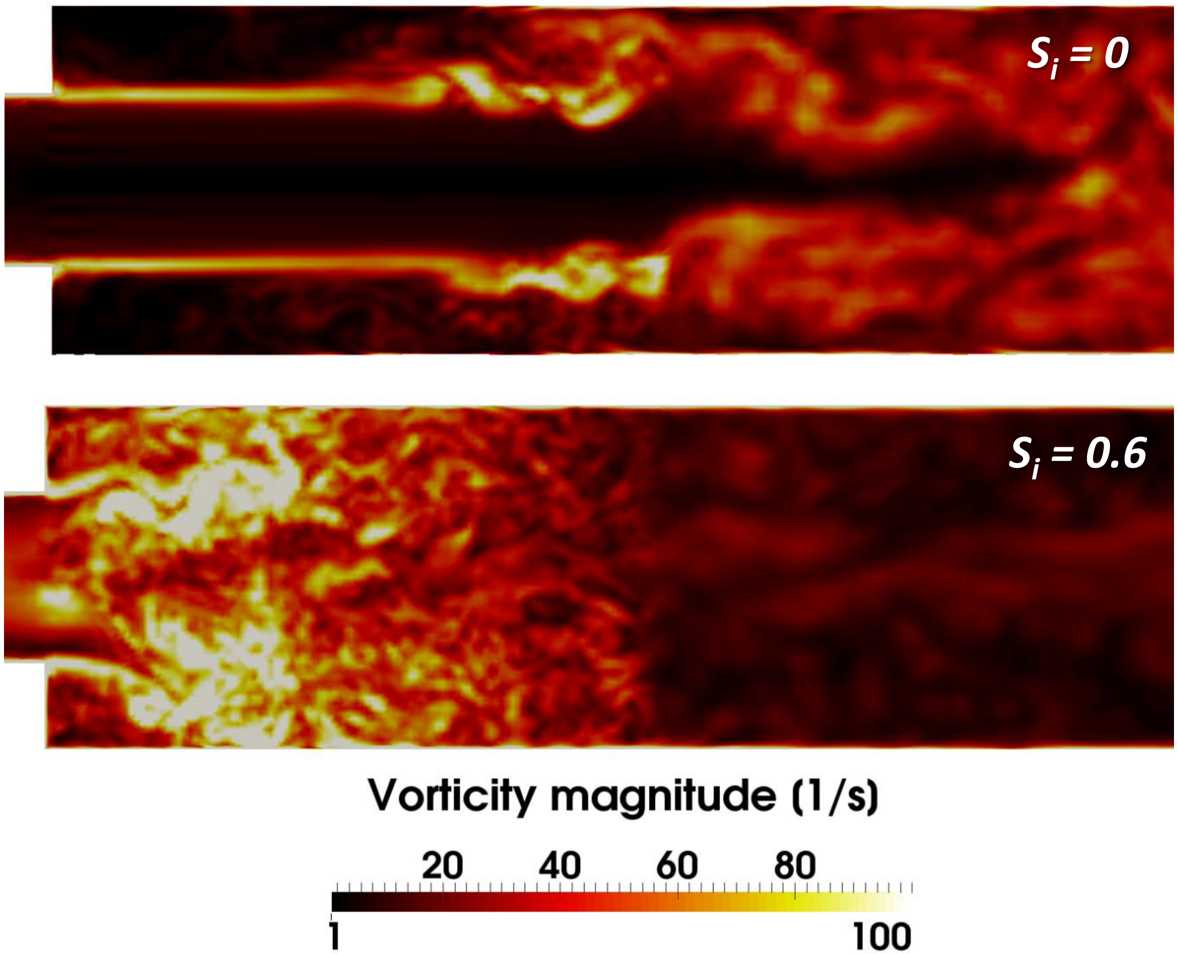
Axial velocity fluctuations

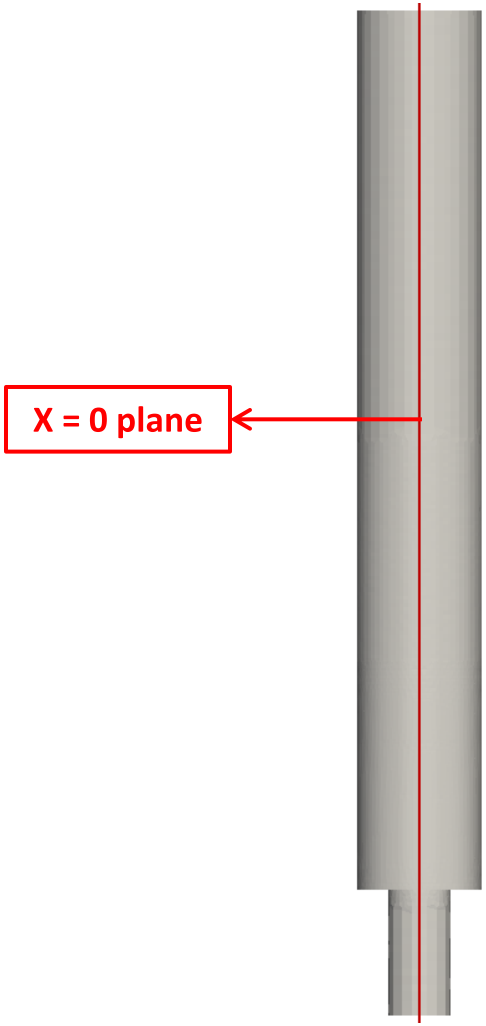


Results, $S_i = 0.6$:

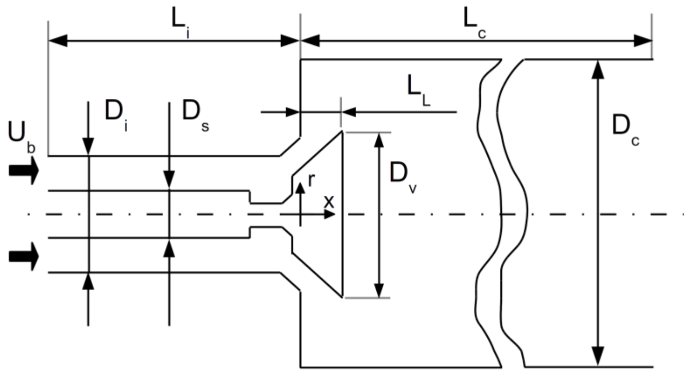
- Too early LES-like behavior with insufficient grid resolution (Modeled Stress Depletion)
- Lack of modeled turbulence content before separation in DDES

Axisymmetric sudden expansion





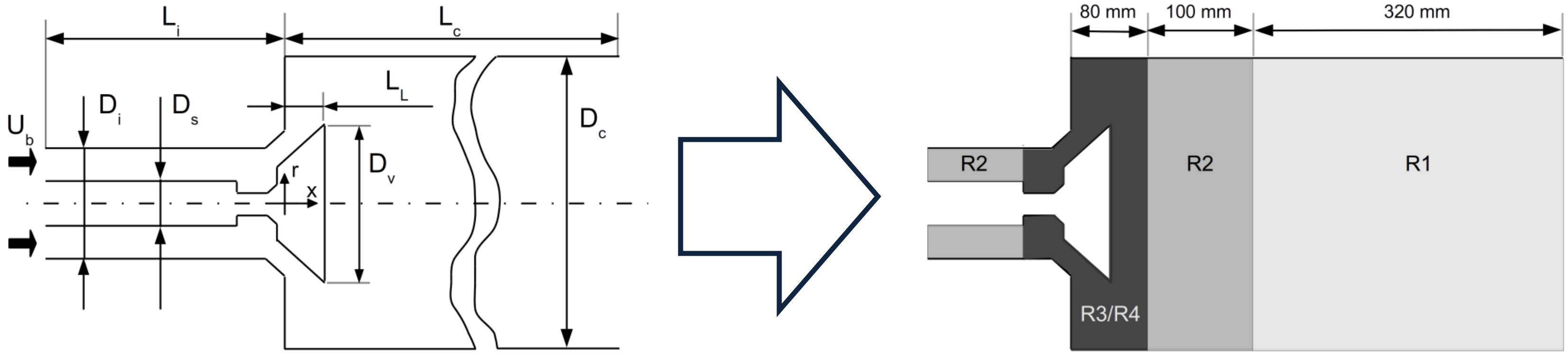
Fixed valve intake port



Preliminary remarks (1):

- Intake port geometry with an axis-centered fixed poppet valve, $\mathbf{Re_b \approx 3 \cdot 10^4}$
- LDA measurements of mean flow and RMS fluctuations available at **x = 20 mm and x = 70 mm**; coarse-LES from Piscaglia et al. (2014) also taken as reference

Fixed valve intake port



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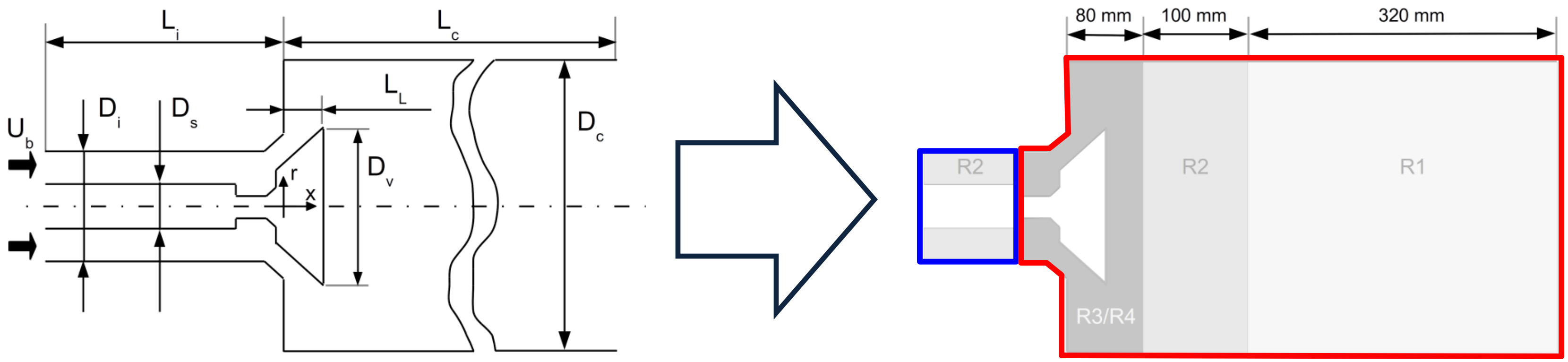
- Two levels of maximum grid refinement (**R0 = D_i/4**): grid #1 (**R3, 1.14 ·10^6 cells**) and grid #2 (**R4, 3.33 · 10^6 cells**)

Fixed valve intake port

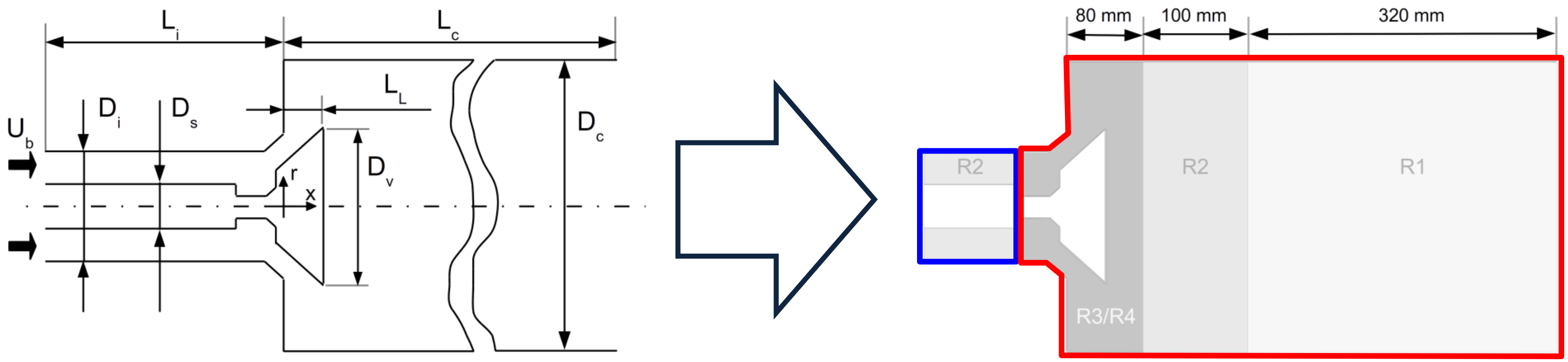


Preliminary remarks (2):

❑**Zonal numerical treatment** for momentum convection in DDES:

- **Linear Upwind (LU) scheme in the steady, attached upstream region**
- **FCD 0.25 in the separated flow region (implicit promotion of RANS/LES triggering)**

Fixed valve intake port



Preliminary remarks (3):

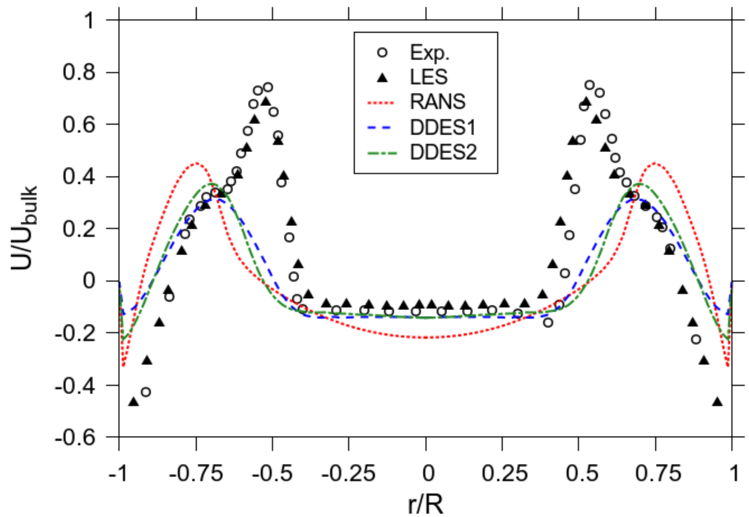
❑**DDES computational procedure:**

1. RANS solution to initialize the flow (experimental data mapped on inlet);
2. DDES run for **1 domain flow through** with statistics turned off;
3. DDES run for **2 flow throughs** with statistics on (mean values and fluctuations)
4. All turbulence statistics extracted from the resolved flow field time history

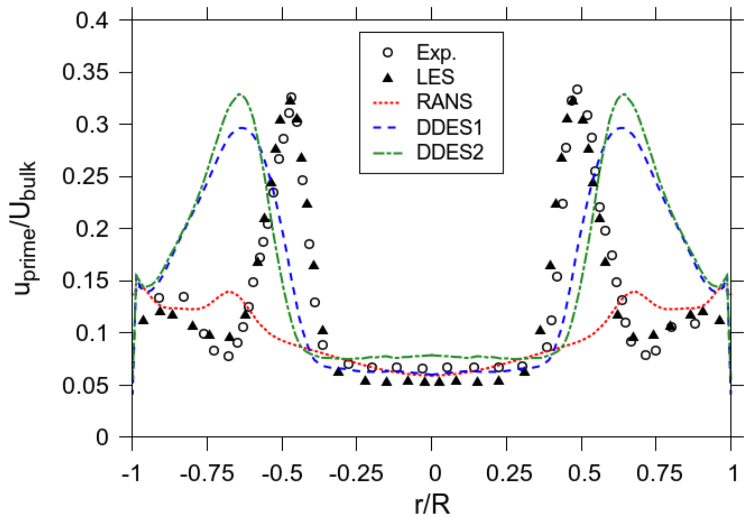
❑**Boundary conditions**: standard incompressible inflow/outflow, wall functions for k and momentum (y+ < 30)

Fixed valve intake port

Axial velocities



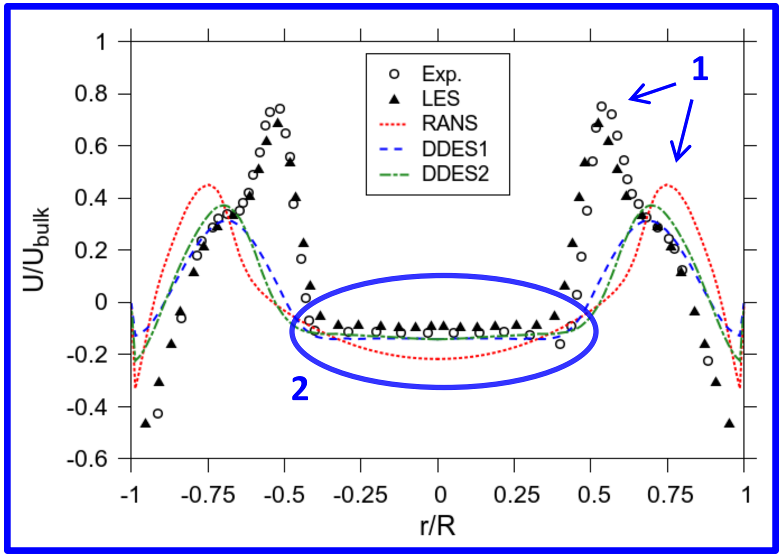
Axial velocity fluctuations



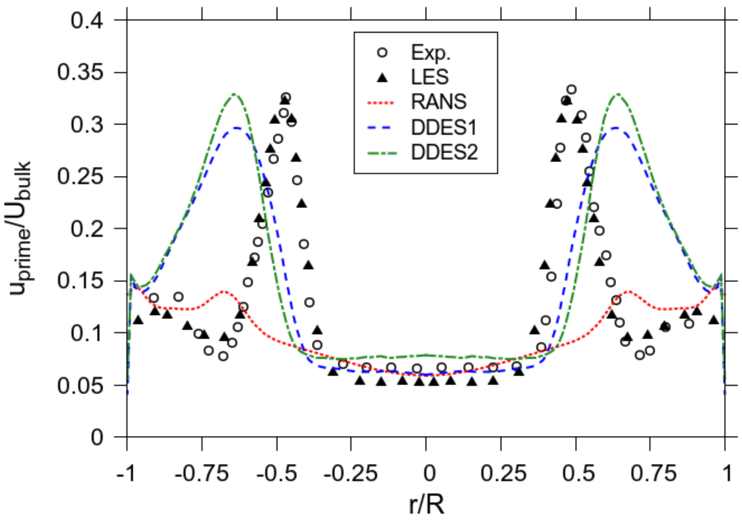
Results, x = 20 mm:

Fixed valve intake port

Axial velocities



Axial velocity fluctuations

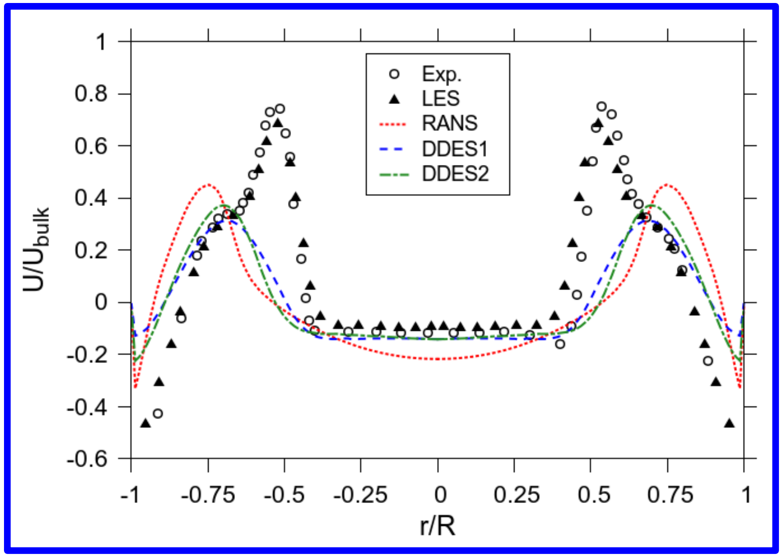


Results, x = 20 mm:

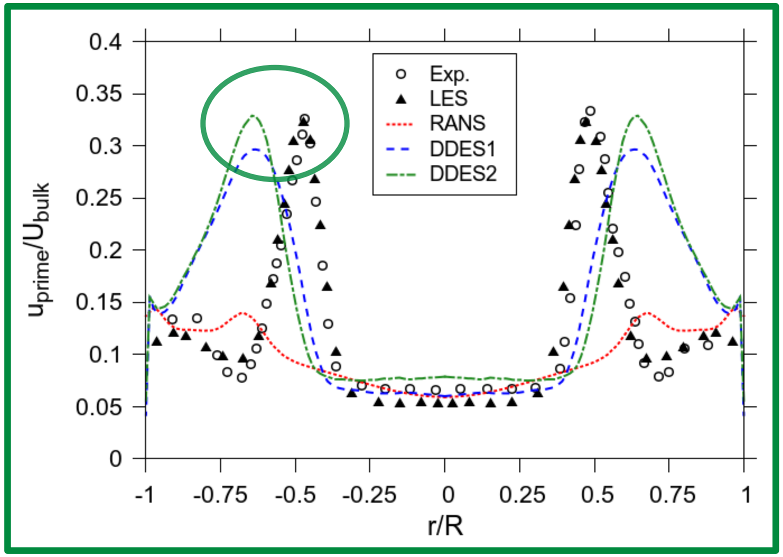
1. Mismatch on the velocity peaks position and magnitude
2. DDES1 and DDES2 predict well recirculation behind valve's head

Fixed valve intake port

Axial velocities



Axial velocity fluctuations

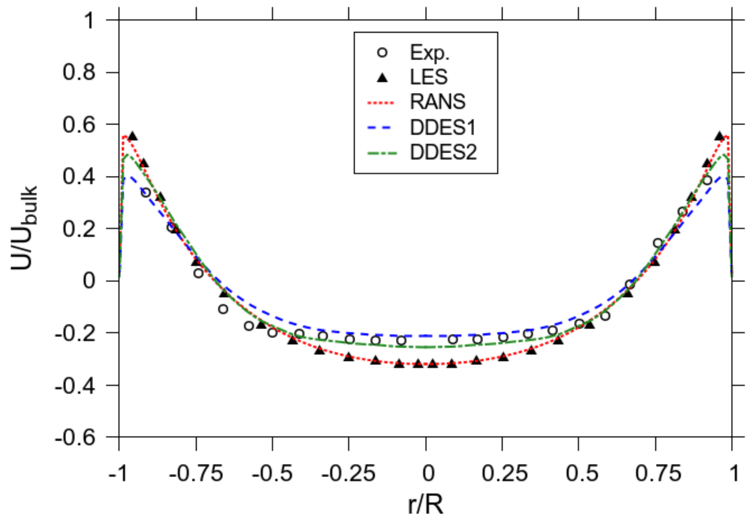


Results, x = 20 mm:

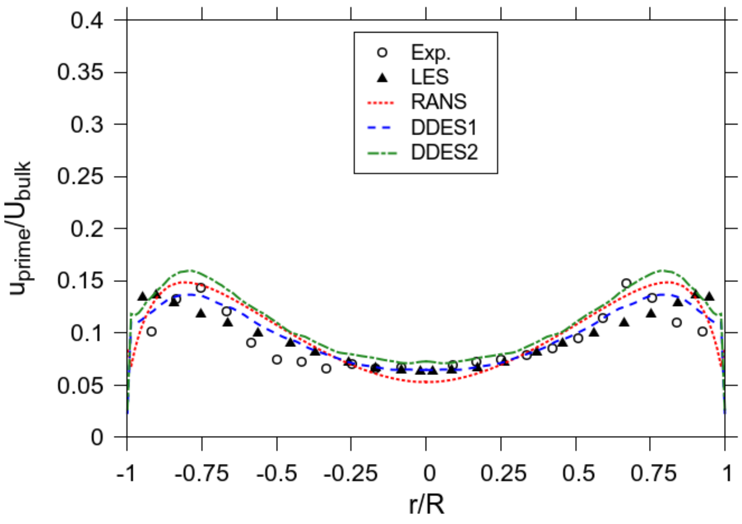
- ❑Still a mismatch on the turbulence peak position
- ❑DDES2 predicts well the peak's magnitude (+14% compared to DDES1, +135% compared to RANS)

Fixed valve intake port

Axial velocities



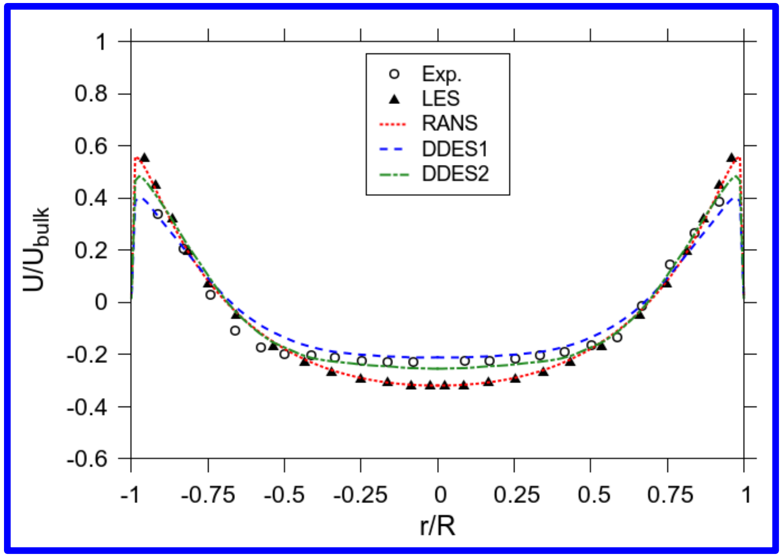
Axial velocity fluctuations



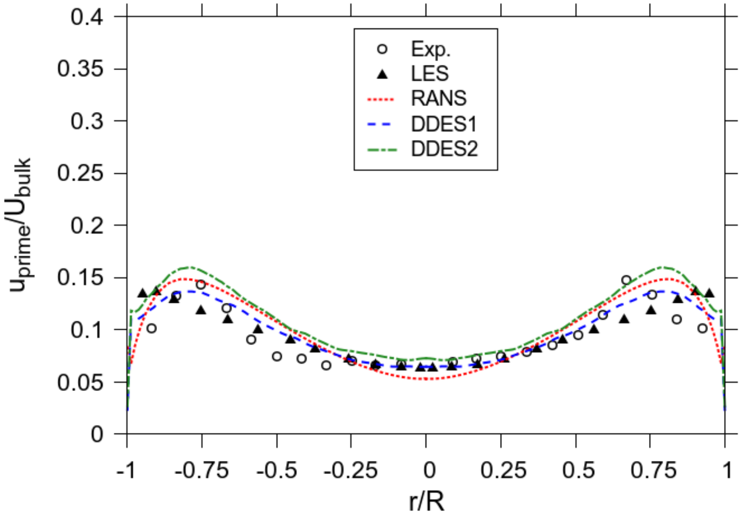
Results, x = 70 mm:

Fixed valve intake port

Axial velocities



Axial velocity fluctuations

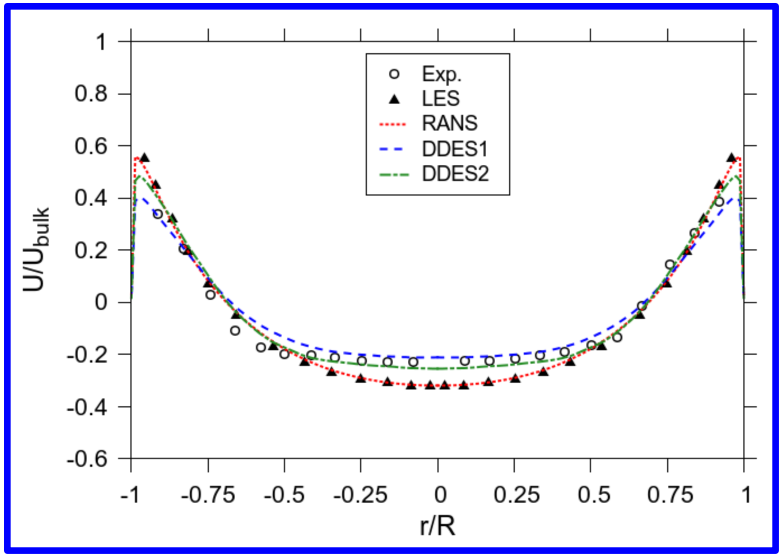


Results, x = 70 mm:

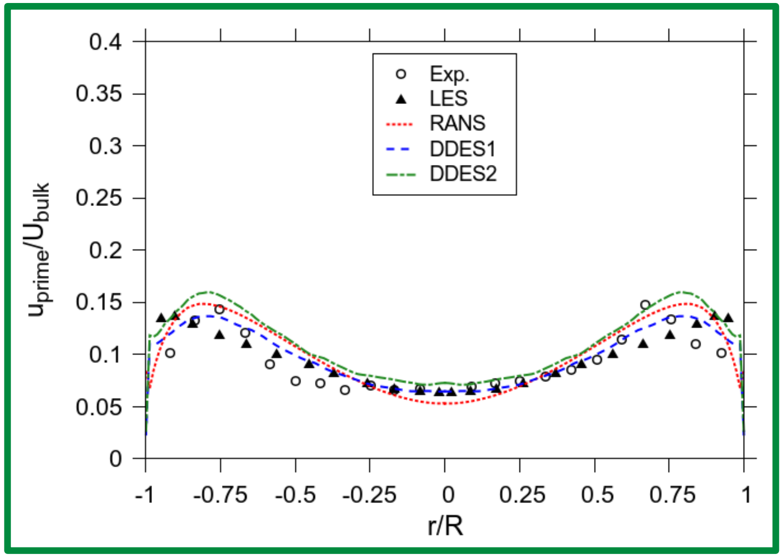
- **RANS results are similar to reference coarse-LES; DDES1 and DDES2 agree well with measurements (DDES2 slightly superior)**

Fixed valve intake port

Axial velocities



Axial velocity fluctuations

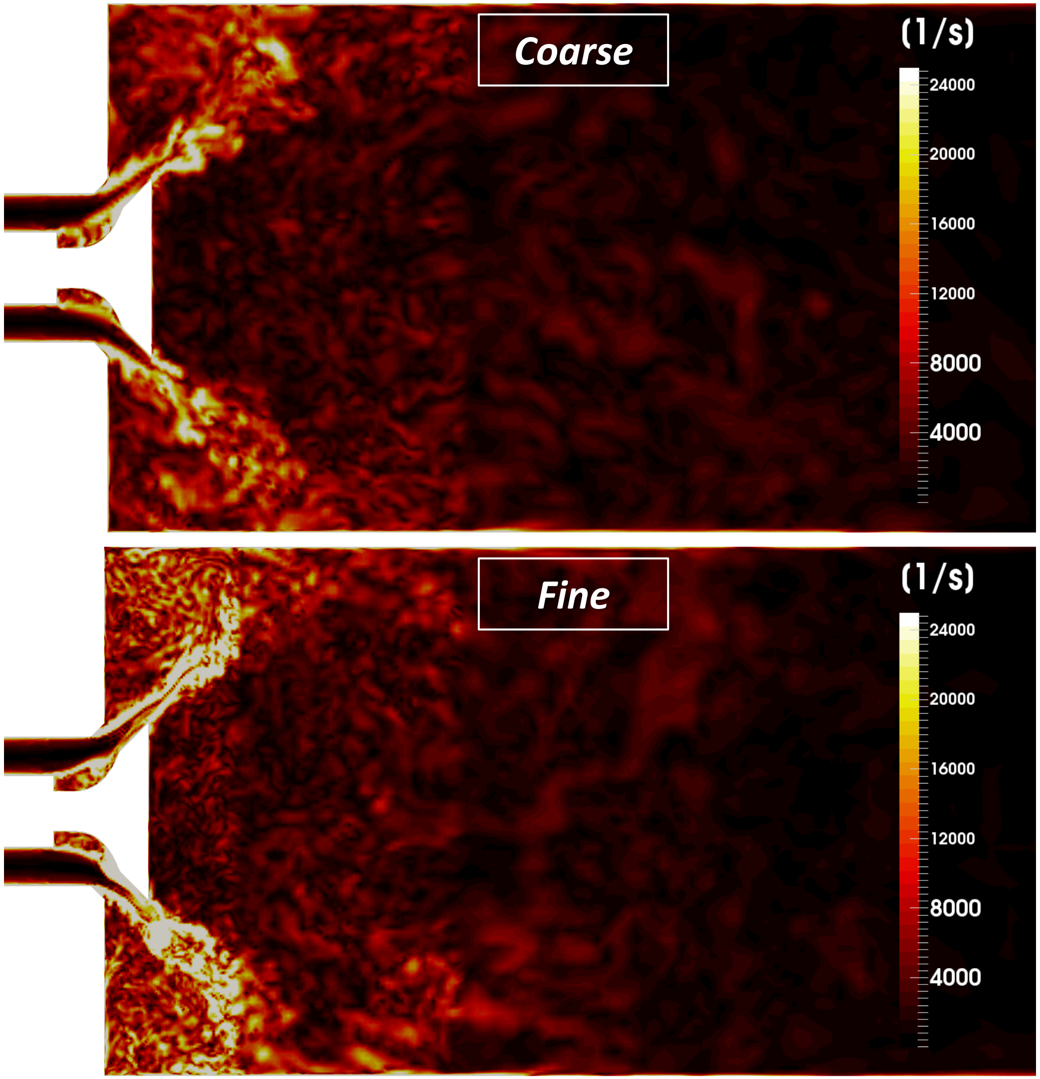


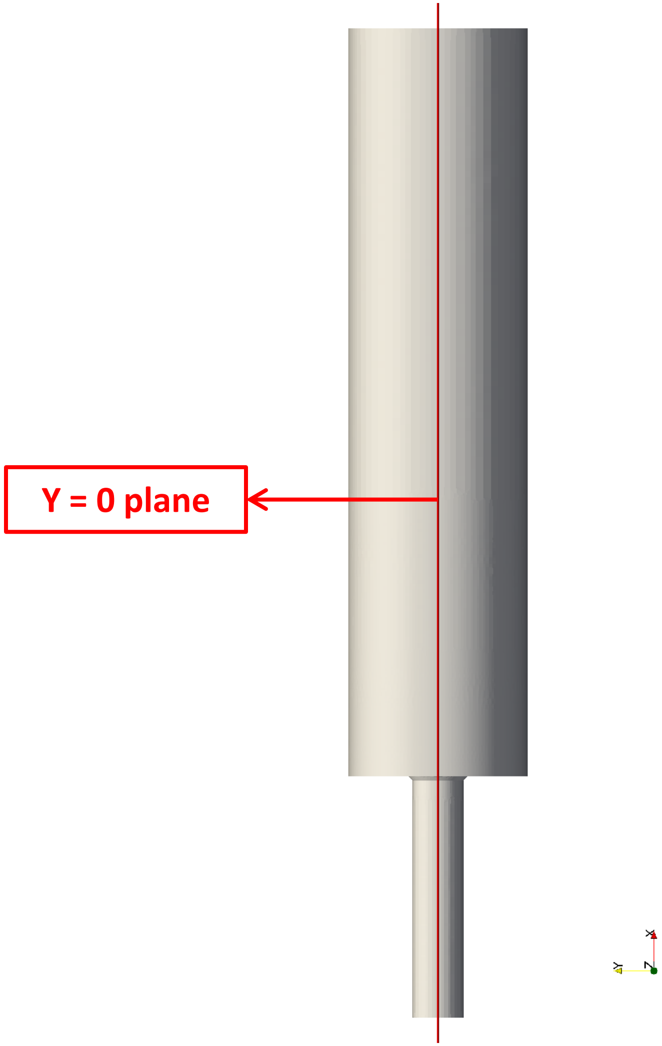
Results, x = 70 mm:

- RANS results are similar to reference coarse-LES; DDES1 and DDES2 agree well with measurements (DDES2 slightly superior)

- DDES2 in fairly good agreement with measurements (slightly better than DDES1, RANS and reference LES)

Fixed valve intake port





Where to improve ?

Initial results' analysis

- **Automatic URANS-to-LES** switching is **not always efficient** (slow transition in some cases, too early in others)

- Improvements can derive from a **fully zonal formulation** (user-defined URANS and LES zones)

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Zonal form of the destruction term:

$$D^{*}_{DDES} = F^{*}_{DDES} \cdot D_{RANS} \quad (1)$$

$$F^{*}_{DDES} = C_{z1} \cdot F_{DDES} + (1 - C_{z1}) F_{ZDES} \quad (2)$$

$$F_{ZDES} = C_{z2} + (1 - C_{z2}) \cdot \left(\frac{l_{k-g}}{C_{DES} \cdot \Delta} \right) \quad (3)$$

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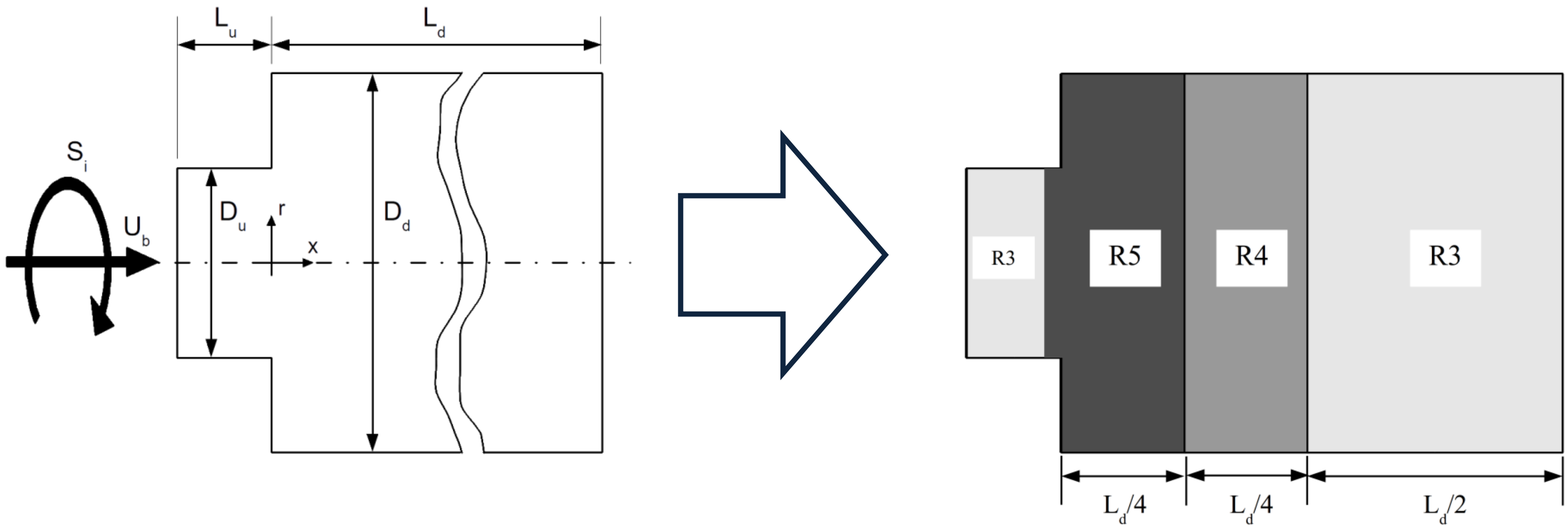
C_{z2} \ C_{z1}	**1**	**0**
1	DDES	RANS
0	DDES	LES

Axisymmetric sudden expansion



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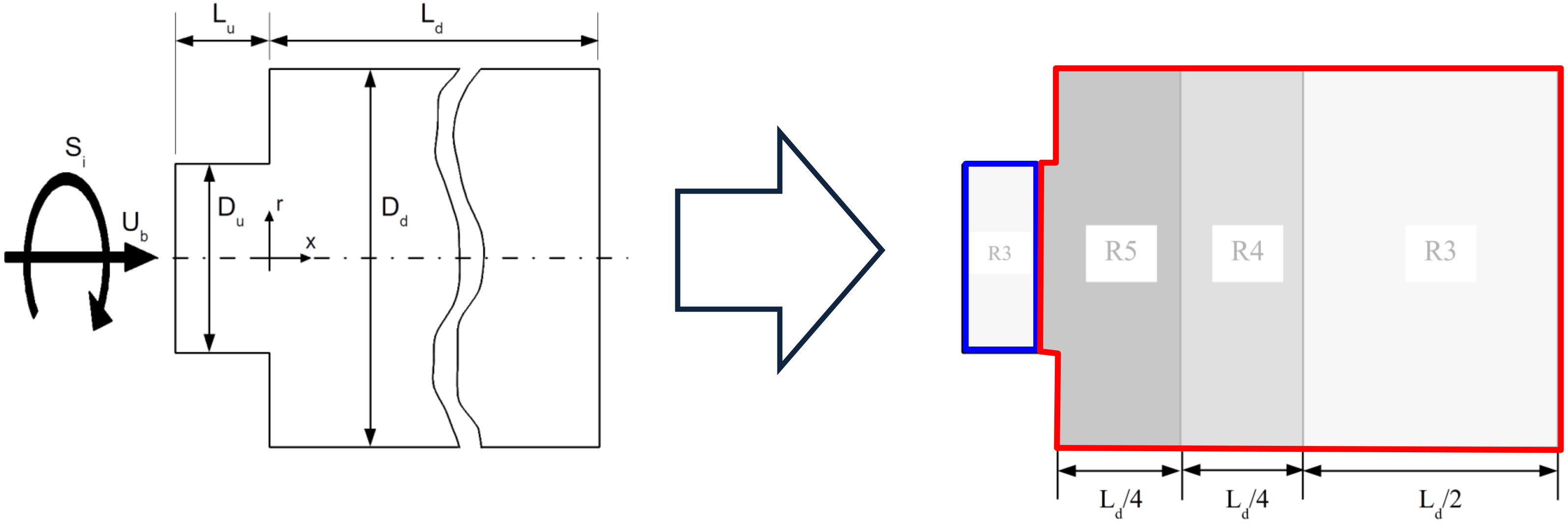
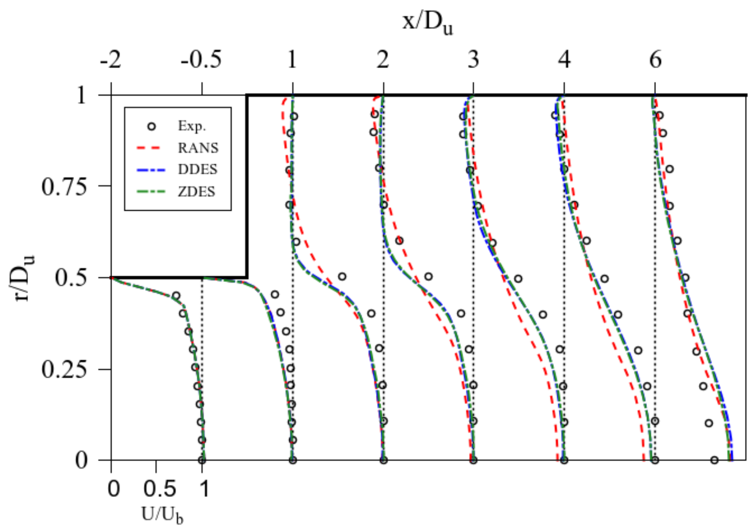


- **C_{z1} equal to 0**, strictly zonal approach applied as follows*:
  - **C_{z2} = 1 (RANS) + LU**
  - **C_{z2} = 0 (LES) + FCD 0.25**

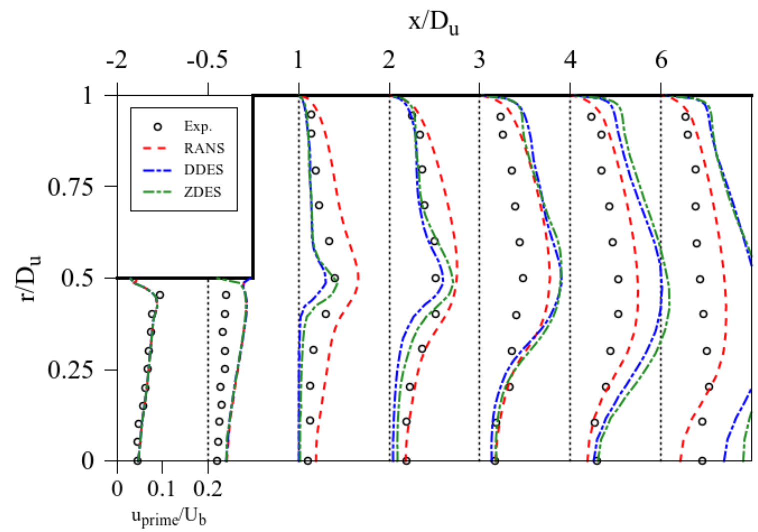
*RANS/LES interface moved slightly upstream from the expansion step

Axisymmetric sudden expansion

Axial velocities



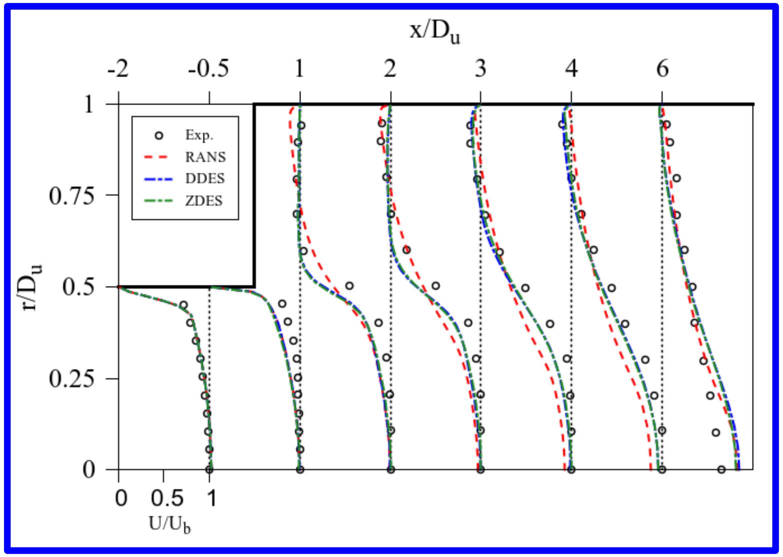
Axial velocity fluctuations



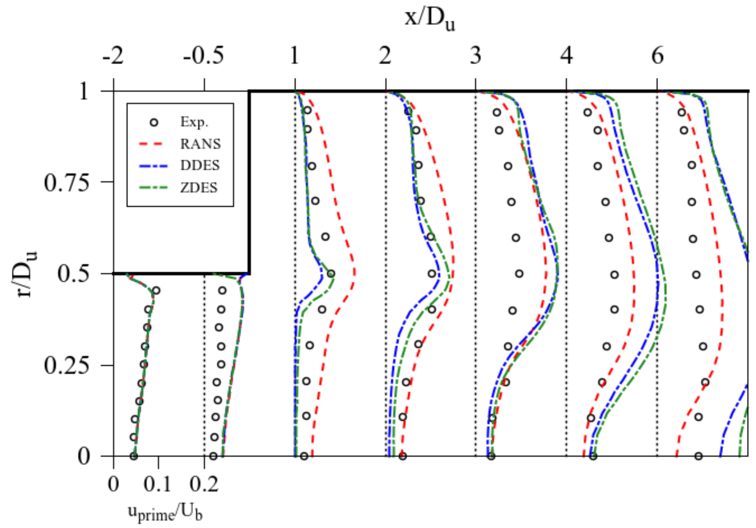
Results, S_i = 0, zonal vs. non-zonal approach:

Axisymmetric sudden expansion

Axial velocities



Axial velocity fluctuations

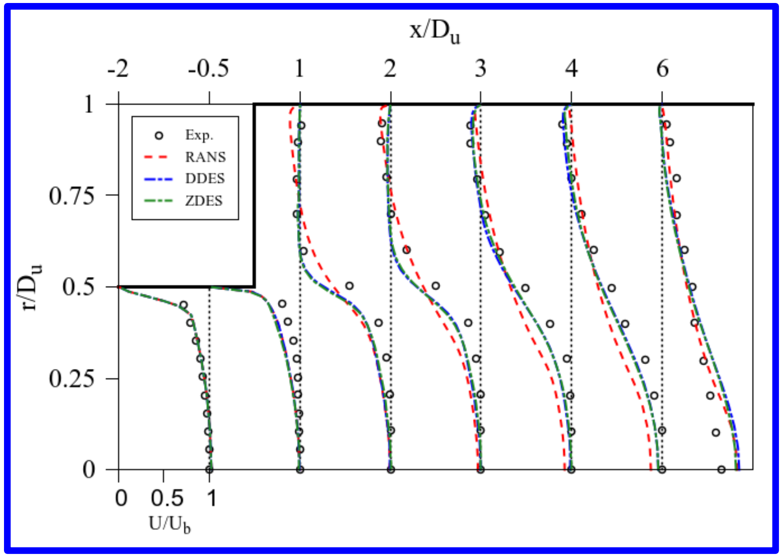


Results, S_i = 0, zonal vs. non-zonal approach:

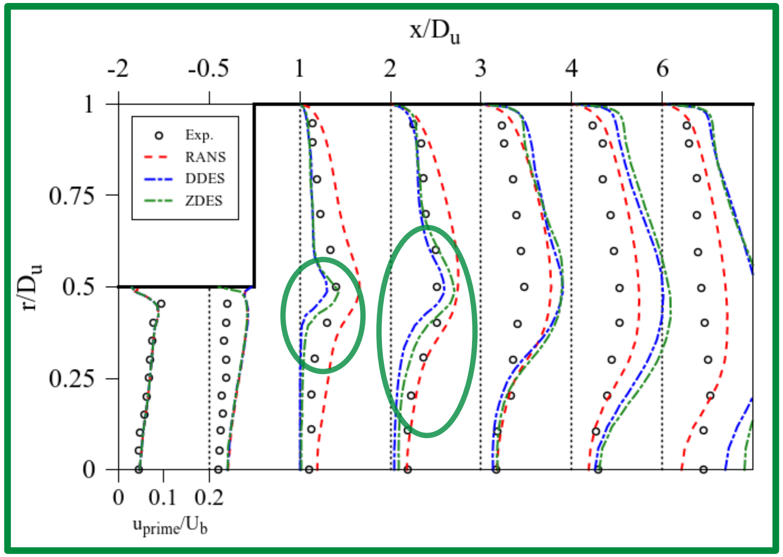
- ❑ **Mean velocity profiles do not change significantly**

Axisymmetric sudden expansion

Axial velocities



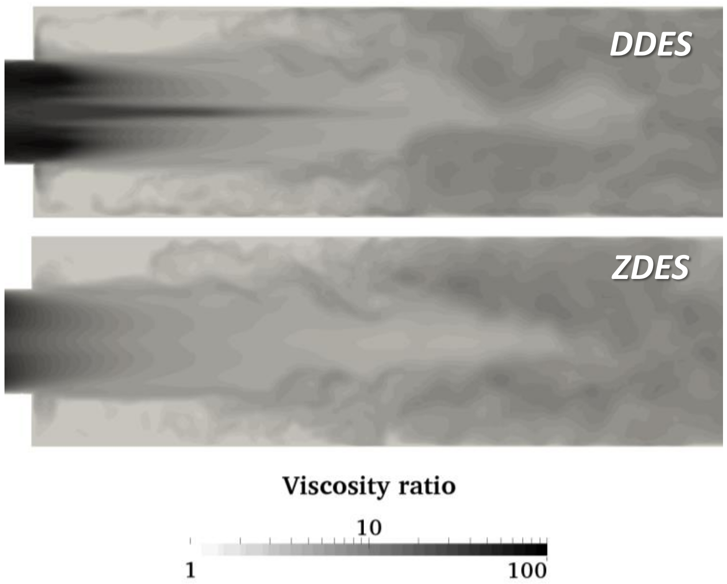
Axial velocity fluctuations



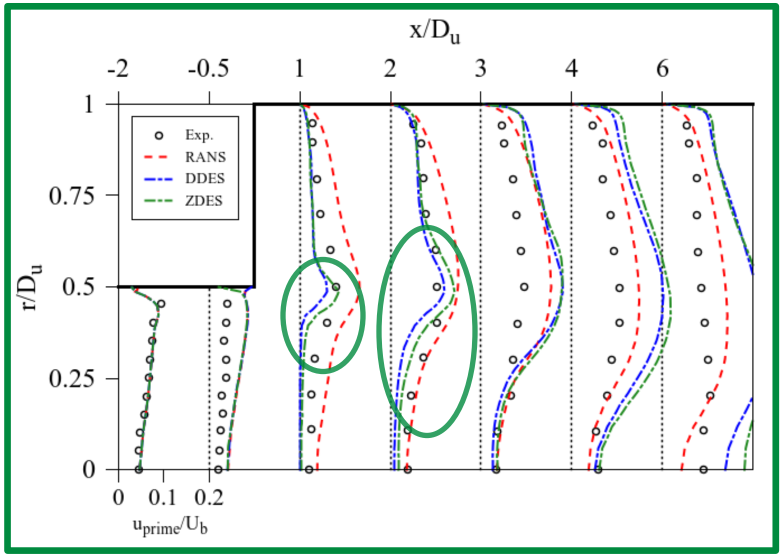
Results, S_i = 0, zonal vs. non-zonal approach:

- Mean velocity profiles do not change significantly
- Resolved turbulence enhancements in the core and shear-later regions (no mesh density increase)

Axisymmetric sudden expansion



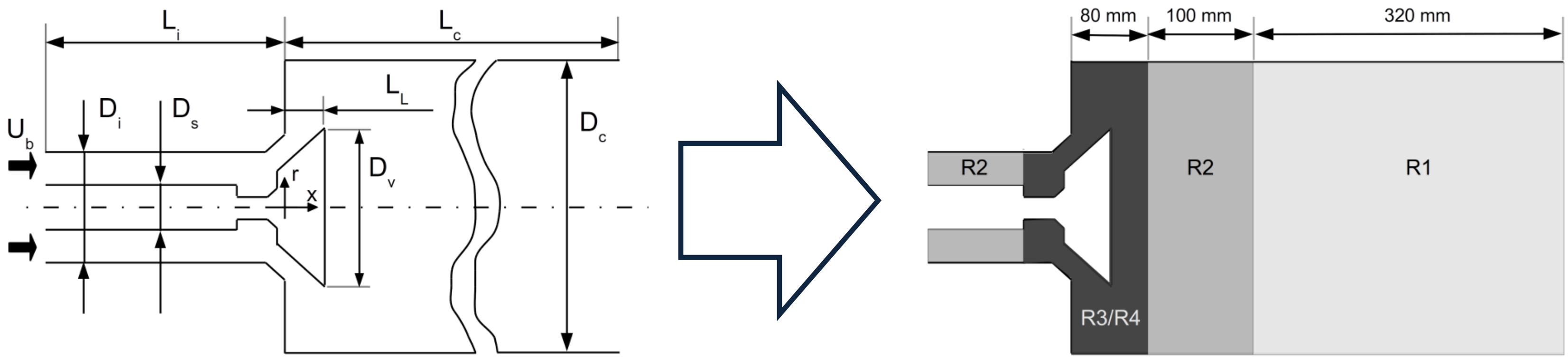
Axial velocity fluctuations



Results, S_i = 0, zonal vs. non-zonal approach:

- ❑More consistent post-separation viscosity scaling
- ❑Resolved turbulence enhancements in the core and shear-later regions (no mesh density increase)

Fixed valve intake port



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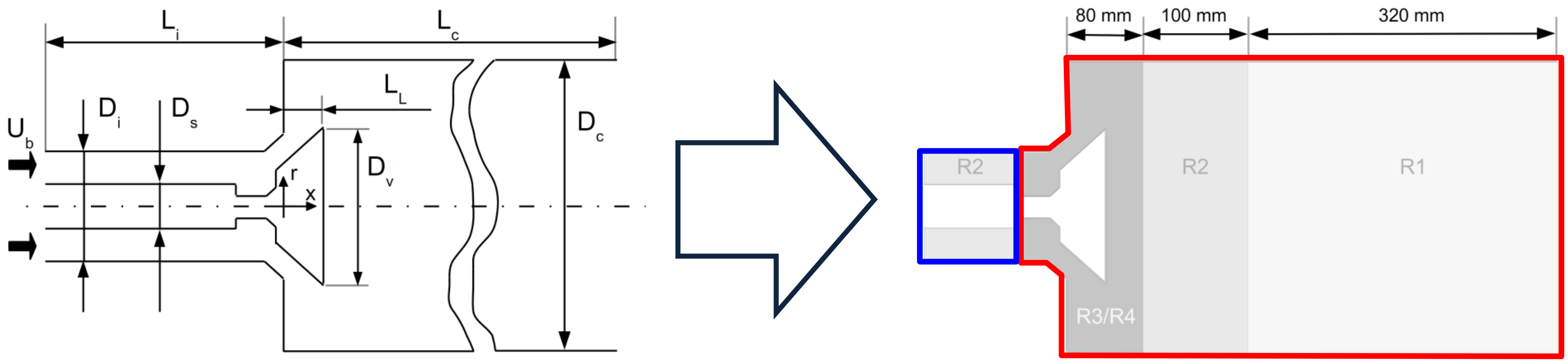

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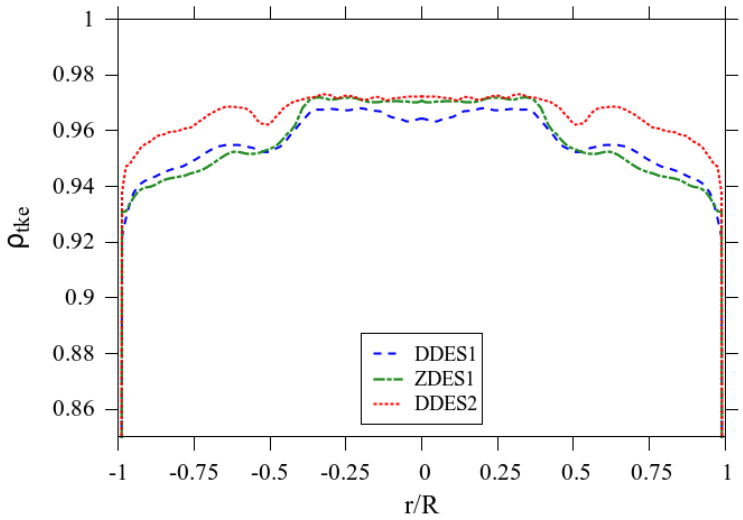
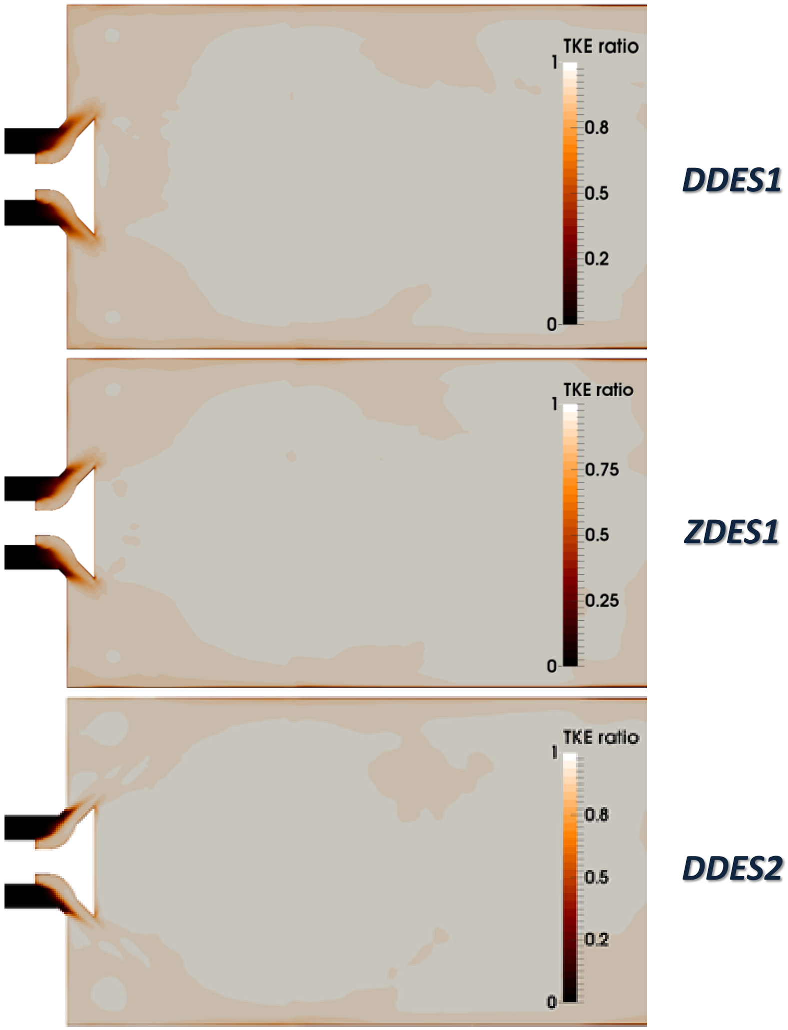
Fixed valve intake port

Resolved vs. total tke ratio (x = 20 mm)



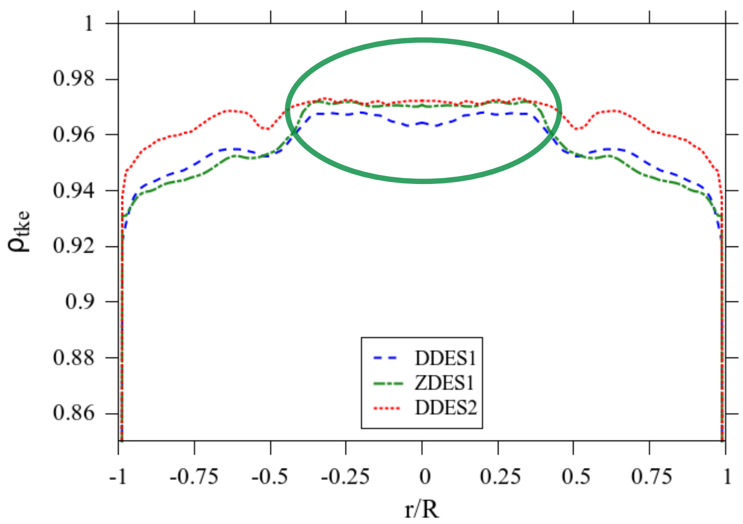
Resolved vs. total tke ratio (axial section)



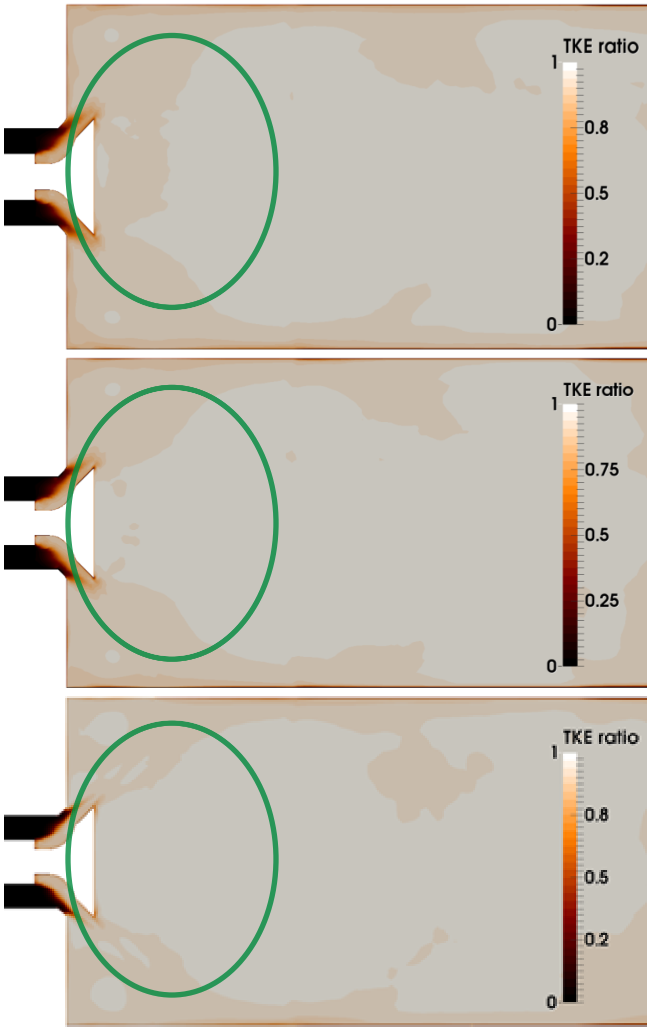
Results, zonal vs. non-zonal vs. mesh density increase:

Fixed valve intake port

Resolved vs. total tke ratio (x = 20 mm)



Resolved vs. total tke ratio (axial section)



DDES1

ZDES1

DDES2

Results, zonal vs. non-zonal vs. mesh density increase:

- **In some flow areas, the effect of LES enforcement is comparable to a 2X mesh refinement in all directions**
- **Potential optimization of cells' distribution across the domain**

Final comments

- The results here shown represent a **promising basis** for future ICE applications and can be summarized as follows:

  1. once calibrated the C_{DES} constant (in conjunction with numerical schemes), the proposed hybrid URANS/LES model has shown **consistent performances in pure LES-sgs mode**;

  2. the first wall-bounded test case (Dellenback's sudden expansion) has shown how **the proposed DDES formulation can be significantly more accurate compared to the RANS closure from which it originates**; switching to a **fully zonal approach** seems to add **further benefits** when the seamless URANS-to-LES transition does not occur as expected;

  3. the second and more complex wall-bounded case (axisymmetric intake port geometry) has highlighted the **importance of local grid refinement** to achieve better mean-flow and turbulent quantities resolution **in the LES-treated part of the flow**; a **more efficient cell density distribution** can be potentially achieved through the **zonal approach.**

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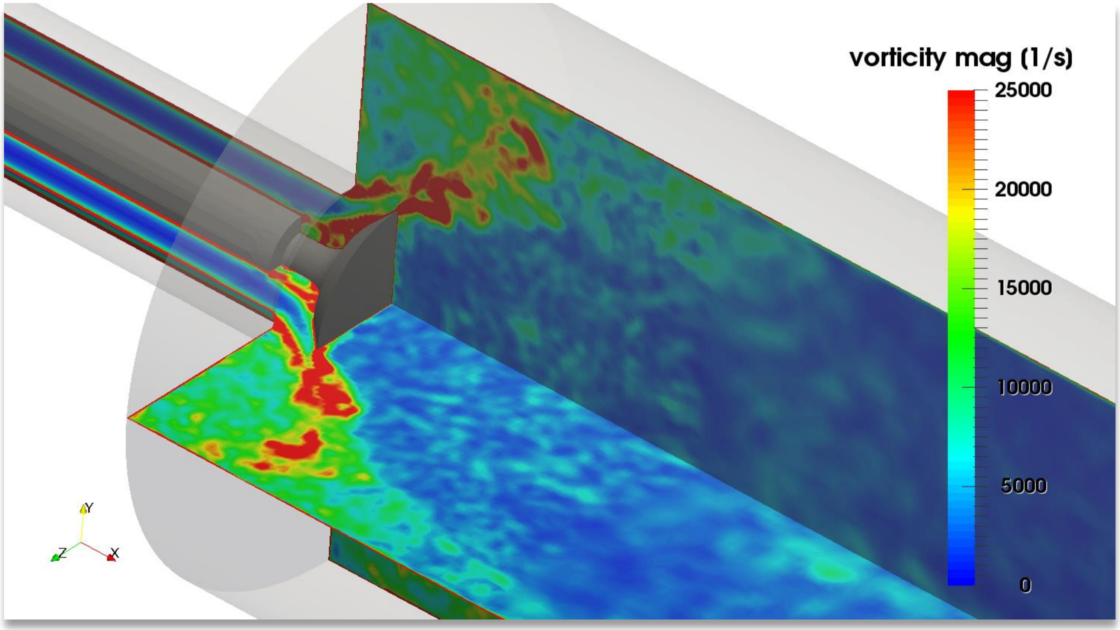
- The **next development steps** will be focused on:

  1. verification of the **limits of the zonal modeling concept;**
  2. more detailed analysis of grid resolution and wall BC requirements (depending on flow regime);
  3. **moving piston/valves handling in a compressible modeling framework (realistic ICE applications)**.


Thank you!

"DES Turbulence Modeling for ICE Flow Simulation in OpenFOAM®"



V. K. Krastev[1], G. Bella[2] and G. Campitelli

[1] University of Tuscia, DEIM School of Engineering
[2] University of Rome "Tor Vergata", Mario Lucertini Engineering Department
[3] West Virginia University, Mechanical and Aerospace Engineering Department