APPLICATION OF ZONAL HYBRID URANS/LES MODELING TO INTERNAL COMBUSTION ENGINE FLOWS

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Outline

- Background
  - URANS/LES hybrids in ICE modeling
  - Motivations
- Zonal modeling formulation & calibration
- Applications
  - Static valve intake flow
  - TCC-III Engine multi-cycle analysis
- Conclusions

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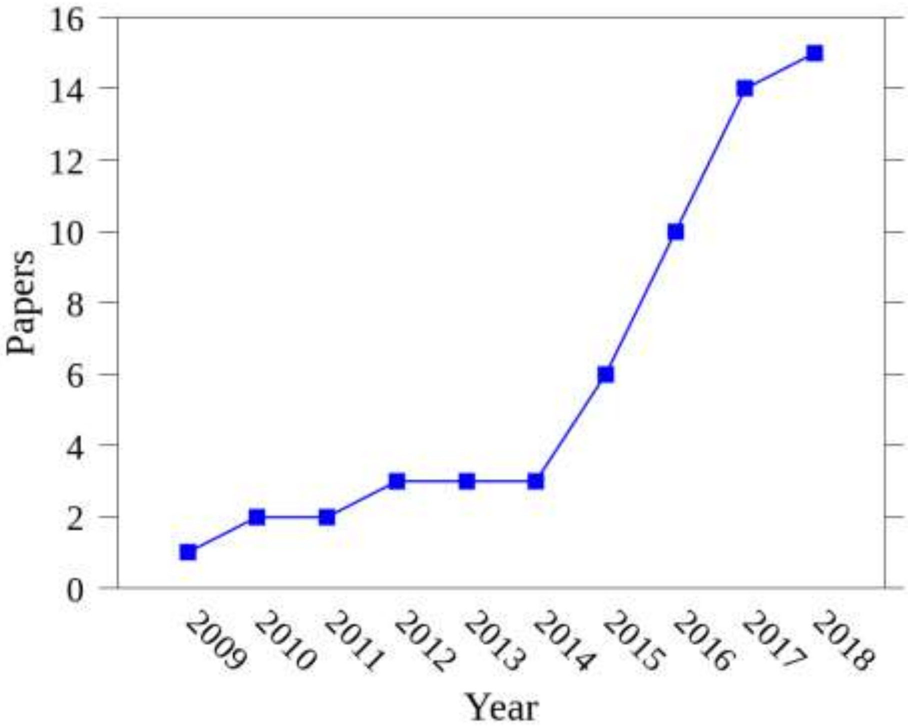
URANS/LES hybrids in the ICE modeling community



Cumulative graph of the published journal papers with relevant hybrid URANS/LES applications in the ICE field (source+: www.scopus.com)

+The collected data might not be fully exhaustive

- LES methods for ICE modeling are being developed for 25 years, **but** …
- …in **recent** years the interest for URANS/LES hybrids is apparently **growing**
- Potential gains in computational **robustness and efficiency**, keeping **scale-resolving capabilites** where needed
- Several seamless (**SAS, DES, DLRM**) and zonal (**ZDES**) alternatives proposed

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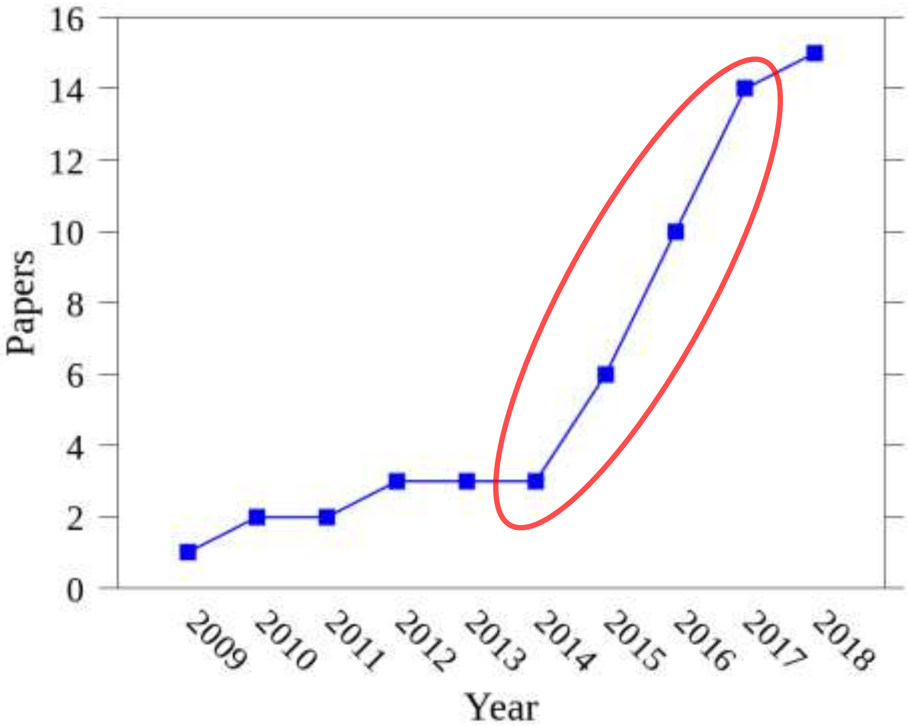

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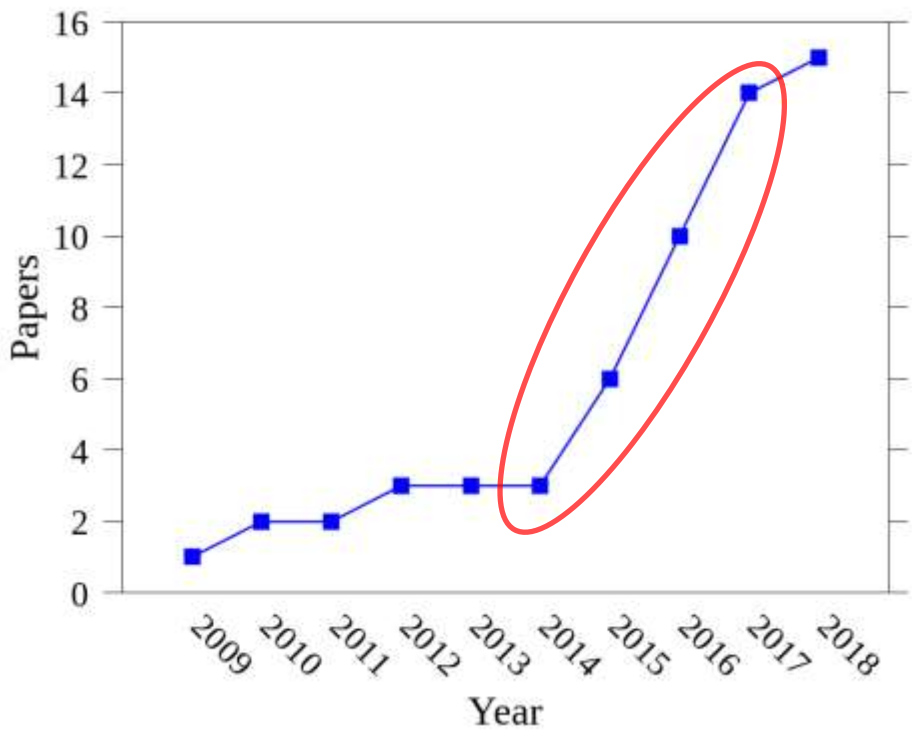

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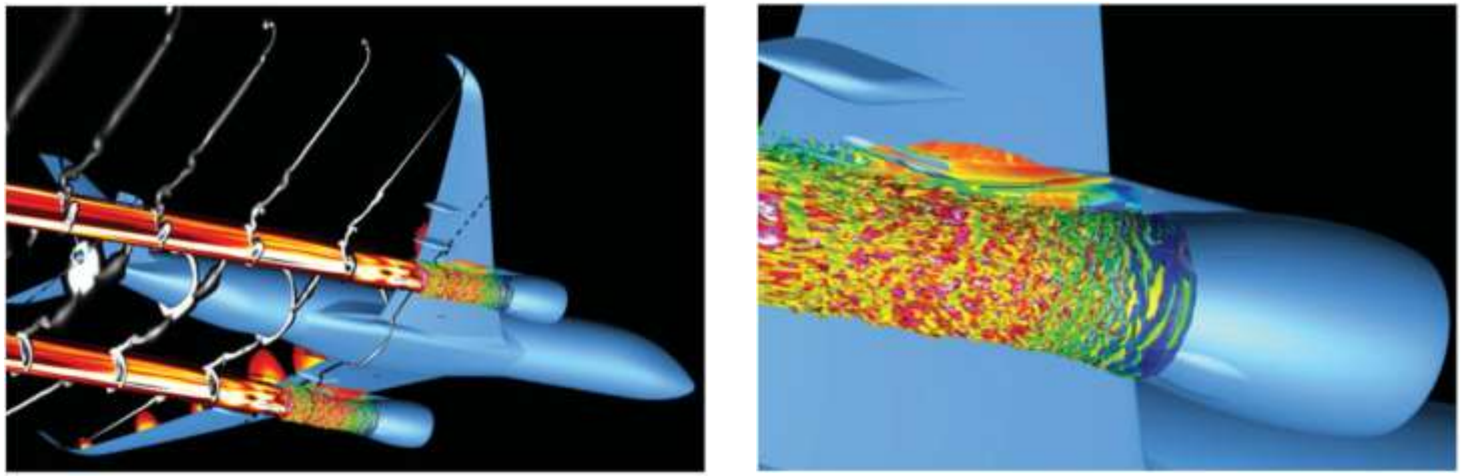
Meanwhile, in the aerospace/turbomachinery engineering fields…



Complete aircraft at scale 1:1 in true flight conditions (Ma=0.8, Re ~ $5\cdot10^7$, ~ $2\cdot10^8$ grid points)$^+$

$^+$*Picture taken from: S.Deck et al, Phil. Trans. R. Soc. A 372: 20130325 (2014).*

- DES and Zonal-DES modeling have proven to be **highly efficient in complex aerospace applications**
- The flexibility of hybrid modeling allows the accurate **resolution of different types of internal and external, flows within the same computational domain**
- Care is needed for the **optimal domain decomposition and numerics choice**

Why (Z)DES for ICE?

- Single, URANS-based turbulence modeling framework
- Activation of LES only where actually needed
- Less troublesome BCs
- Reported to be competitive with LES on sub-optimal grids, especially for wall-impinging flows[+]

[+]See e. g. *K. Keskinen et al. International Journal of Heat and Fluid Flow 65 (2017) 141–158*

More specifically:

- ○ Assess if a (relatively) basic ZDES model is capable of handling complex multi-cycle engine simulations with a **reasonable** level of accuracy

↓

- ✓ **Comparable** with experimental data sets
- ✓ **Comparable** with modern LES approaches on **engineering-grade meshes**

From two-equation URANS to (Z)DES

Basis:

- General URANS two-equation form:

$$\frac{\partial k}{\partial t} + \mathrm{C}_k = \mathrm{P}_k - \mathrm{S}_k + \mathrm{D}_k$$
$$\frac{\partial \psi}{\partial t} + \mathrm{C}_\psi = \mathrm{P}_\psi - \mathrm{S}_\psi + \mathrm{D}_\psi$$
$$\mu_t = f\left(k, \psi\right)$$

- Strelets et al. (2001) showed that URANS can be turned into DES **by modifying S_k only**

TKE sink term modification (1)

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TKE sink term modification (1)

$$S_{k,RANS} = \frac{k^{3/2}}{l_{RANS}}; \quad l_{RANS} = f(k, \psi)$$

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

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

From two-equation URANS to (Z)DES

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- General URANS two-equation form:

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

$$S_{k,DES} = F_{DES} S_{k,RANS}$$

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

Final form

From two-equation URANS to (Z)DES

Seamless DES:

- URANS-to-LES managed entirely by the model (**user decisional load kept to a minimum**), but…
- …the **triggering mechanism is not always efficient**

Zonal DES:

- URANS and LES (or DES) regions **explicitly marked** by the user
- Better **control of the solution behavior** (at the expense of **nontrivial *a-priori* decisions**)
- Good candidate for **complete ICE simulation**

TKE sink term modification (2)

$$S^{*}_{k,DES} = F^{*}_{DES} S_{k,RANS}$$

$$F^{*}_{DES} = C_{z1} F_{DES} + \left(1 - C_{z1}\right) F_{ZDES}$$

$$F_{ZDES} = C_{z2} + \left(1 - C_{z2}\right)\left(\frac{l_{RANS}}{C_{DES}\Delta}\right)$$

From two-equation URANS to (Z)DES

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$$F_{ZDES} = C_{z2} + \left(1 - C_{z2}\right)\left(\frac{l_{RANS}}{C_{DES}\Delta}\right)$$

C_{z1}	C_{z2}	*Simulation type*	*Mode*
0	1	URANS	I
1	1/0	DES	II
0	0	LES	III

Implementation overview

Which turbulence model?

- **RNG k-ε** model
  - Improved, shear-dependent ε-equation
  - Widely adopted in the ICE community

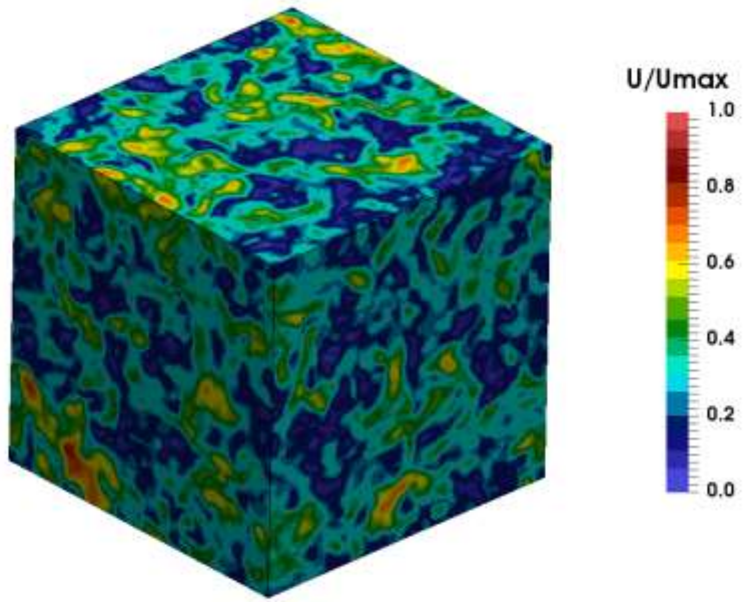
Which CFD code?

- **STAR-CD v4.22c** (Siemens PLM)
  - **Unstructured** FVM code
  - **Second-order** accurate in space and time
  - ZDES formulation implemented through user-supplied **Fortran subroutines**

Methodology implementation/calibration:

- The C_{DES} value must ensure a consistent **turbulent energy decay** in mode III (**pure LES**)
- The optimal value depends on:
  - the specific underlying **turbulence model** (k-ε, k-ω…)
  - the accuracy/behavior of the **discretization schemes**
- **Calibration tests needed**

C_{DES} calibration: turbulence box

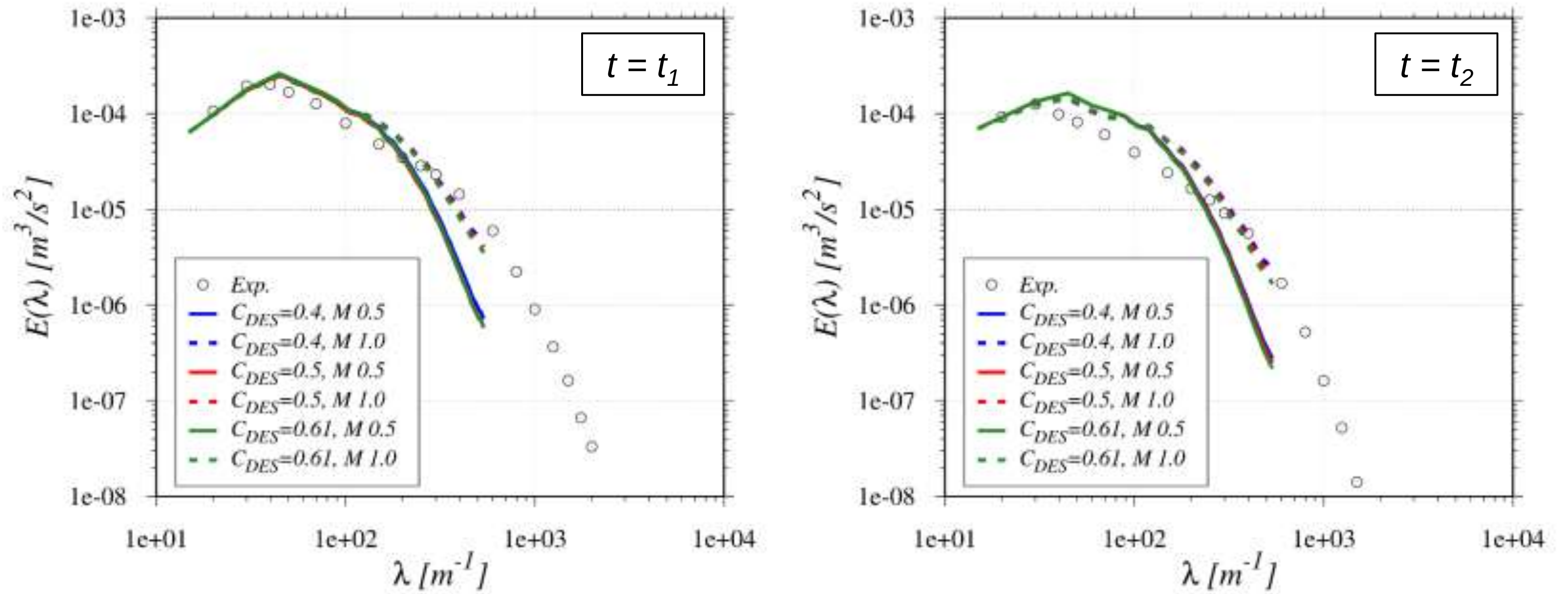


- Standard test for DNS and SGS models
- Cubic domain with cyclic BCs in each direction, N^3 perfectly cubic cells (N=64)
- Flow field initialized with an incompressible divergence-free turbulent spectrum
- Turbulence is left to **spontaneously decay** driven by **mode III of ZDES**
- C_{DES} is varied in the 0.4-0.61$^+$ range
- **MARS** scheme for momentum convection (BF = 0.5 and BF = 1)
- Comparisons with the Comte-Bellot and Corrsin [§] database (**energy spectra**)

$^+C_{DES}$ = 0.61 is the first “standard” value reported in the literature for k-ε based DES models

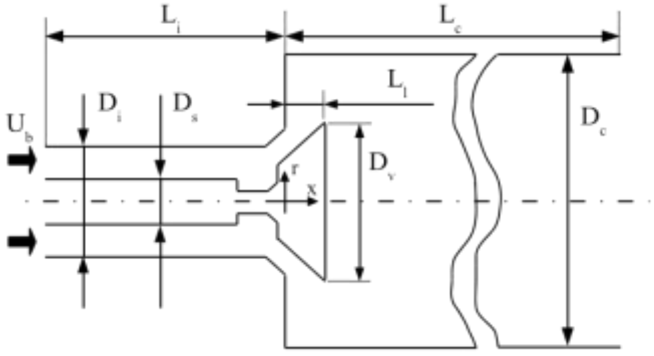
[§] G. Comte-Bellot G and S. Corrsin *Journal of Fluid Mechanics 1971; 48(2): 273–337*.

C_{DES} calibration: turbulence box



- **The BF effect is dominant**
- BF = 1 assumed as default for the LES mode (mode III)
- C_{DES} = 0.61 assumed as standard

Case overview



Valve Stem Diameter (D_s)	16 mm
Intake Duct Diameter (D_i)	34 mm
Cylinder Diameter (D_c)	120 mm
Valve Head Diameter (D_v)	40 mm
Intake Duct Length (L_i)	140 mm
Cylinder Length (L_c)	300 mm
Valve Lift (L_L)	10 mm
Inlet Bulk Velocity (U_b)	60 m/s
Fluid	air at NIST standard conditions
Inlet Bulk Reynolds Number (Re_b)	~ 3 x 10^4

Preliminary remarks:

- Intake port geometry with an axis-centered fixed poppet valve, $\mathbf{Re_b \approx 3 \times 10^4}$
- **LDA (velocity) and axial pressure** measurements available

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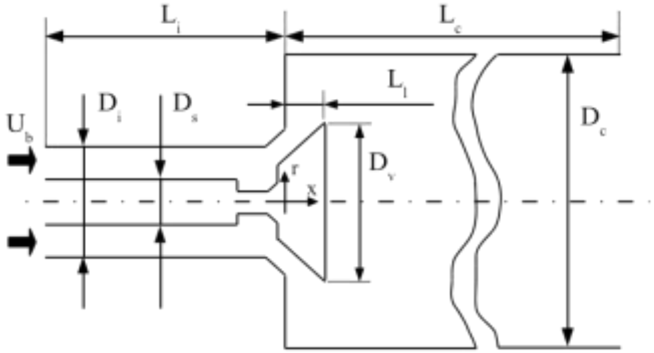
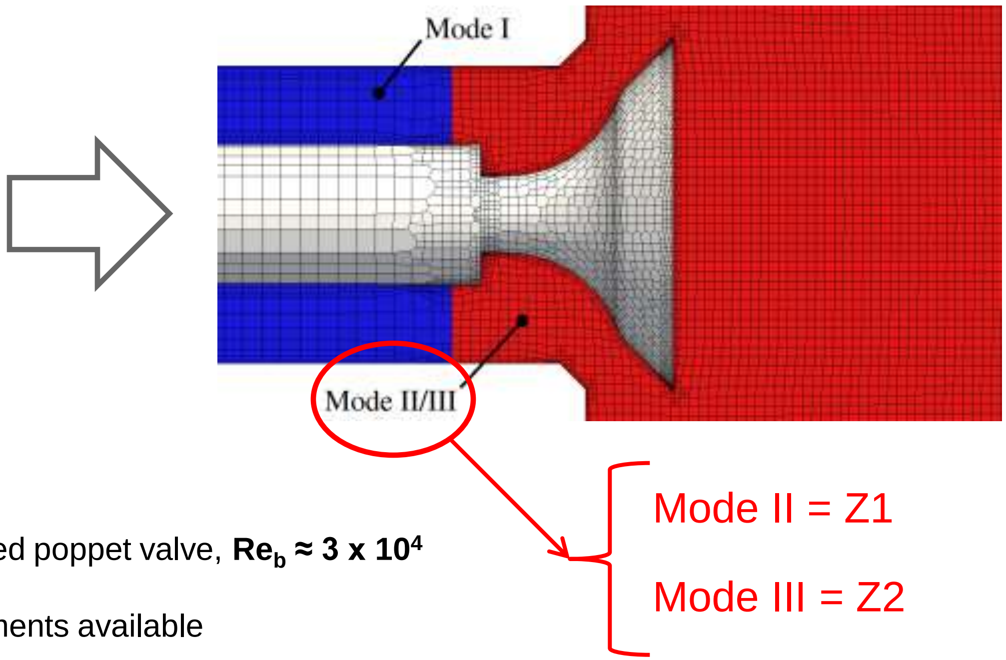


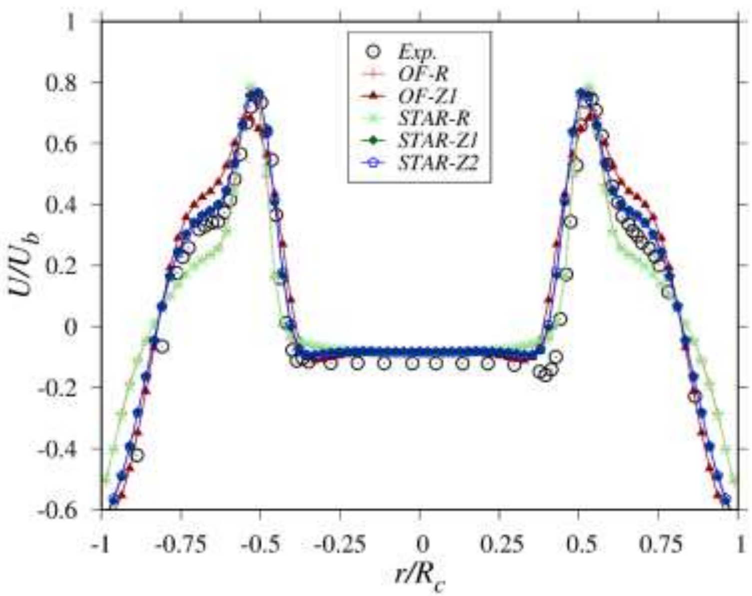


Preliminary remarks:

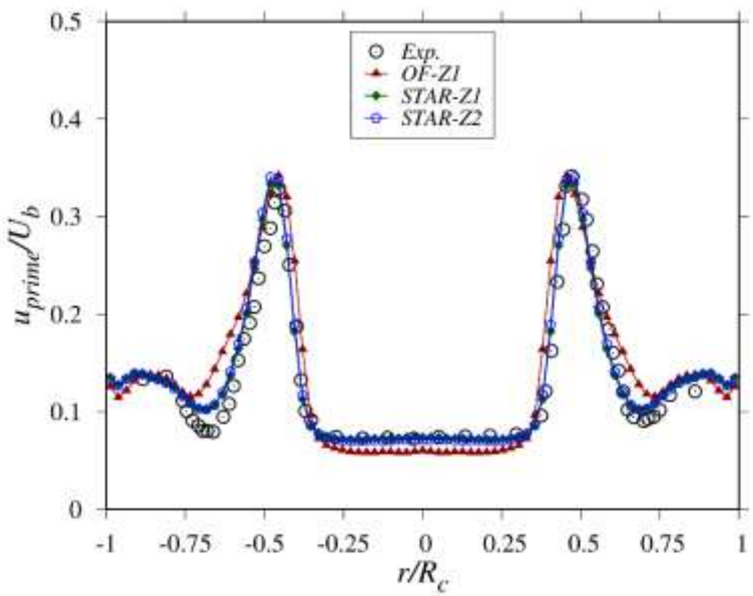
- Intake port geometry with an axis-centered fixed poppet valve, $\mathbf{Re_b \approx 3 \times 10^4}$
- **LDA (velocity) and axial pressure** measurements available
- **Mode I** numerics: **MARS 0.5** for momentum and scalars
- **Mode II/III** numerics: **MARS 1** for momentum, MARS 0.5 for scalars
- Standard inflow/outflow incompressible BCs, WFs at the walls
- Comparisons with experiments and **OpenFOAM** results (**same turbulence model and grid**, similar numerics)

Results (x = 20 mm)

Mean axial velocity

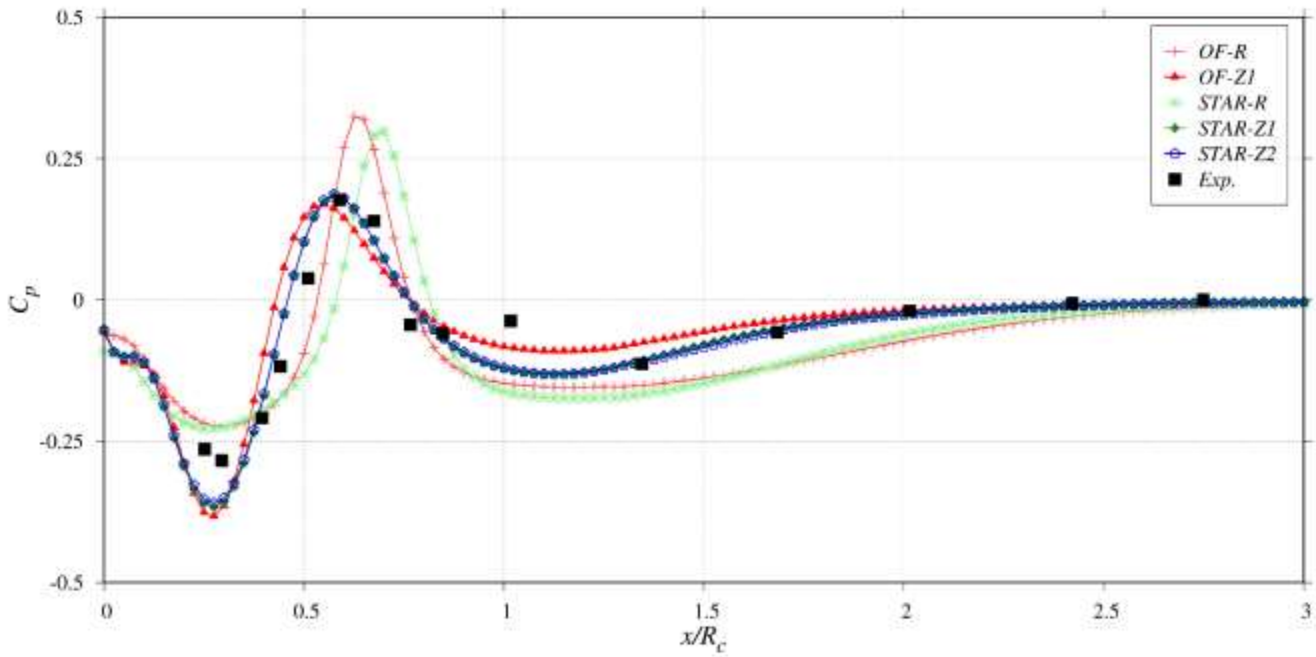


RMS axial velocity fluctuation



- Significant improvements compared to steady RANS profiles (code-by-code differences due to **numerics**)
- Z1 and Z2 **time-averaged** profiles very close (Mode II is likely to trigger **LES in most of the domain**)

Results (axial pressure development)



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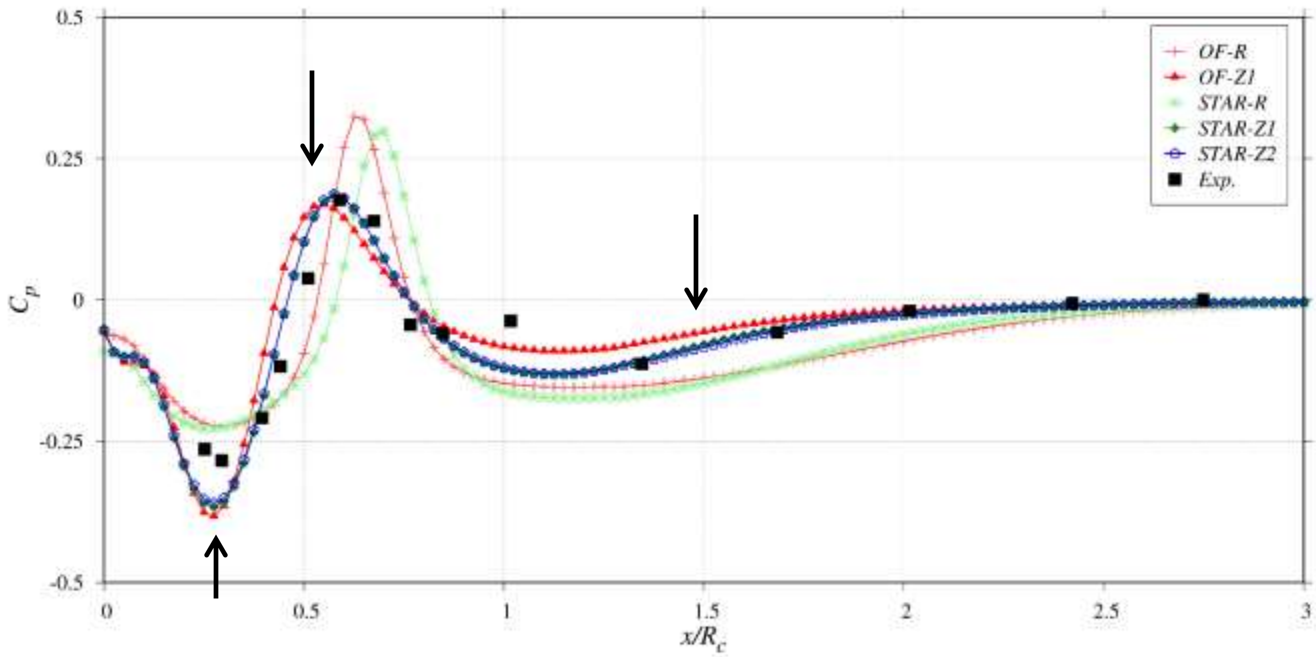
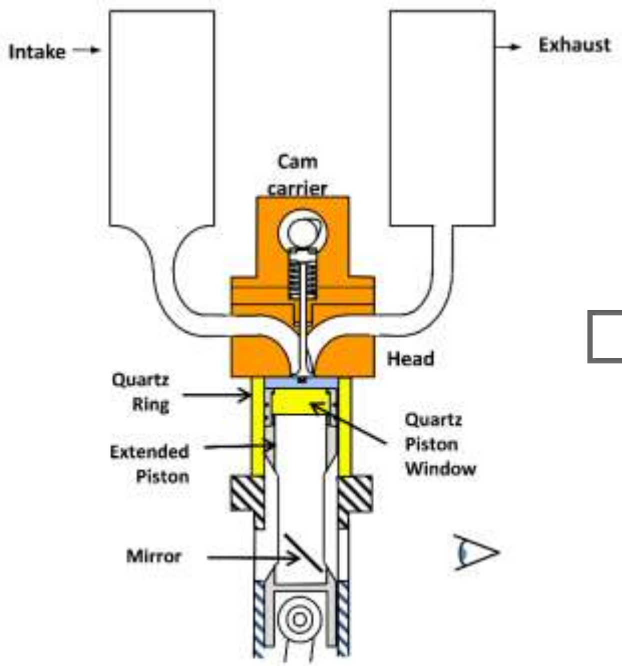


- Even more pronounced improvements compared to RANS (same code-by-code differences)
- Z1 and Z2 **time–averaged** profiles very close (Mode II is likely to trigger **LES in most of the domain**)

Applications – TCC III

Case overview

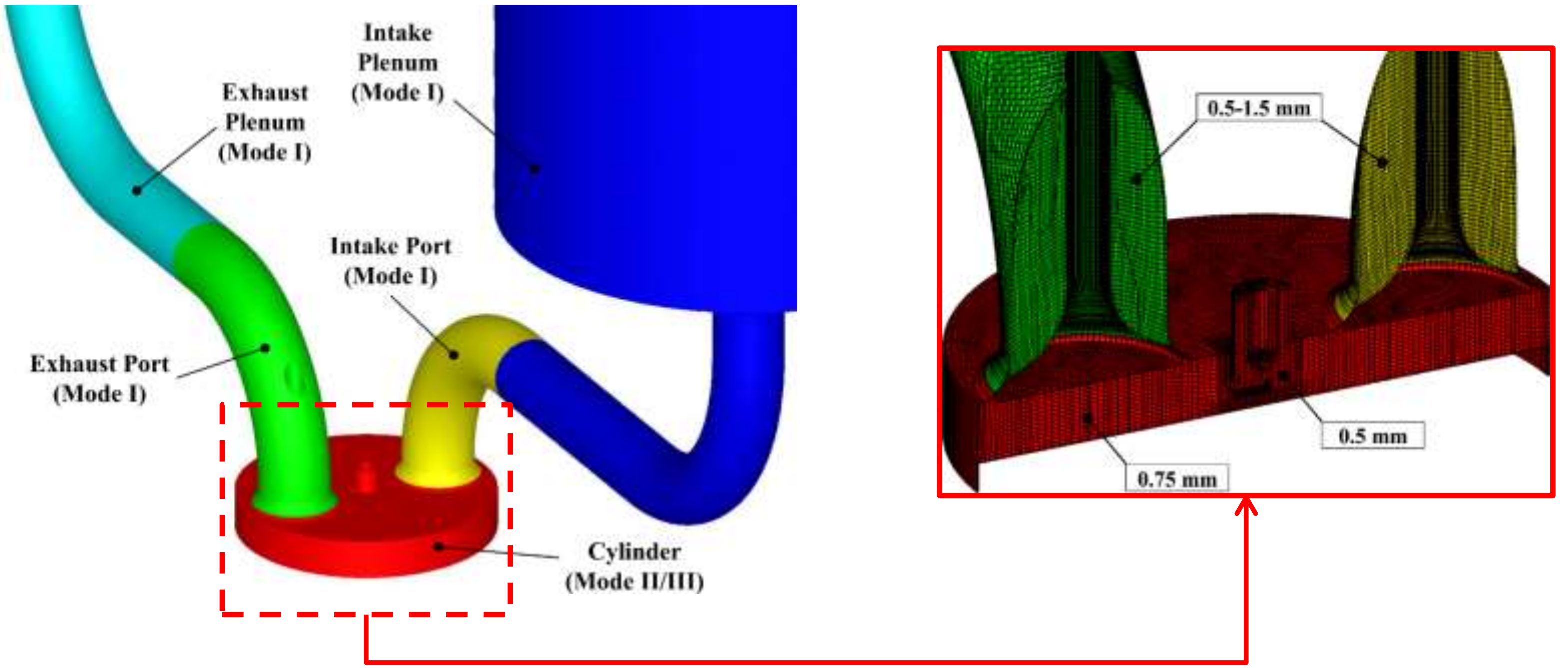


Engine Data	
Bore	92 mm
Stroke	86 mm
Connecting rod length	231 mm
Geometrical compression ratio	10:1
Operation	4-stroke
N. of valves	2
Combustion chamber type	Pancake
RPM	1300
Intake manifold pressure	40 kPa

Preliminary remarks (1):

- Selected for the **ease of reproduction** and large experimental **PIV** data set
- **1300 RPM and 40 kPa** intake manifold pressure
- Availability of LES data sets from UniMoRe

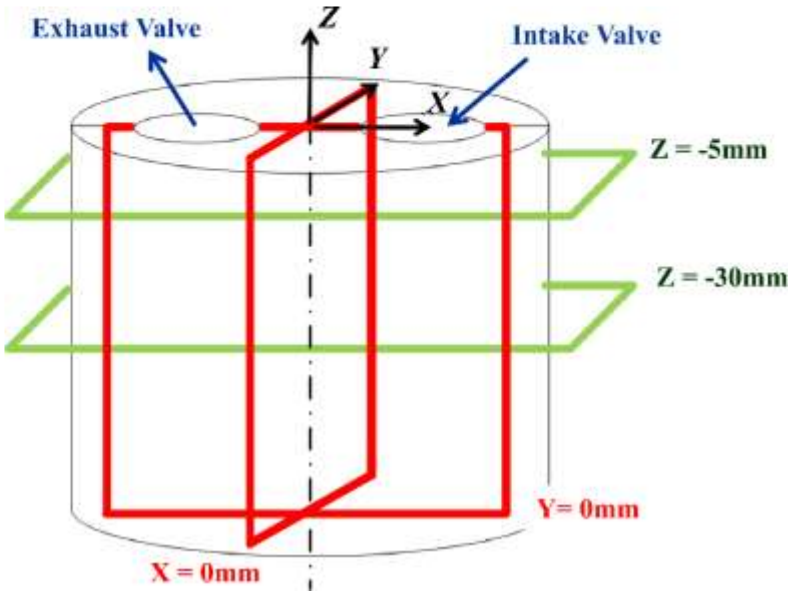
Case overview



Preliminary remarks (2):

- Full domain splitted in 5 zones (cylinder, intake/exhaust ports, plenums)
- **Only the cylinder** zone treated in scale-resolving mode (**Mode II or Mode III**) → Mode II = TCC-Z1; Mode III = TCC-Z2
- Max 2M cells at BDC, ~ 0.75 mm base cell dimension in the cylinder

Case overview



$$\langle u_i \rangle = \frac{1}{n}\sum_{j=1}^{n} u_{i,j}$$

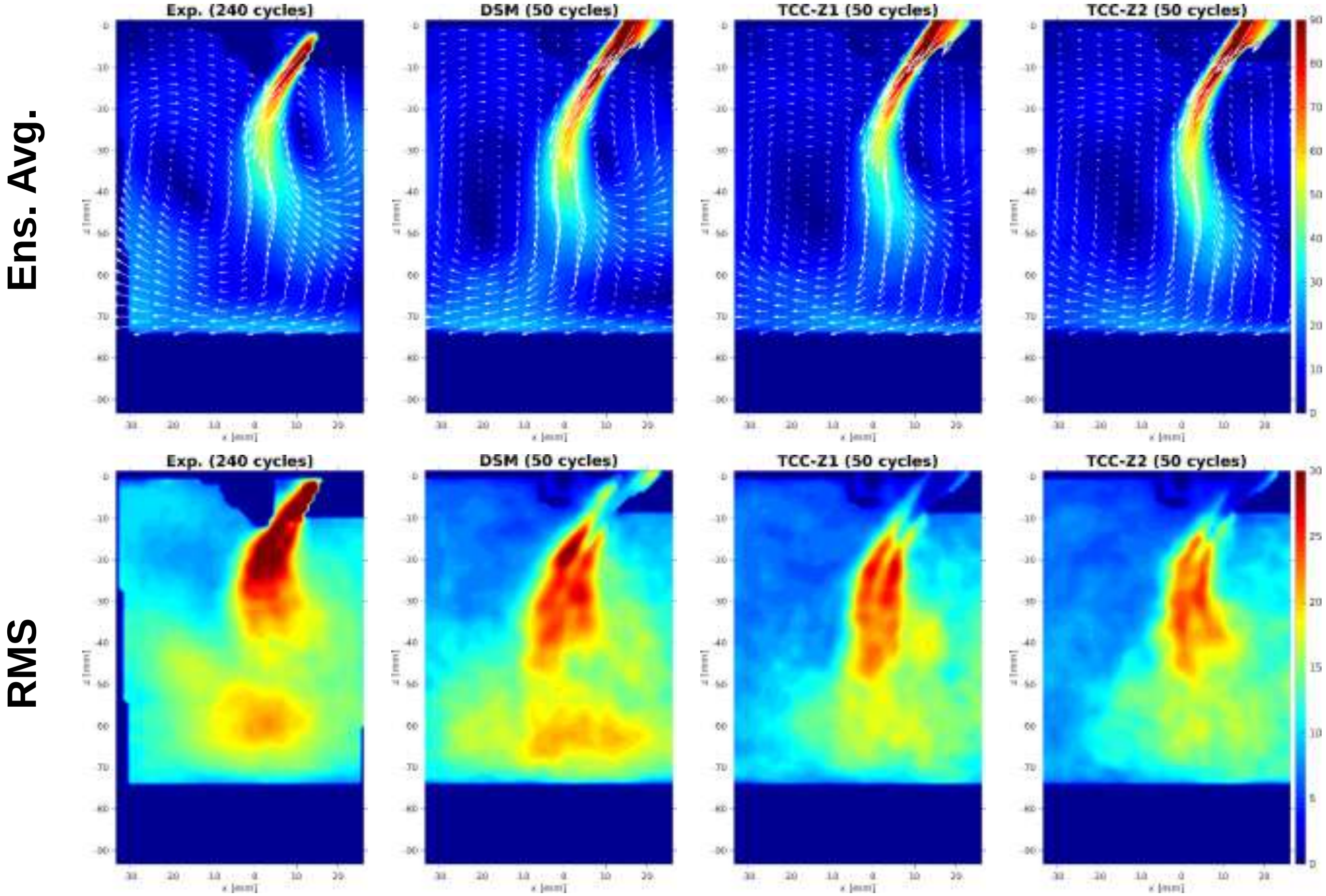
$$u_{i,rms} = \sqrt{\frac{1}{(n-1)}\sum_{j=1}^{n}\left(u_{i,j} - \langle u_i \rangle\right)^2}$$

i = PIV grid point
j = cycle number
$n = 50$

Preliminary remarks (3):

- Postprocessing initially focused on the **vertical planes**
- **S_2013_10_24_01** and **S_2014_02_05_02** reference data sets (same windows/resolution in the simulations)
- Previous **LES DSM** results (on the same CFD grid) added for comparison

Results (Y = 0): 475 CA



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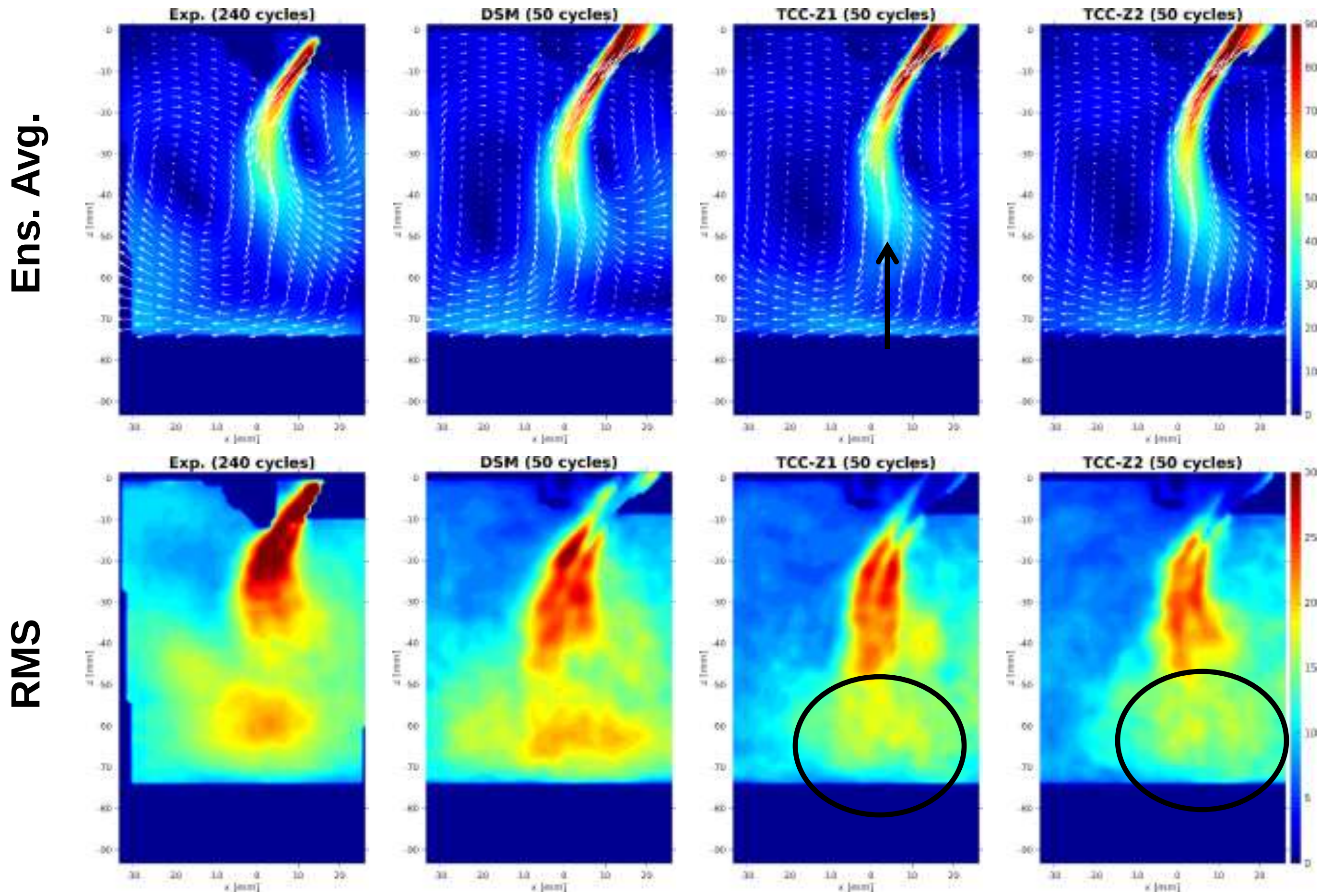
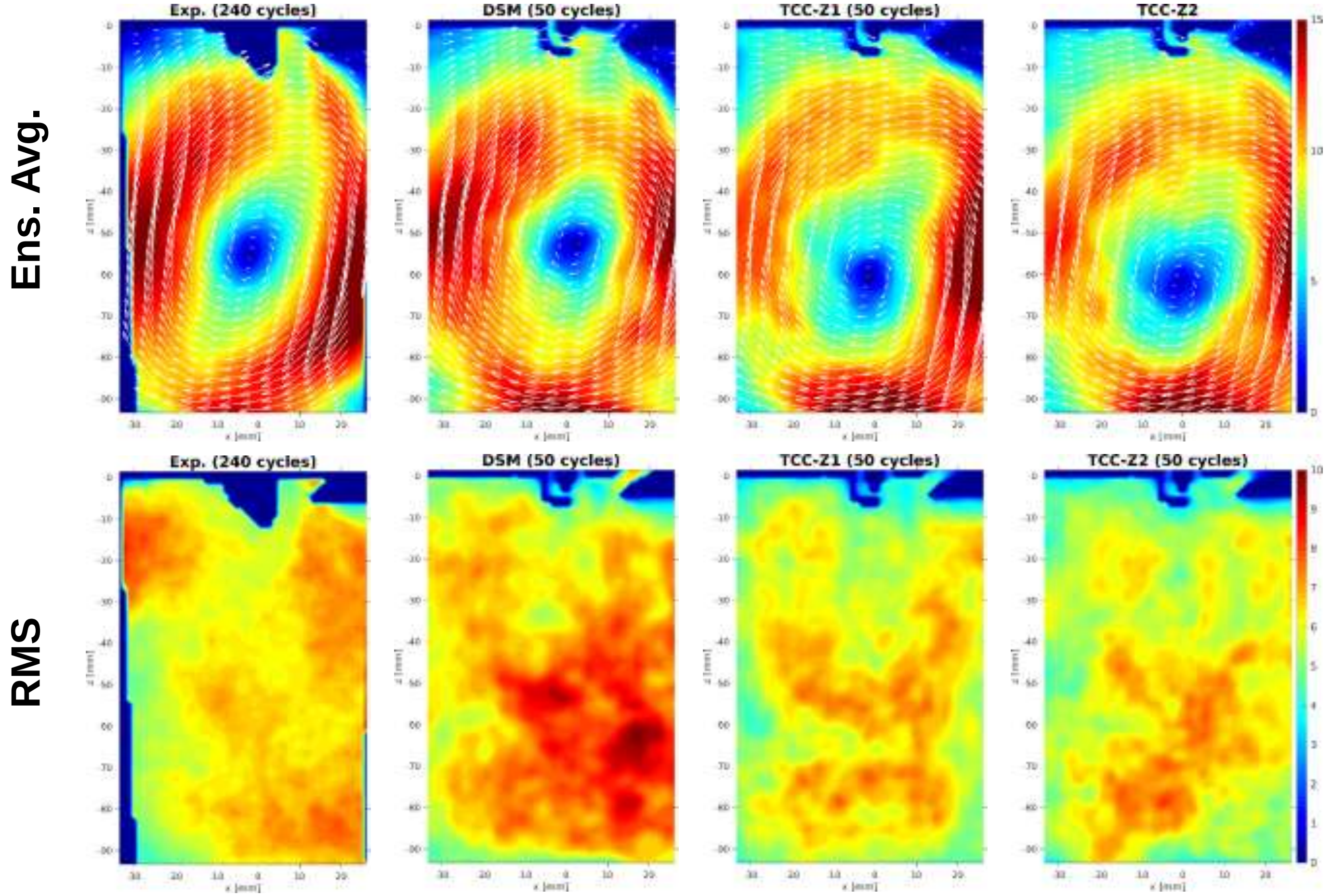


- Good **average jet shape** prediction by TCC-Z1 (added modeled visosisty?)
- Underestimation of RMS fluctuations close to the piston head

Results (Y = 0): 540 CA



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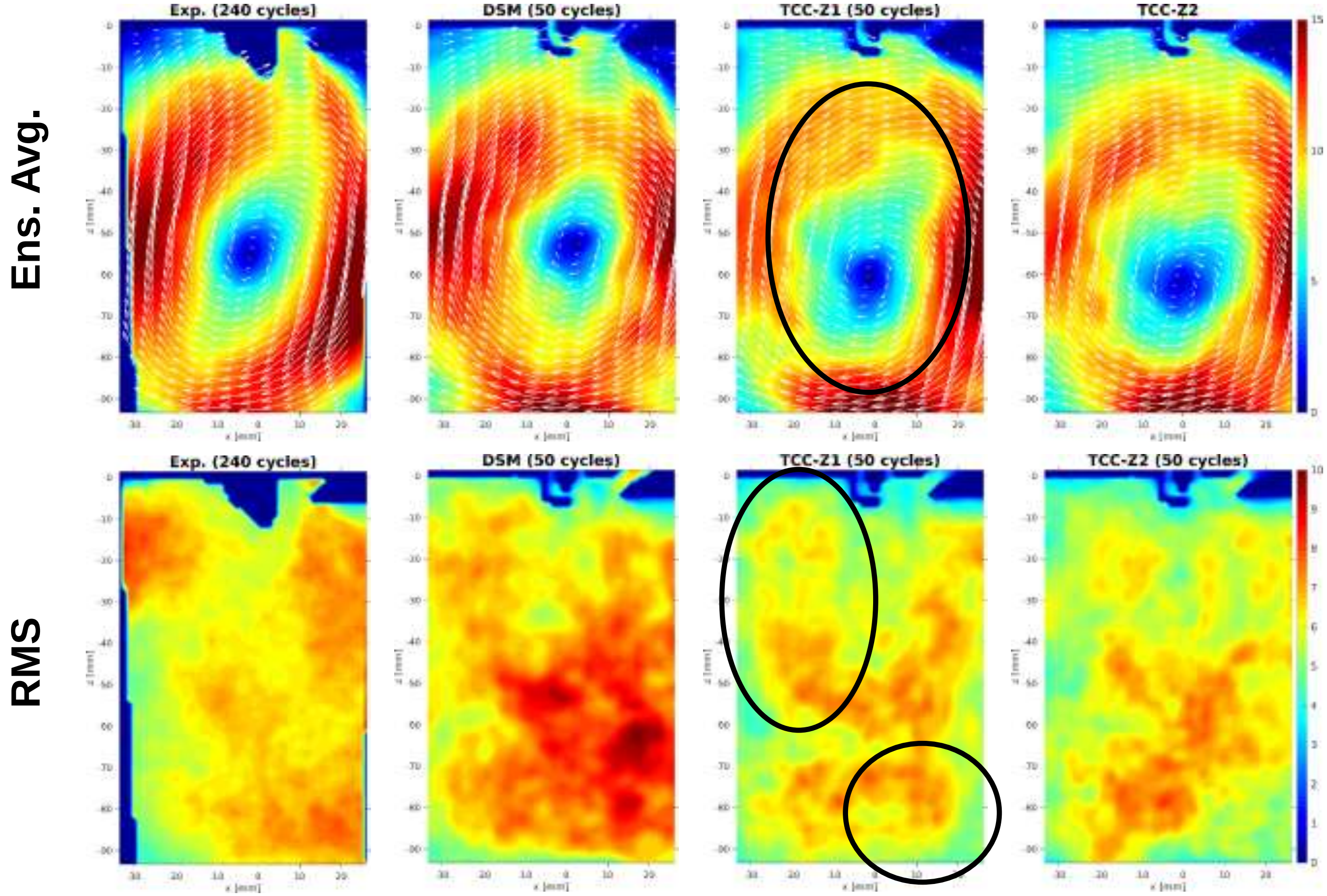
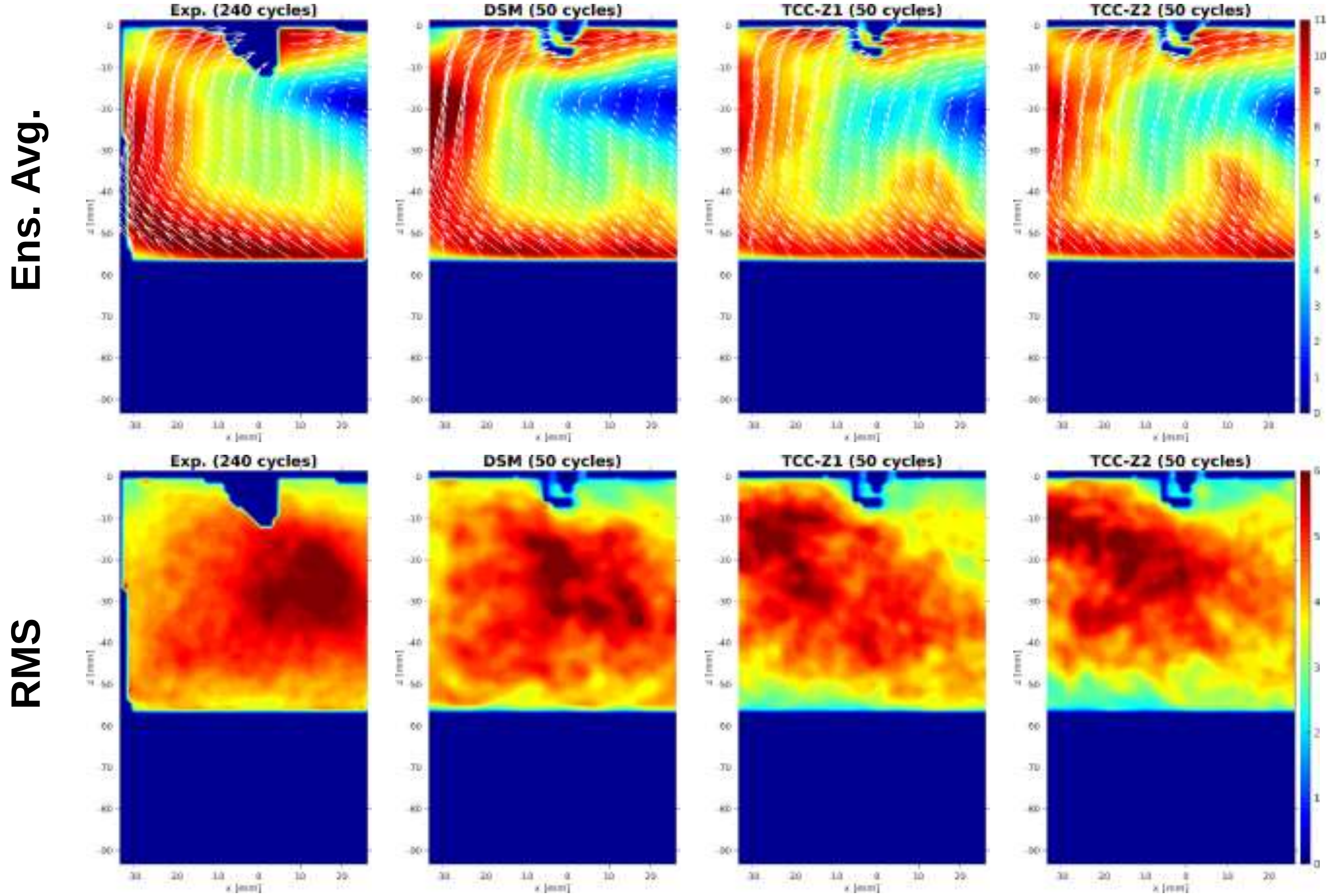


- **DSM closer to experiments**
- TCC-Z1 slighlty **more consistent** with DSM and experiments

Results (Y = 0): 630 CA



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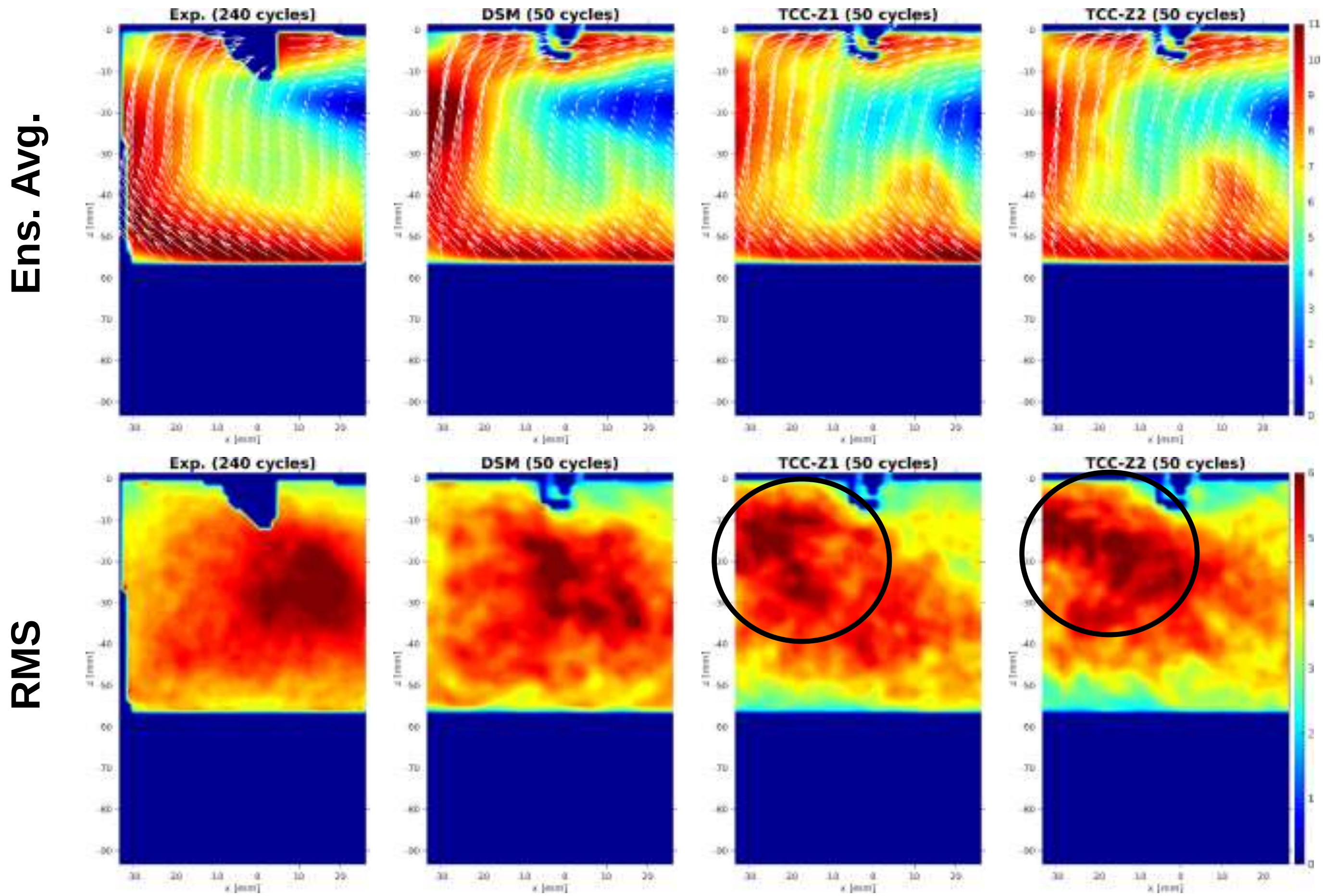
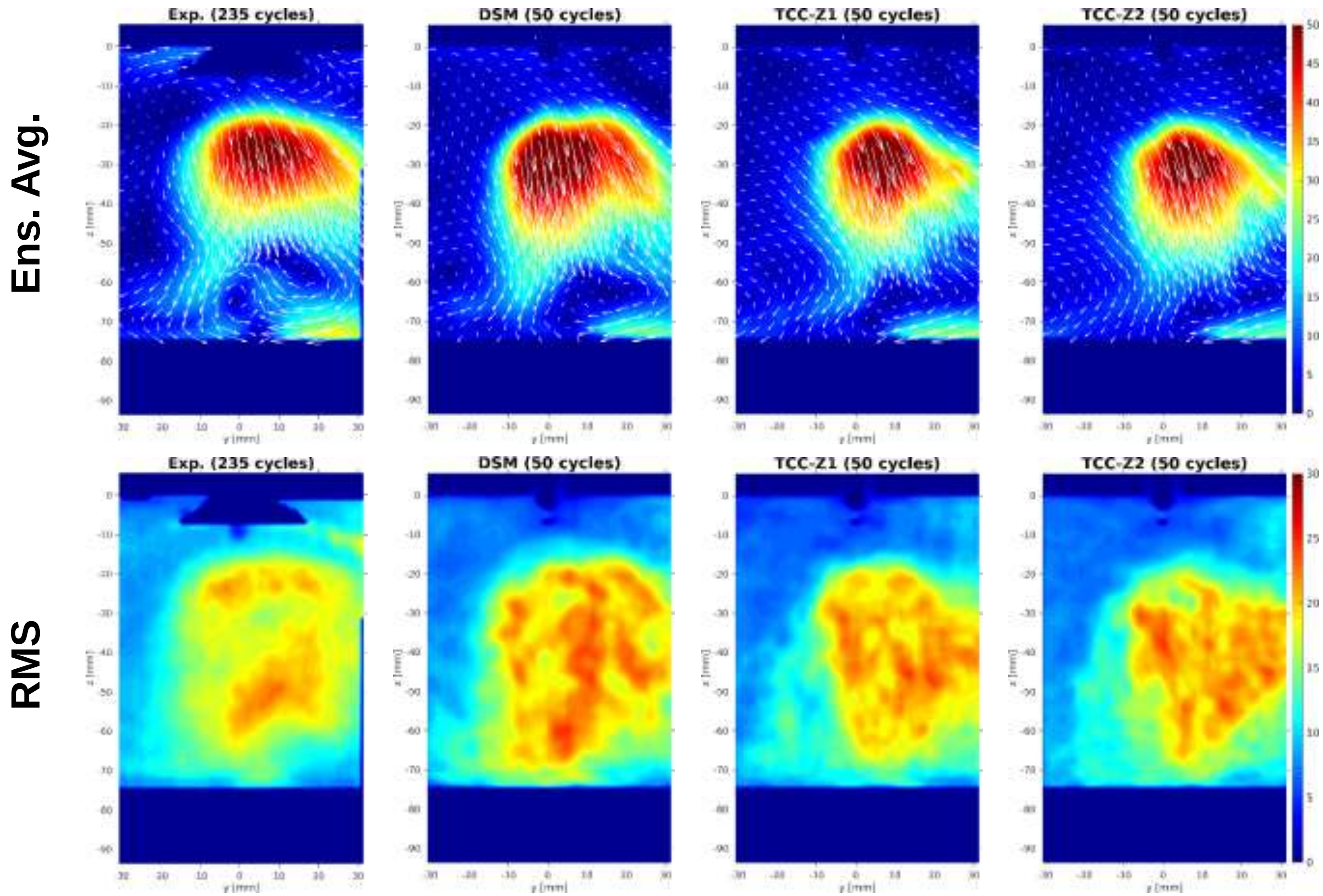


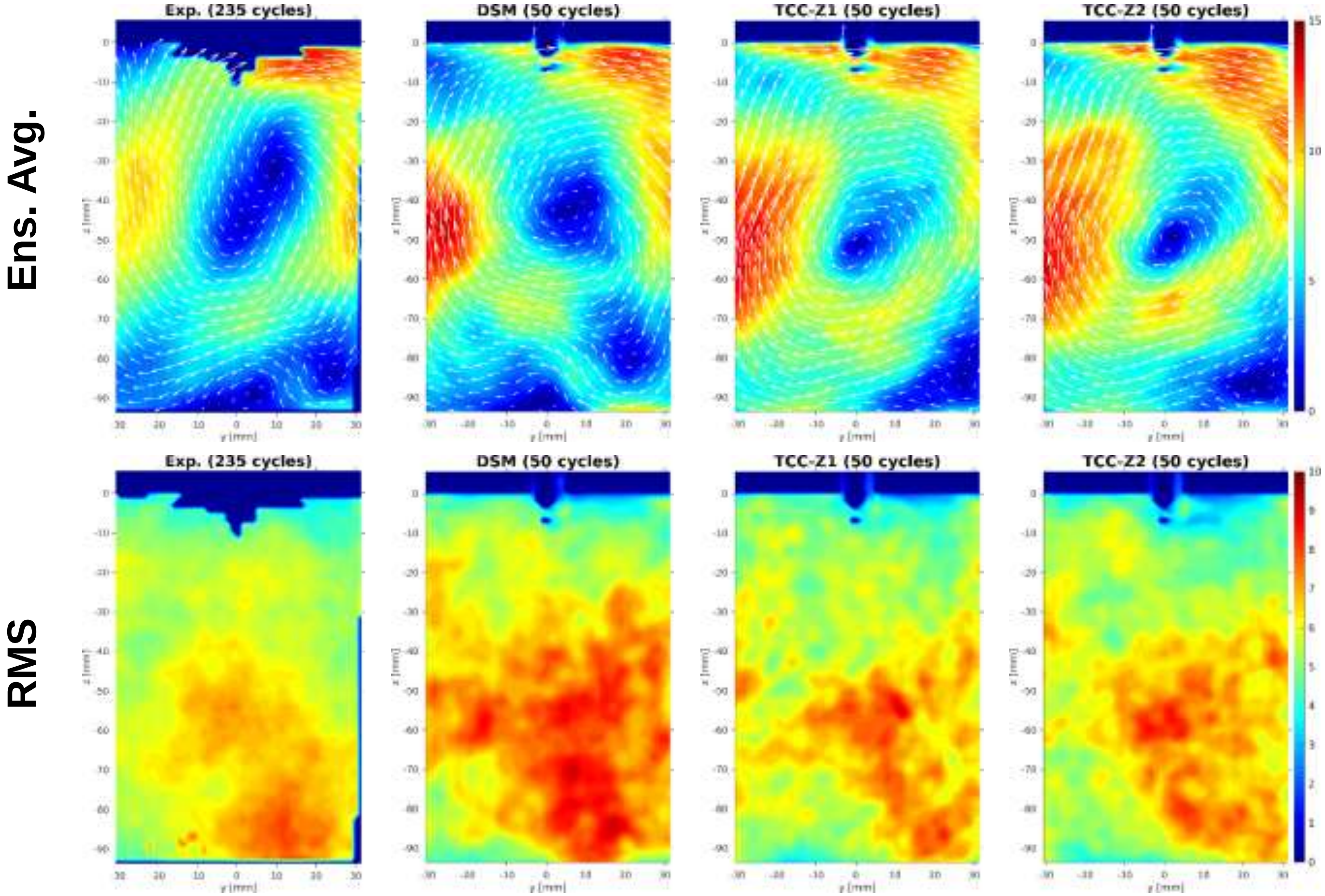
- DSM still in good agreement with the experiments
- Anomalous shift of the RMS peak values

Results (X = 0): 475 CA



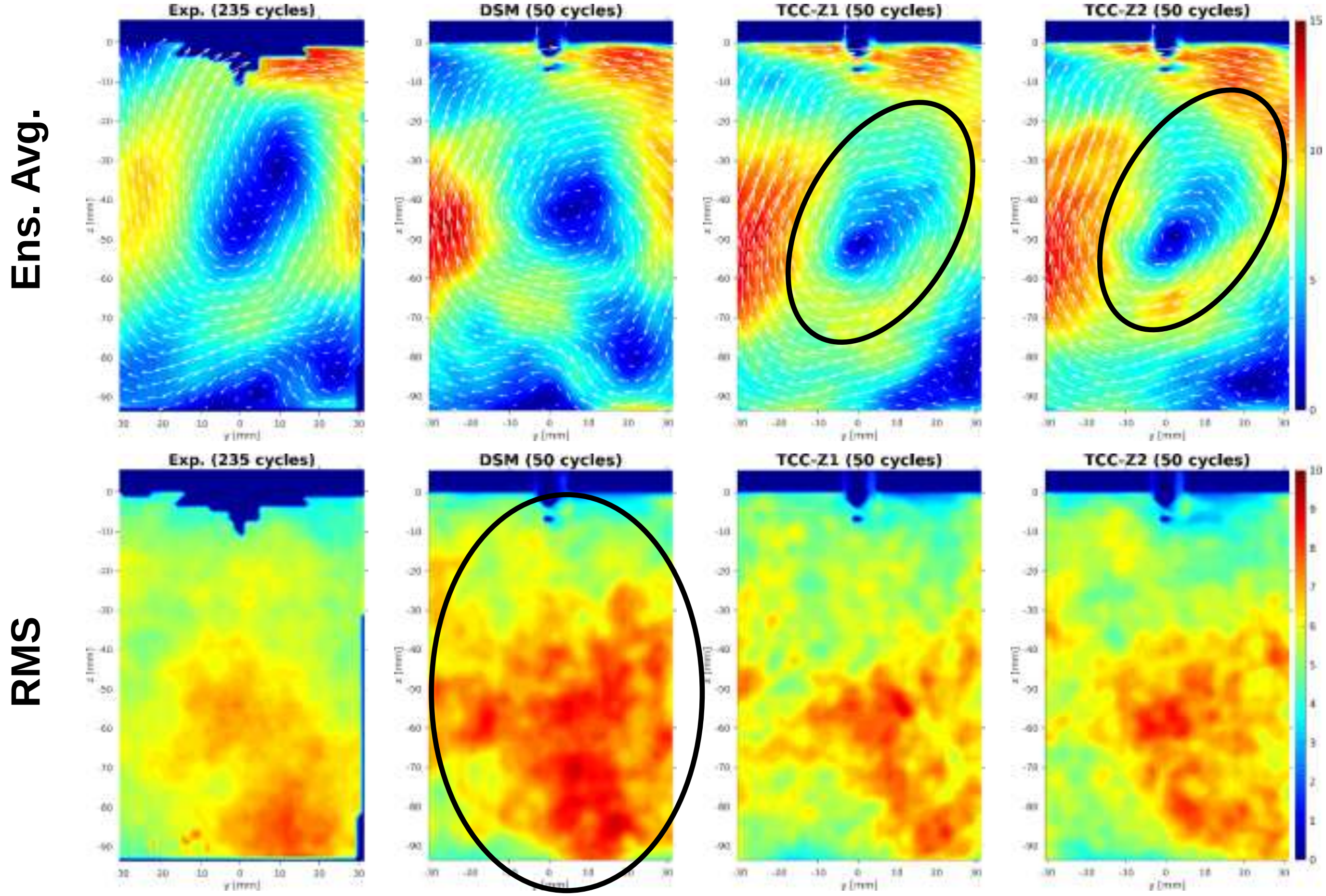
- **Good overall consistency** for all numerical predictions
- Small differences persist between TCC-Z1 and TCC-Z2

Results (X = 0): 540 CA



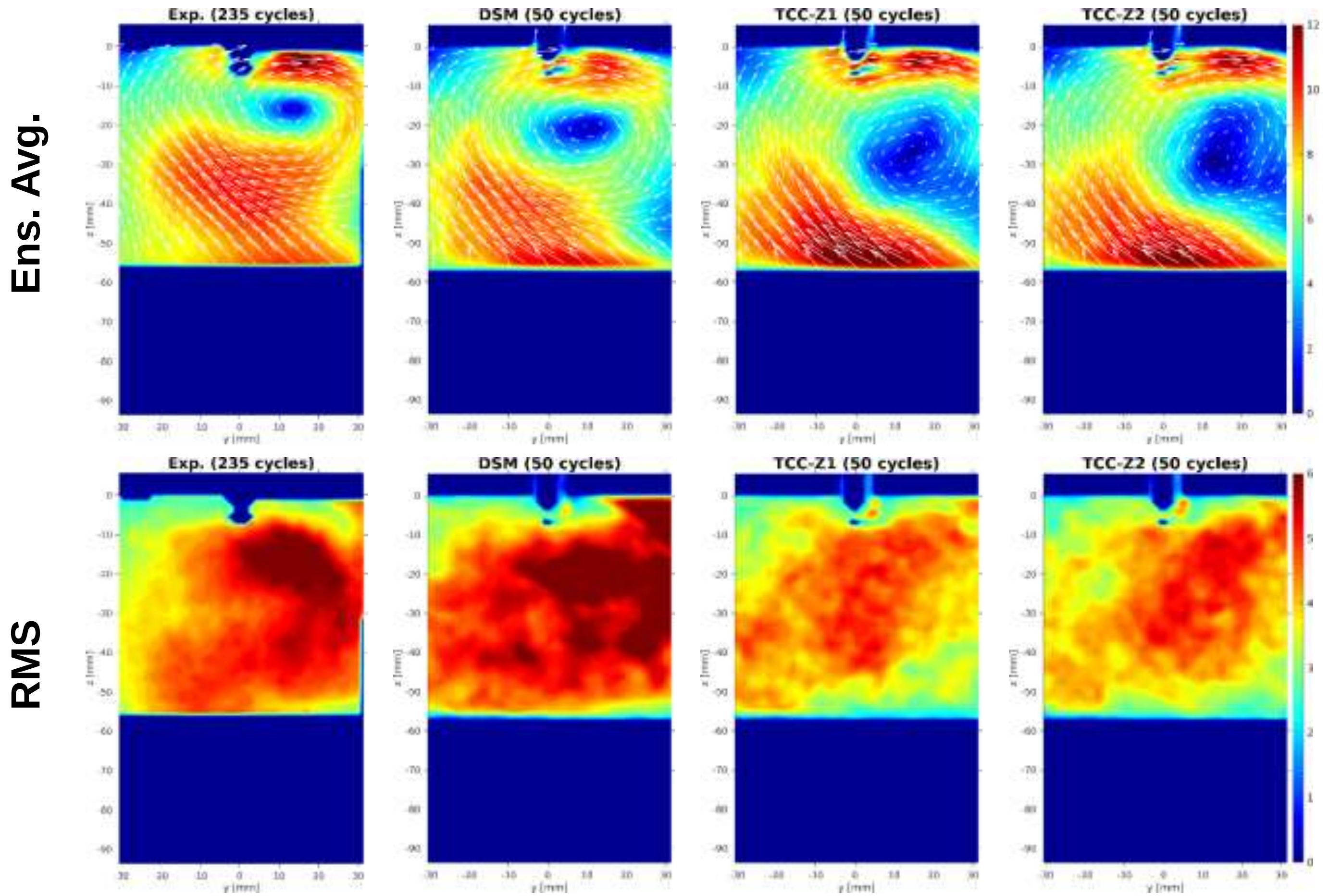
Applications – TCC III

Results (X = 0): 540 CA



- Much better **main vortex average shape** description for TCC-Z1 and TCC-Z2
- DSM seems to overestimate RMS fluctuations

Results (X = 0): 630 CA



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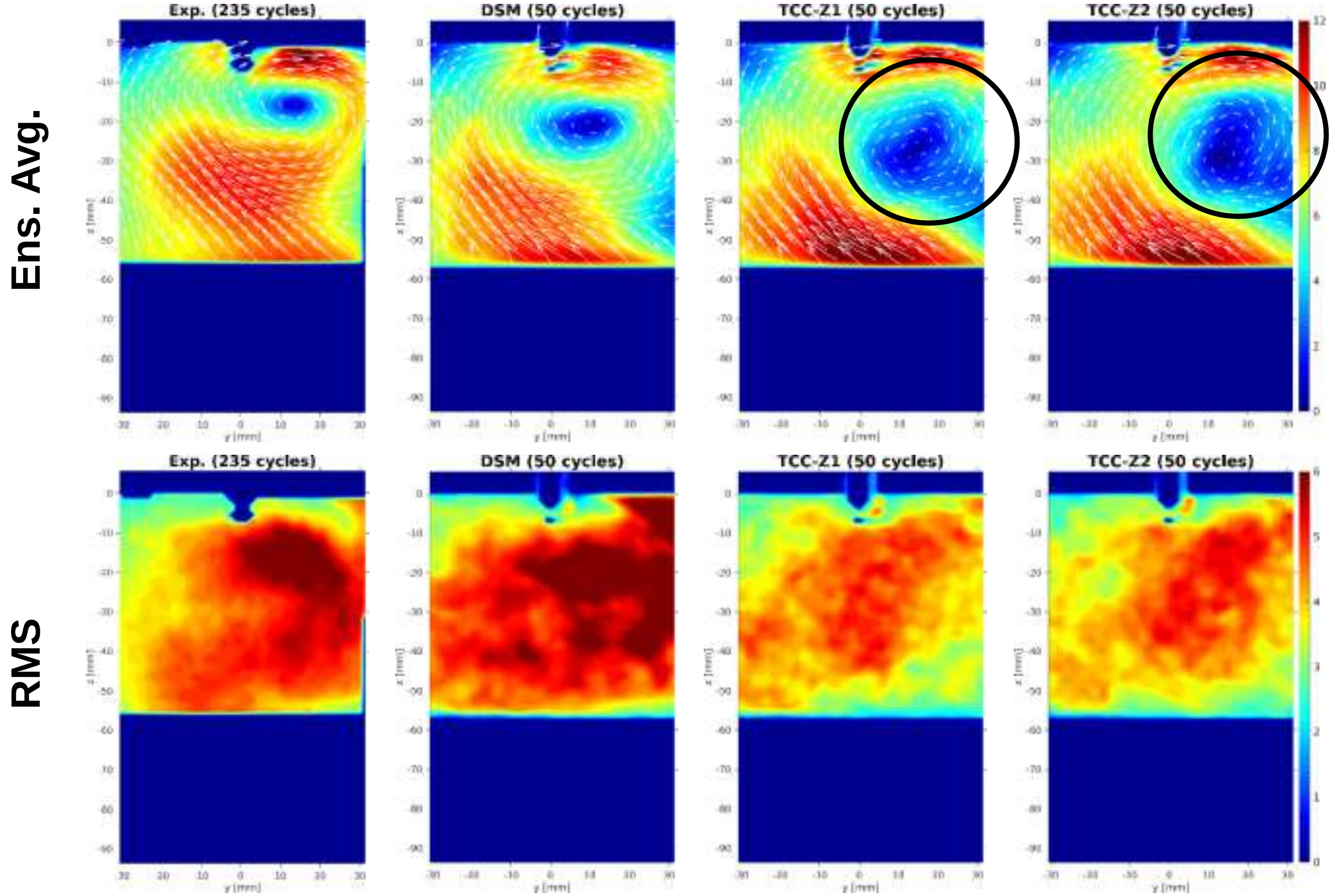

- Vortex compression **better described by DSM**
- TCC-Z1 (still) **slightly more consistent** than TCC-Z2 (average flow)

Final remarks

- Is the evaluated ZDES formulation **reasonably adequate** for engine multi-cycle simulation?

Final remarks

- Is the evaluated ZDES formulation **reasonably adequate** for engine multi-cycle simulation?

Yes, but…

What's next?

- More TCC-III results (in progress):
  - complete the analyses on the vertical planes (LES quality indicators, LES or DES for the cylinder?);
  - more planes;
  - different zonal setups.
- Modeling aspects (LES mode, wall modeling)
- Different engines (pentroof, 4 valves, GDI?)
- Combustion?

Conclusions

Acknowledgments

- ✓ **GM** (through the GM University of Michigan Automotive Cooperative Research Laboratory, Engine Systems Division). ⇒ ✓ TCC-III database
- ✓ **Siemens PLM Software Inc.** ⇒ ✓ STAR-CD software licensing (through UniMoRe HPC resources)

Conclusions