11th OpenFOAM Workshop
Guimarães, Portugal, June 26th-30th 2016

Hybrid RANS/LES of Moving Boundary Problems: Application to In-Cylinder Flows

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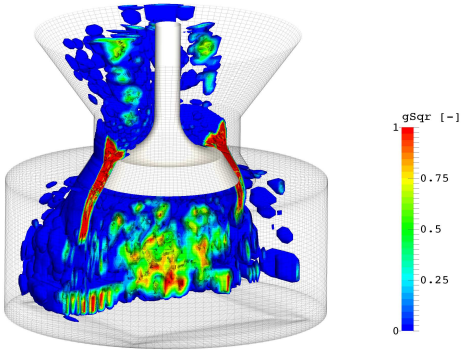
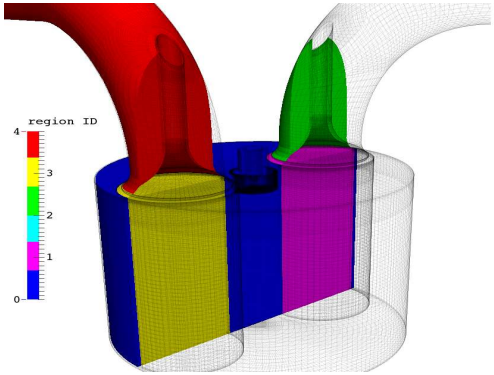
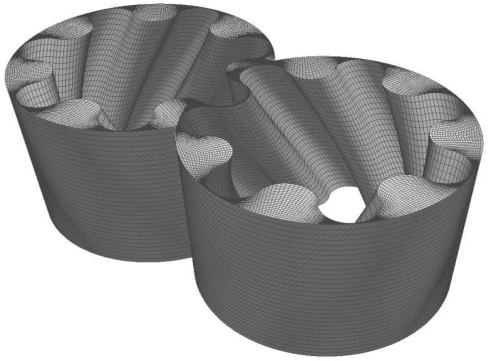
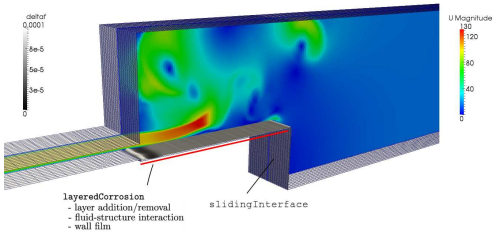
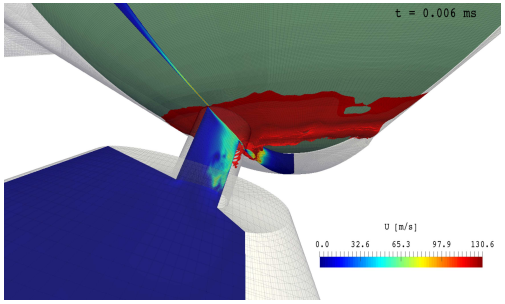
Motivation

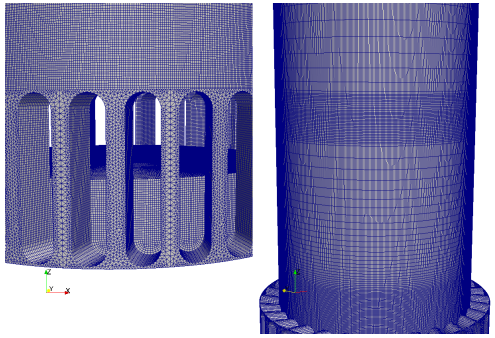










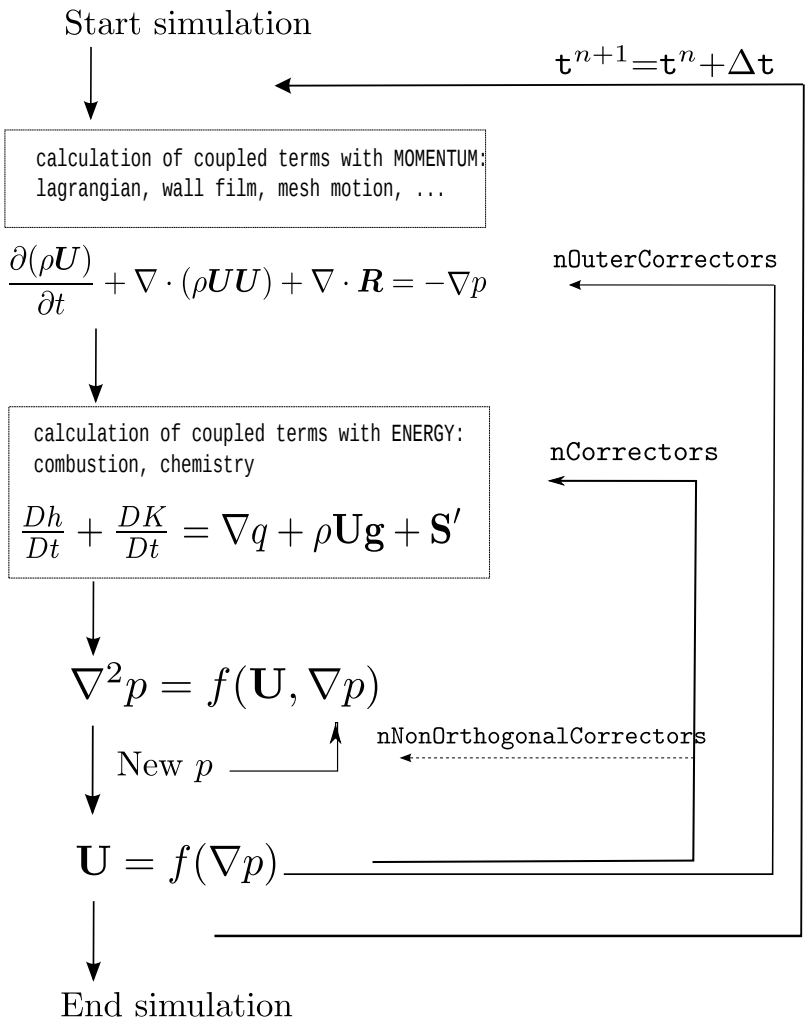


Goal: *time-resolved simulation of turbulent flows in moving grids*

To begin with...

- **Parallel Automatic Mesh Motion with Topological Changes**
  - → SAE 2013-24-0027, LES4ICE-2012, IMEM 2013, IMEM 2014
    - implementation of `slidingInterface`, `attachDetach` into the "Foundation" release
  - → SAE 2015-01-0384
    - Improvements and extensions of the dynamic mesh class
    - run-time addition of user-defined moving components to existing motion solvers
  - → IMEM 2015 (`https://imem.cray.com/2015/agenda-2015.html`)
    - combined operation of topology modifiers with Arbitrary Mesh Interface (AMI)
    - compressible dynamic solver: `topoEngineFoam`
    - automatic decomposition with topological changes: `$SRC/parallel`
- **Time resolved turbulence modeling of wall-bounded flows**
  - → Comput Fluids 93, Comput Fluids 117, FTC-2015 95(2)
    - LES of IC engines
  - → SAE Int. J. Engines 8 (2), pp. 426-436
    - **Scale-adaptive hybrid RANS/LES turbulence modeling (DLRM model)**

Current development (dynamic solver)



Improvements to the solver

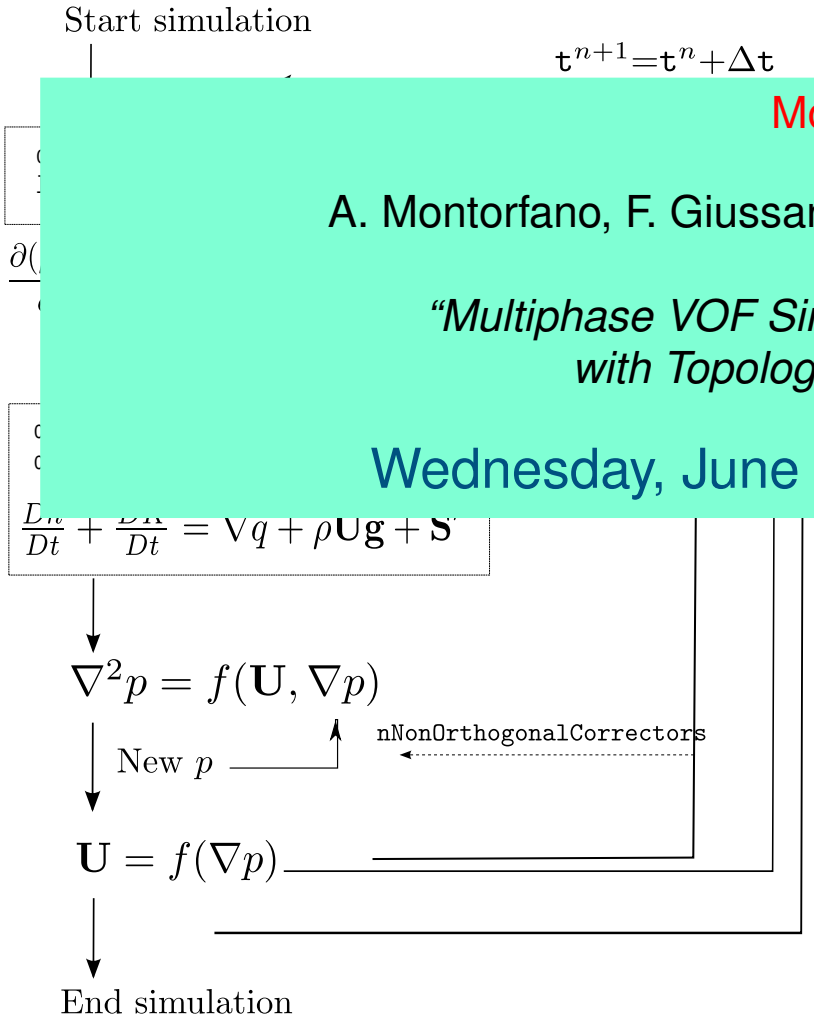
- 2nd order time discretization **(bug fix)**
- Grid Conservation Law (GCL) **(bug fix)**
- Strict coupling between pressure and energy
- Interpolative mapping

Improvements to the mesh class

- Run-time selection of mesh modifiers
- Run-time selection of point motion law
- Proxy class `topoManager` to handle:
  - modifiers creation/update
  - modifiers activation/deactivation
  - flux correction
  - remapping

All the presented work is fully compatible and tested with the release by the OpenFOAM® Foundation **versions** `3.0.x` **and** `-dev`**.**

Current development (dynamic solver)



Improvements to the solver

- 2nd order time discretization **(bug fix)**

More detail in:

A. Montorfano, F. Giussani, F. Piscaglia, J. Hélie, S.M. Aithal

"Multiphase VOF Simulation Of Gasoline Injectors with Topologically Changing Grids"

Wednesday, June 29th @ room S1, h. 10.50

- Run-time selection of point motion law
- Proxy class `topoManager` to handle:
  - modifiers creation/update
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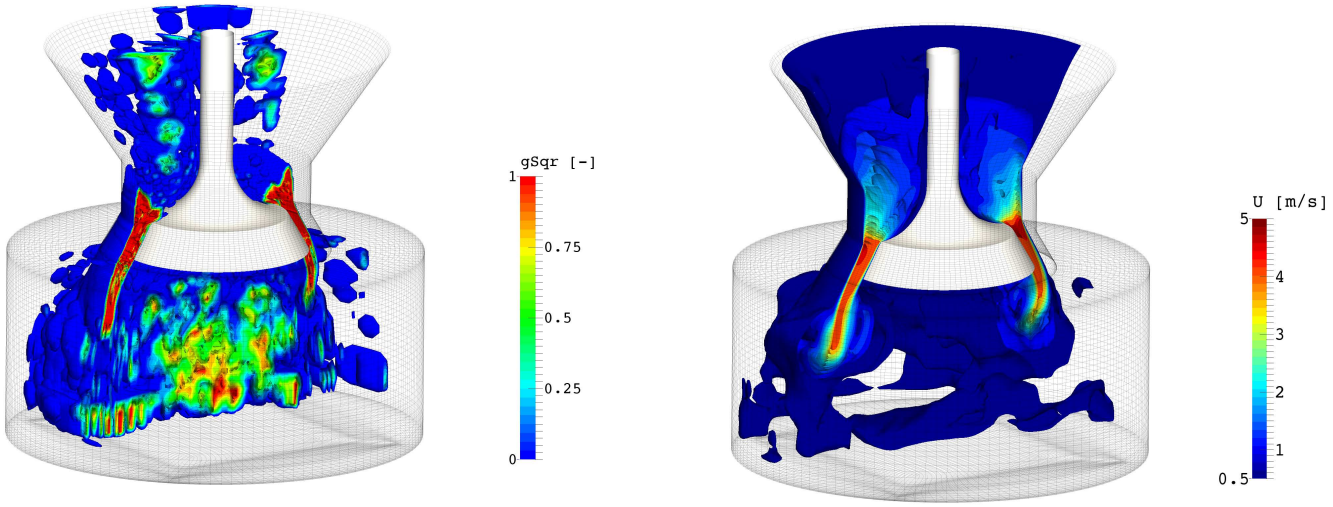
Hybrid RANS/LES



- **Hybrid RANS/LES $\rightarrow$ Scale-Adaptive Dynamic Filtering**:
  - discriminate between **resolvable and unresolvable scales**
  - **is able to automatically switch between LES and URANS**.
  - RANS-like case setup (mesh requirements, boundary and initial conditions, . . .);
  - reasonable computational cost

Scale-Adaptive Dynamic Filtering

A filter function **is directly applied to the Reynolds stress tensor**:

$$\hat{\mu}_t = g^2 \mu_t^{\text{RANS}}$$

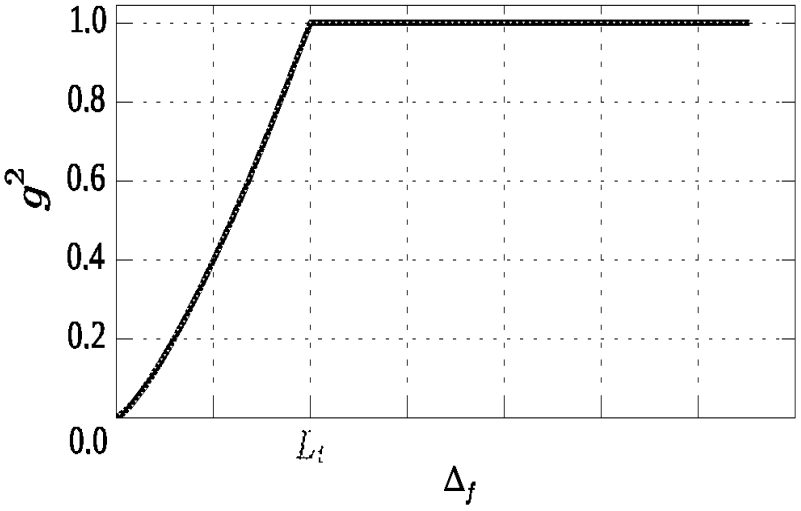
$$g \equiv (\ell_t / L_t)^{2/3} \begin{cases} < 1 & \text{if } \ell_t < L_t \rightarrow \mu_t = g^2 \rho \dfrac{k}{\omega} \quad \text{(LES/RANS)} \\ = 1 & \text{if } \ell_t >= L_t \rightarrow \mu_t = \rho \dfrac{k}{\omega} \quad \text{(RANS)} \end{cases}$$

- The filter is a function that is defined as (Gyllenram 2008):

$$g \equiv (\ell_t / L_t)^{2/3}$$

being:

- ℓ_t: integral length of the resolved scales
- L_t: integral length of the modeled scales



Scale-Adaptive Dynamic Filtering

Local modeled scales from RANS:

$$L_t \sim k^{1/2}/\omega$$

Local **resolvable** scales:

$$\Delta_f = \max(\alpha|\mathbf{U}|\delta t,\ \Delta_{\text{eq}})$$

where:

- $\alpha|\mathbf{U}|\delta t$ is the maximum resolvable scale **according to time resolution**
- Δ_{eq} is the maximum resolvable scale **according to mesh spacing**

$$\ell_t = \min\left[\Delta_f, L_t\right]$$

Piscaglia, F., Montorfano, A., and Onorati, A., *SAE Int. J. Engines*, 2015

Dynamic Length-scale Resolution Model

Piscaglia,Montorfano, Onorati
SAE Int. J. Engines, 2015

Basics of DLRM:

- **Maximum resolvable scale (by time) is limited by CFL instead of δt**

$$\alpha = \frac{\mathrm{CFL}_{\mathrm{max}}}{\mathrm{CFL}_i}$$

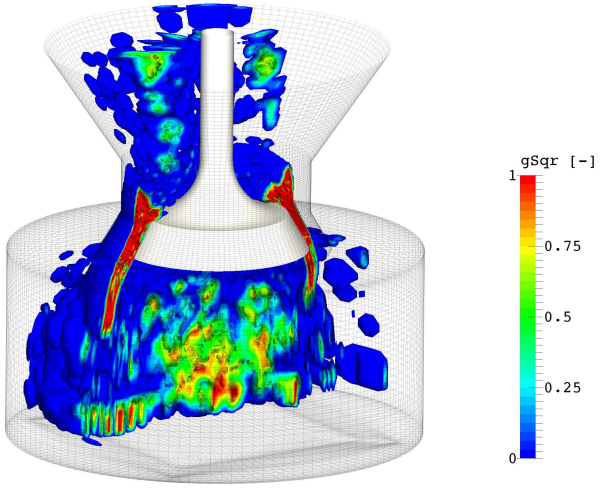
  - More restrictive criterion wrt. fixed α
  - Ensures spatial coherence in cases of jet flows (like through **engine valves**)

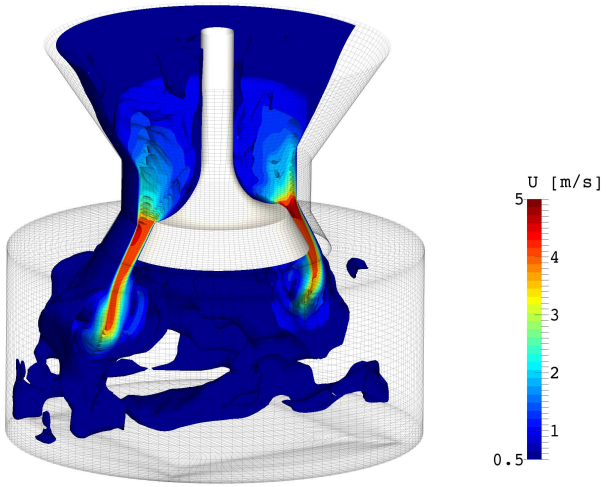
- **Δ_{eq} is the maximum equivalent filter width**

$$\Delta_{\mathrm{eq}} = \min\left[\mathrm{LSR}, \mathrm{LSR}_{\mathrm{max}}\right] \cdot \ell_{di} \qquad \ell_{di} = 60\,\nu^{3/4}\varepsilon^{-1/4}$$

  - "industrial" LES can give good results with $LSR = \overline{\Delta}/\ell_{di} = 5 \div 7$
  - Less restrictive criterion wrt. mere filter width $\overline{\Delta}$

Validation with Experiments





STATIC MESH (SAE 2005-01-0395):

- Swirling flow in a abrupt expansion
- Flow around a poppet valve

DYNAMIC MESH WITH TOPOLOGICAL CHANGES:

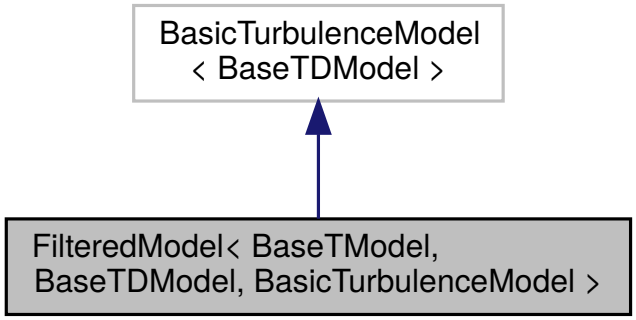
- An engine-like geometry → (`https://imem.cray.com/2015/agenda-2015.html`)
- A square piston engine with a guillotine valve → **NOW**

Implementation in OpenFOAM-3.0.x

DLRM is implemented in OF-3.0.x according to the new turbulence library templatization:

$$\mu_t = \alpha\, \mu_{\text{RANS}} + (1-\alpha)\mu_{\text{LES}}$$

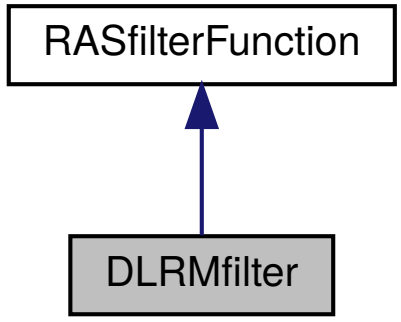
Template class: `FilteredModel<>`



- `FilteredModel` templated on basic model (e.g. $k-\omega$ SST), transportModel, thermophysical properties
- LES model to be blended with is selected run-time (can be `laminar`, i.e. ILES)
- filter function selected run time

$$\alpha = f(\text{local flow conditions})$$

Abstract class `RASfilterFunction`



- derived class with actual filter implementation: DLRM, . . .
- Can be applied to any combination of RANS/LES model

Implementation in OpenFOAM-3.0.x

DLRM is im n:

$$\mu_t =$$

Templa ion

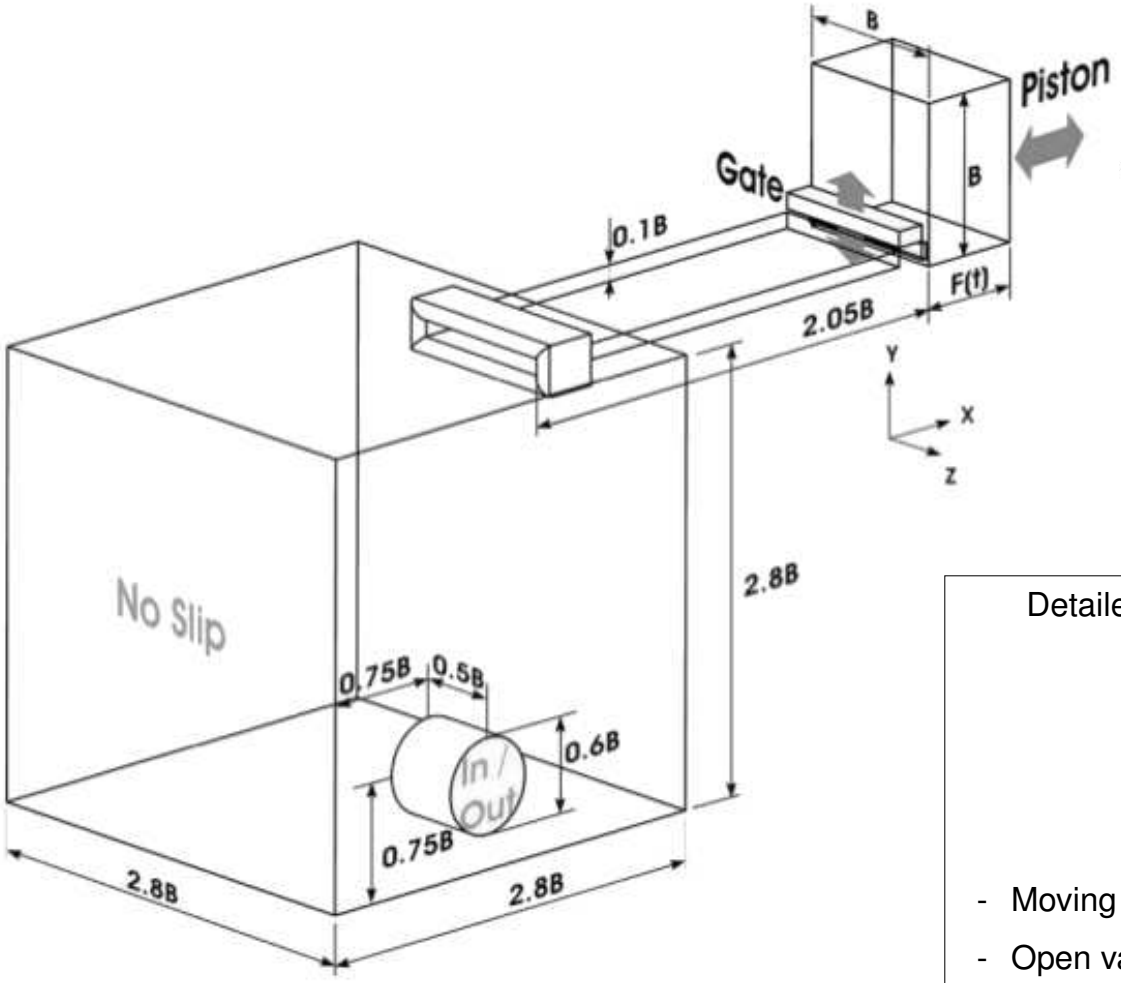
Filtere
Base

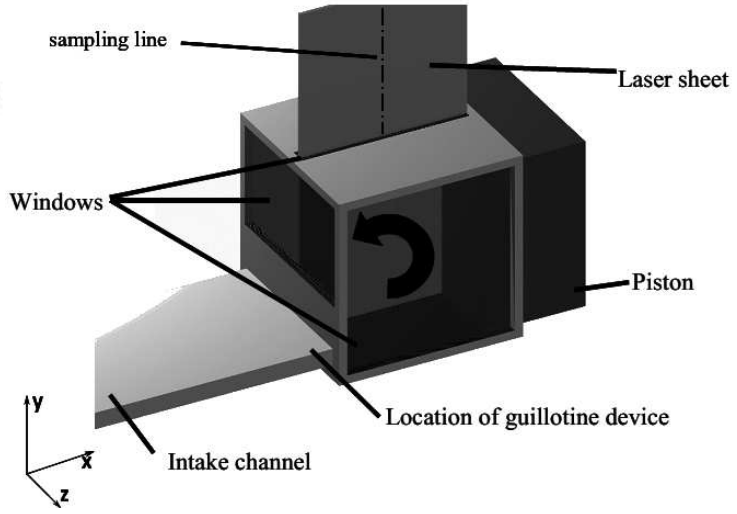
- Filtered
(e.g. $k -$
thermoph n of
- LES mod
run-time
- filter func

```
// file constant/turbulenceProperties

simulationType RAS;

RAS
{
    // the name of model is the corresponding RANS model to be used as
    // base prefixed with 'filtered'
    RASModel filteredkOmegaSST;

    turbulence on;
    printCoeffs on;

    filterCoeffs
    {
        // name of filter function
        filter DLRM;

        // LES model to blend with
        lesModel laminar;

        // other model parameters
        maxLSR 5;
    }
}
```

Test case: Square Piston Engine

Cold Optical Engine with **Square Piston & Straight Intake Port**





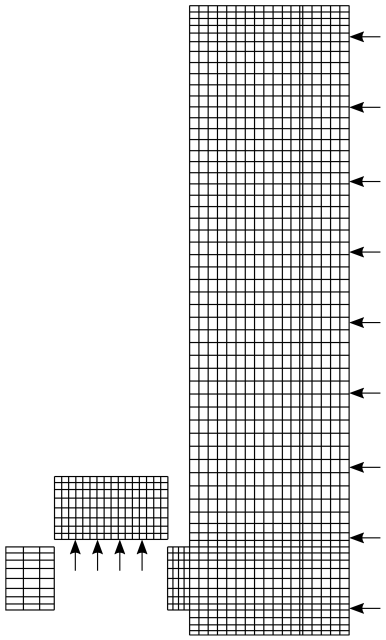
Detailed 2-d PIV measurements provided by

isae Institut Supérieur de l'Aéronautique et de l'Espace ENSMA

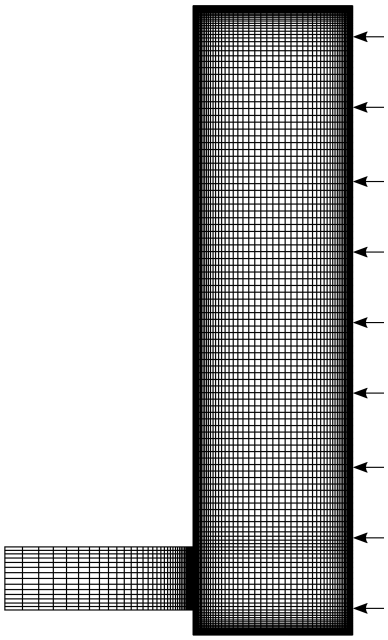
- Moving valve mode, 720 CA/cycle
- Open valve mode, 360 CA/cycle

Test case: Square Piston Engine

Cold Optical Engine with **Square Piston & Straight Intake Port**



"moving valve" mode



"open valve" mode

- Mesh size: 1.1M at TDC, 2.4M at BDC

Working modes:

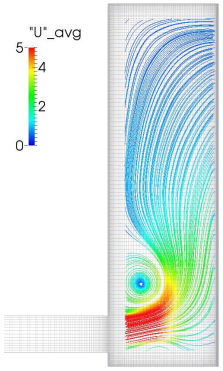
- "**moving valve**": the guillotine moves up and down to mimic the stages of a four-stroke engine;
- "**open valve**": the guillotine is constantly open

Numerical Setup:

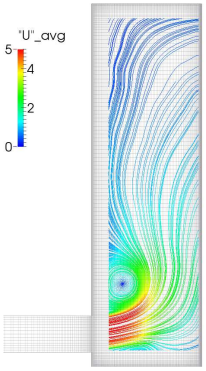
- 2-step backward Euler for time
- LUST for $\nabla \cdot \mathbf{U}$
- first/second order schemes for convection of other qties (k,ω,h,...)
- Turbulence modeling: DLRM
- 10 cycles simulated, average on last 8.

Square Piston: open-valve case

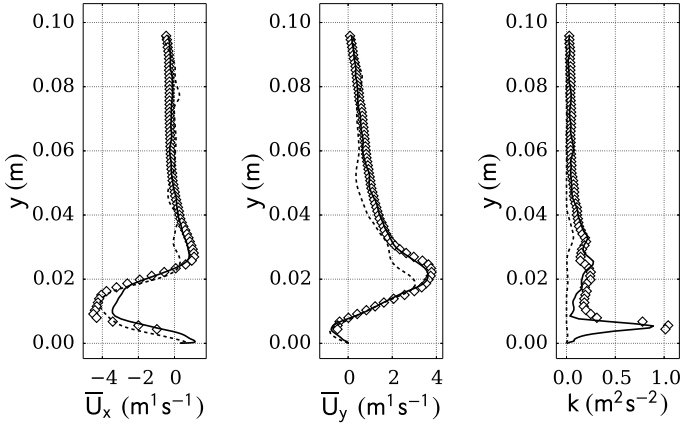
CA = 34 deg



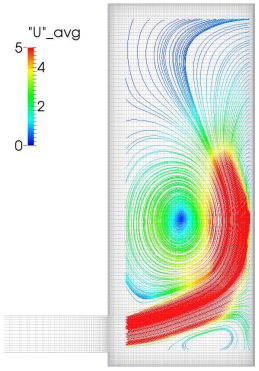
Experiment: 34 (CA)



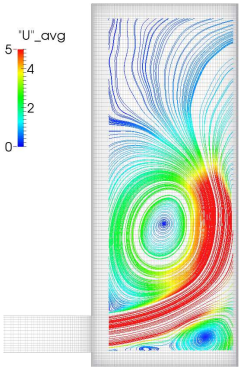
DLRM: 34 (CA)



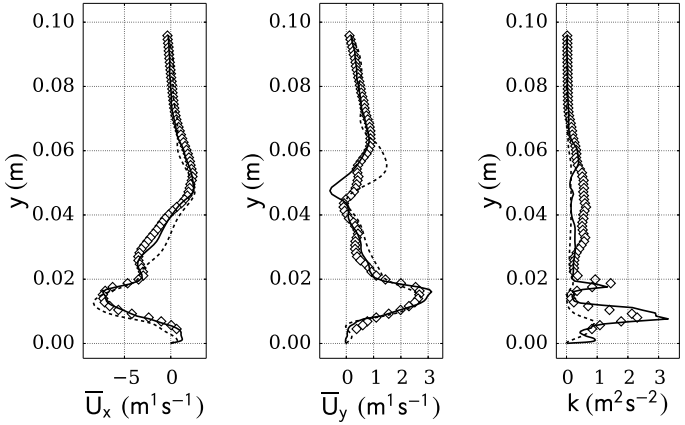
CA = 56 deg



Experiment: 56 (CA)

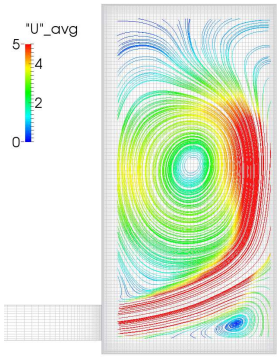


DLRM: 56 (CA)

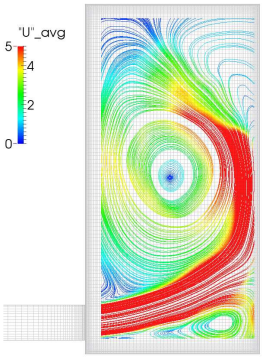


Square Piston: open-valve case

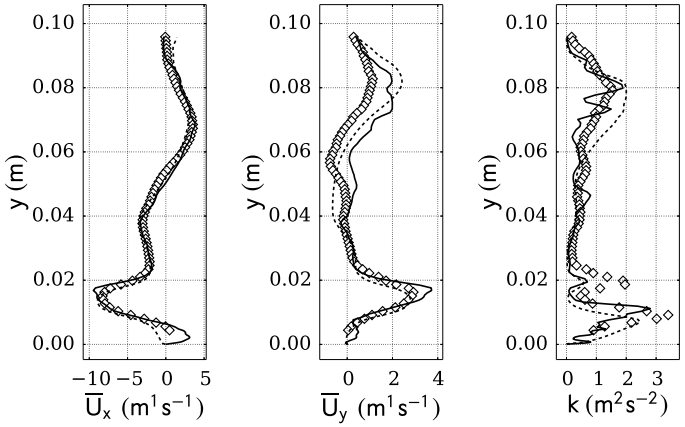
CA = 73 deg



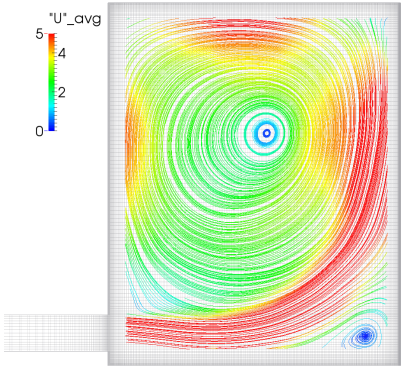
Experiment: 73 (CA)



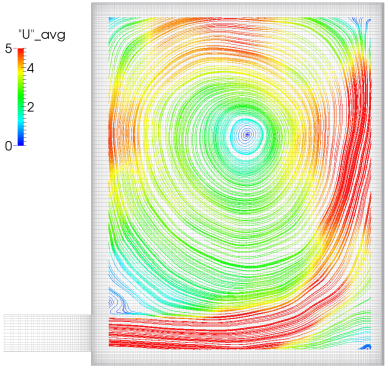
DLRM: 73 (CA)



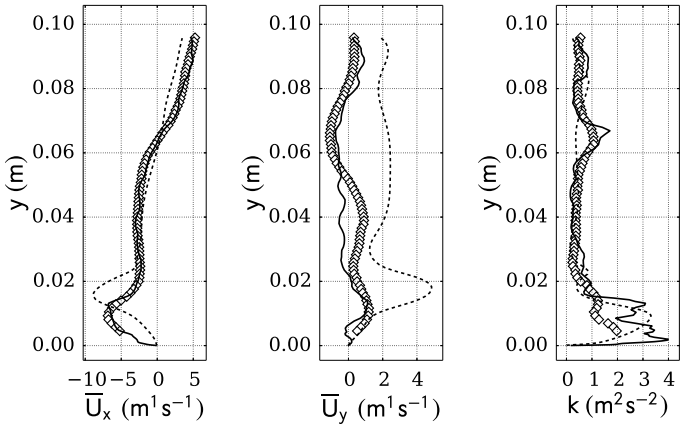
CA = 121 deg



Experiment: 121 (CA)

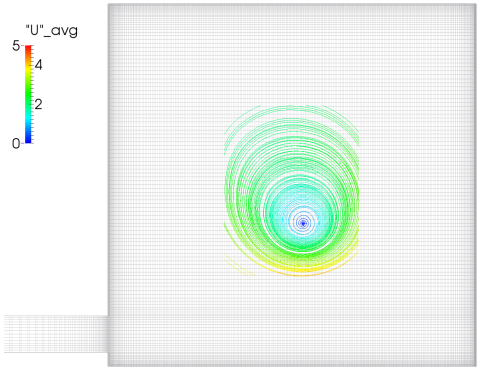


DLRM: 121 (CA)

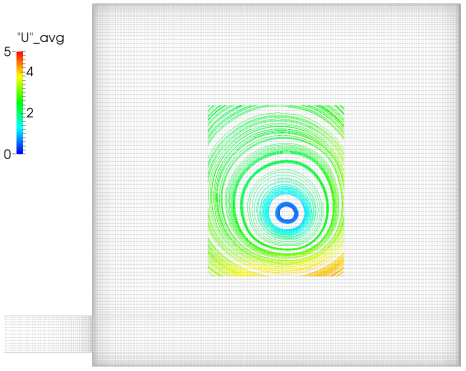


Square Piston: open-valve case

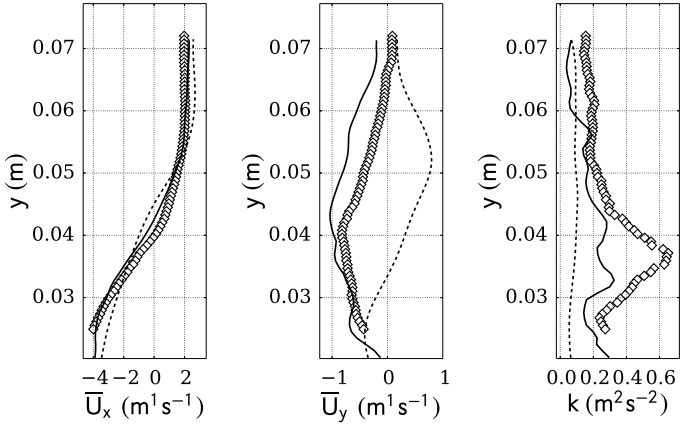
CA = 185 deg



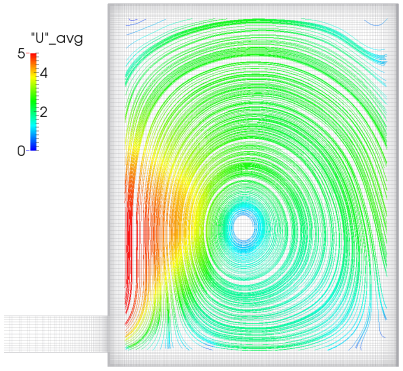
Experiment: 185 (CA)



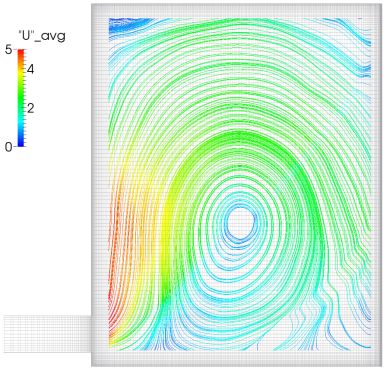
DLRM: 185 (CA)



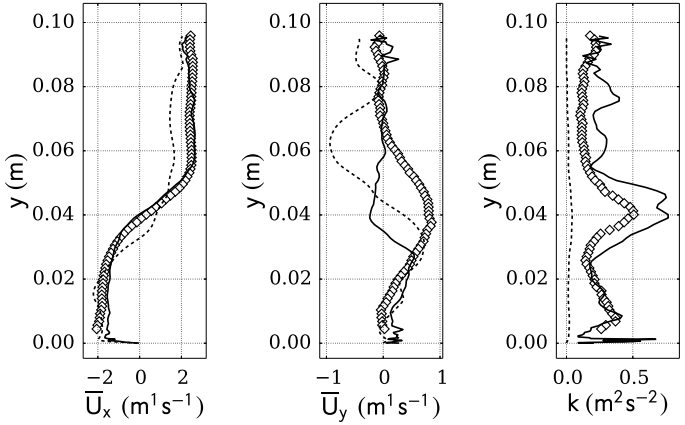
CA = 247 deg



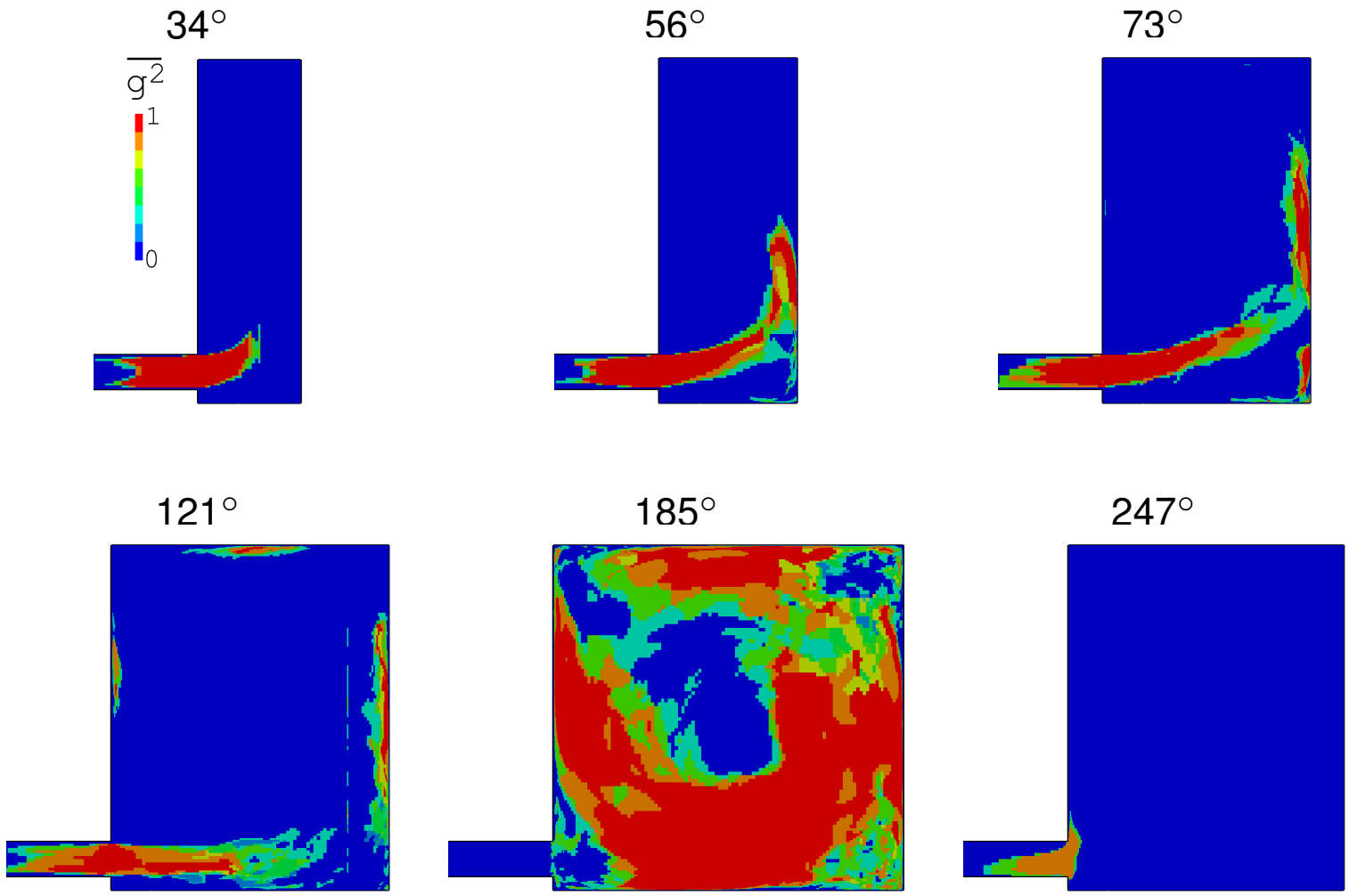
Experiment: 247 (CA)



DLRM: 247 (CA)

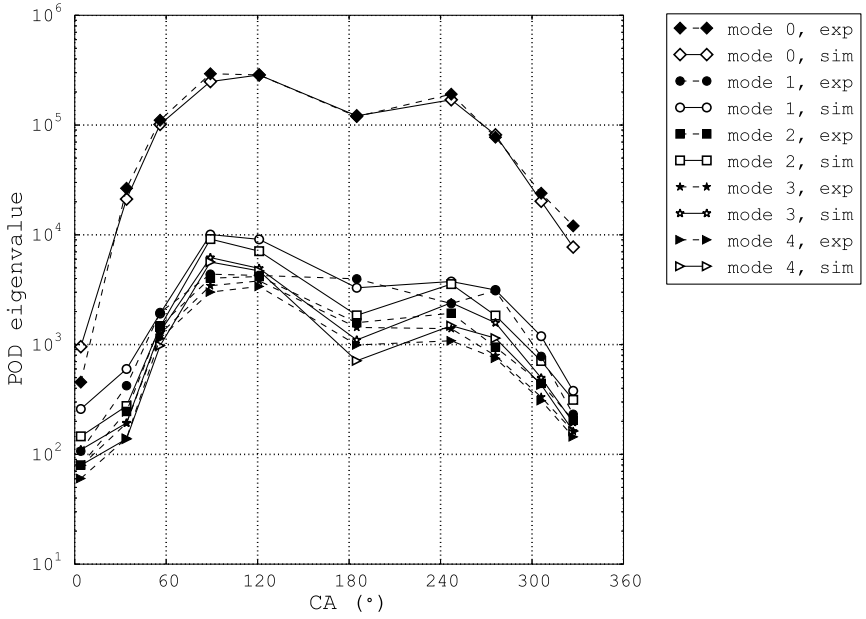


Model evaluation: g^2

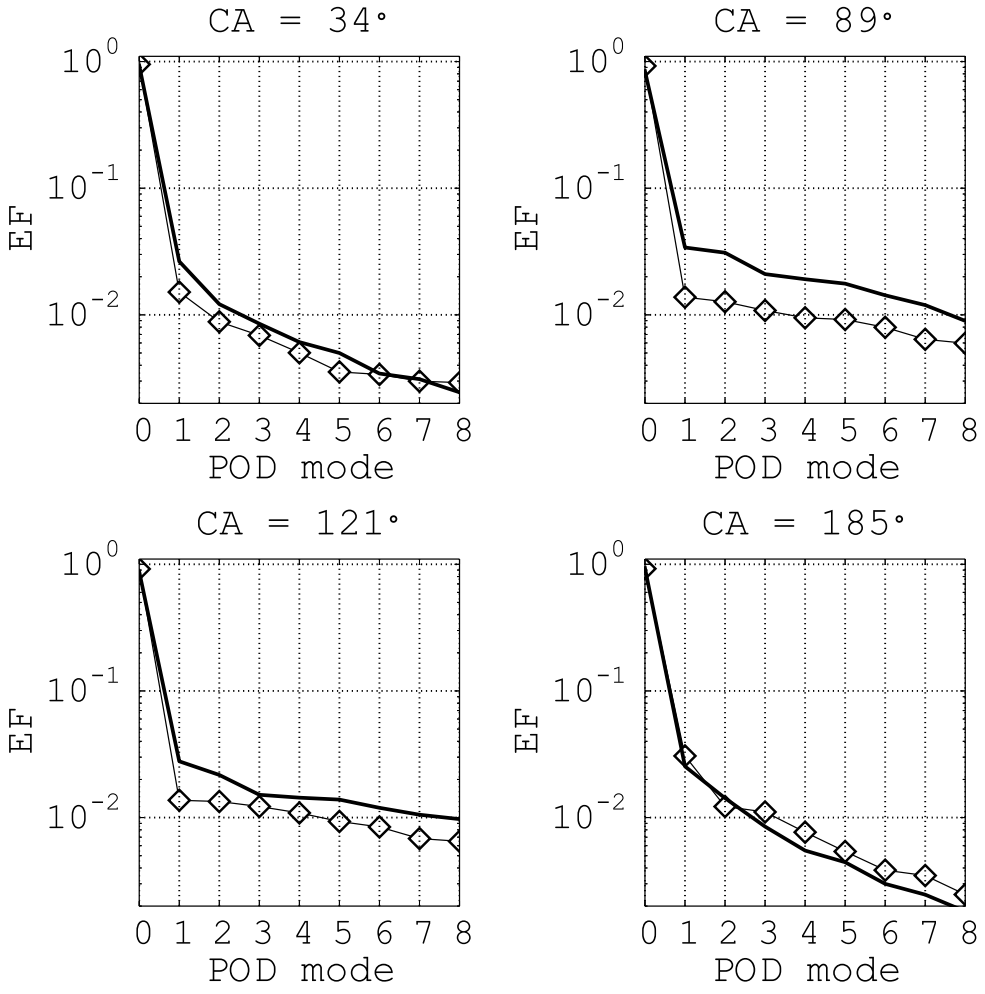


POD – eigenvalues

Proper Orthogonal Decomposition of simulated vs. experimental results: Eigenvalues.

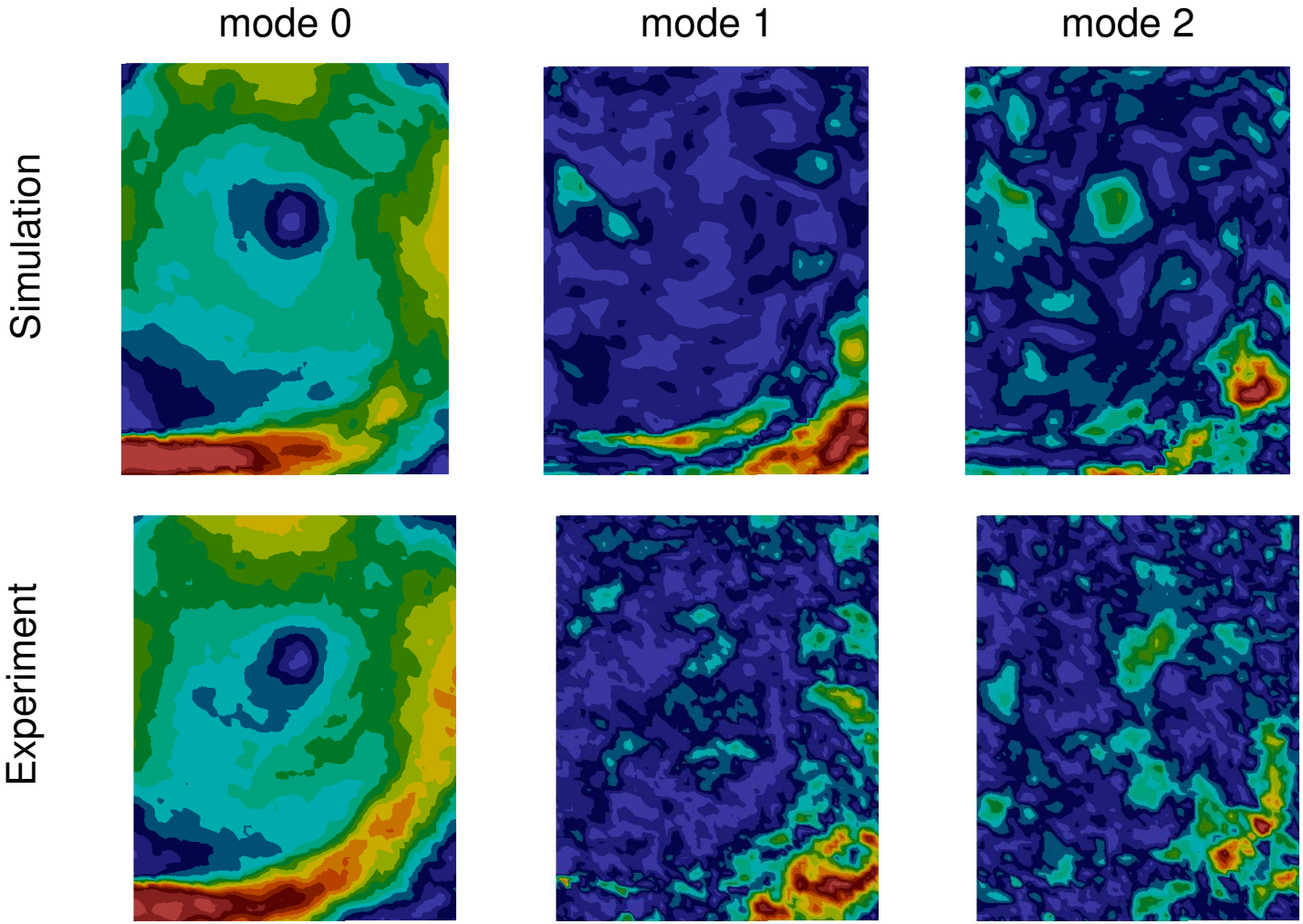


Wu, Montorfano, Piscaglia, Onorati. "A Study of the Organized in-Cylinder Motion by an Adaptive Scale-Resolving Turbulence Model". *Submitted to Flow, Turbulence and Combustion*



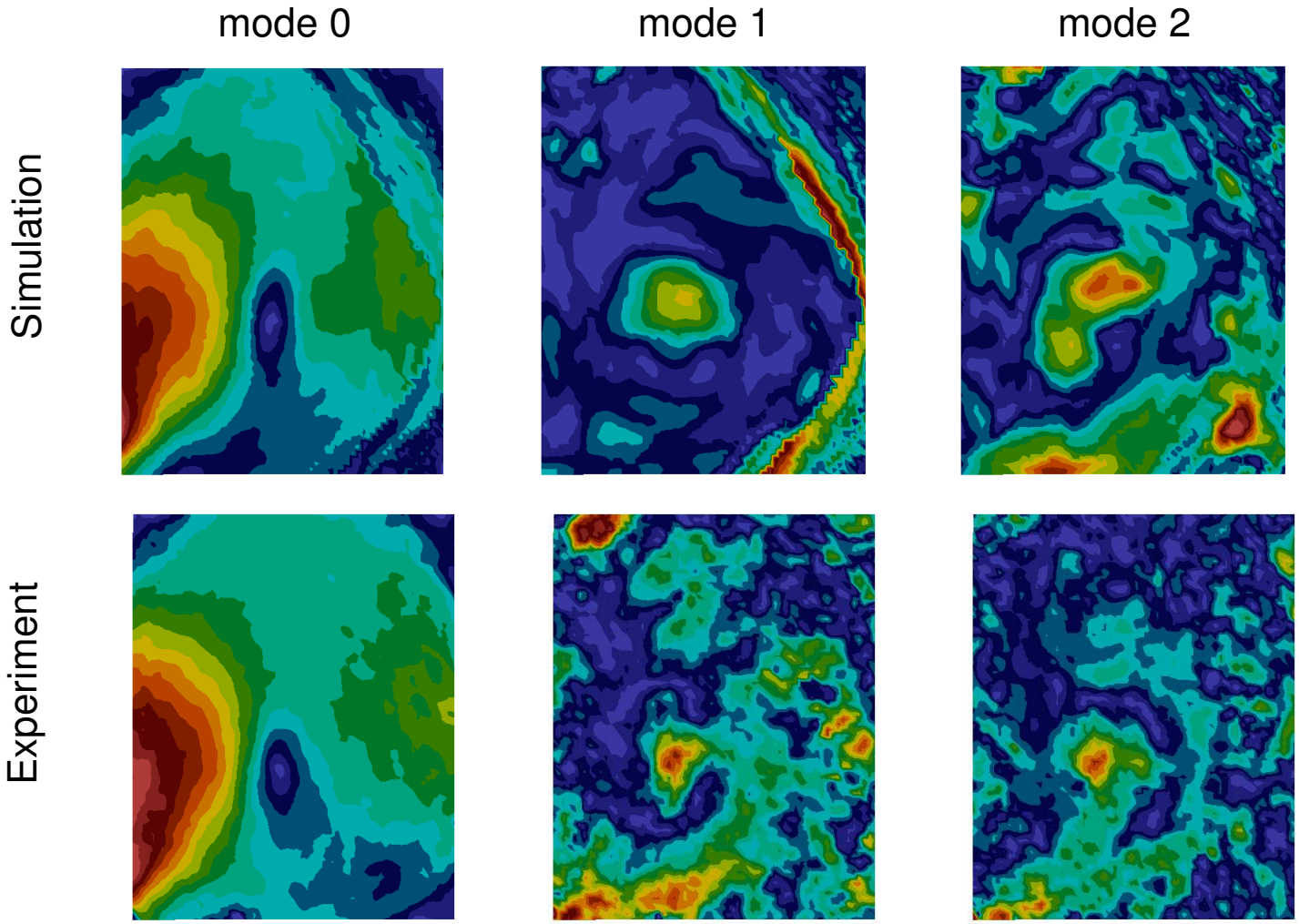
POD – eigenvectors

Crank Angle = 121° ATDC



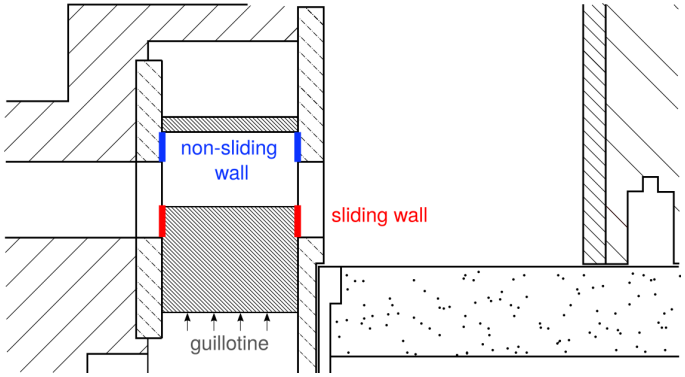
POD – eigenvectors

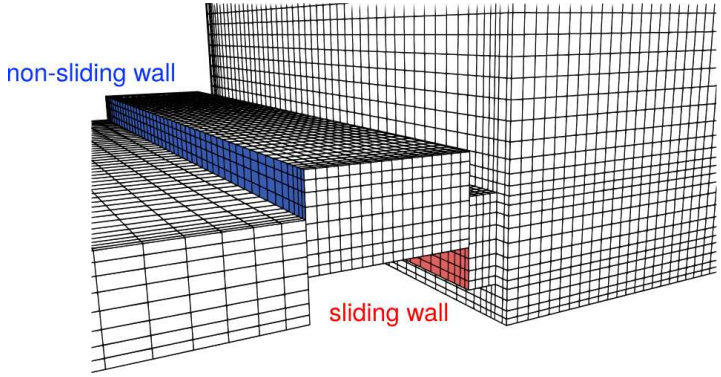
Crank Angle = 247° ATDC



Square Piston - moving guillotine valve

Cold Optical Engine with **Square Piston & Straight Intake Port**





In the real configuration:

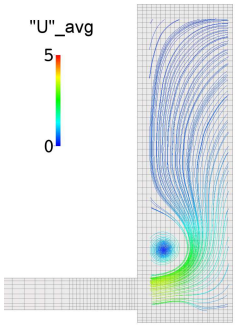
- wall boundaries marked in red in have a non-zero tangential velocity;
- the upper walls of the guillotine “chamber” (in blue) are fixed

Red and blue faces are dynamically updated at each crank time angle with a **no-slip BC**:

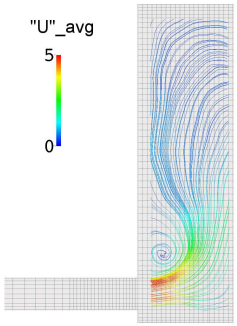
- **blue** faces: $\mathbf{U} = 0$
- **red** faces: $\mathbf{U} = \mathbf{U}_{\text{valve}}$ (tabulated)

Square piston with guillotine valve

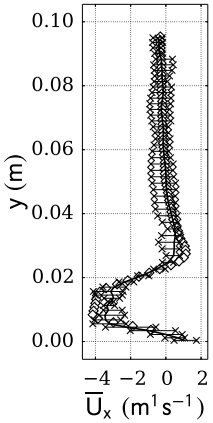
CA = 35 deg

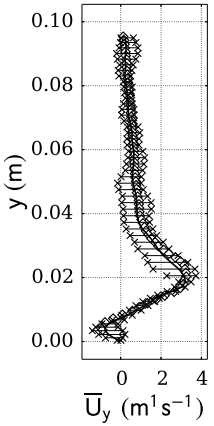


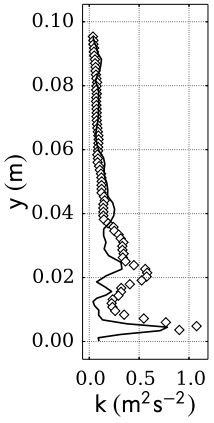
Experiment



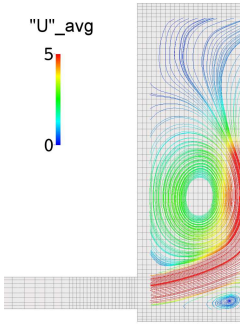
DLRM



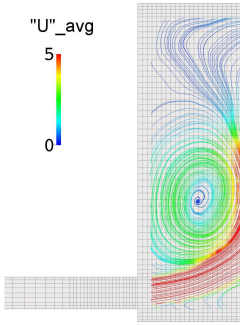




CA = 57 deg



Experiment



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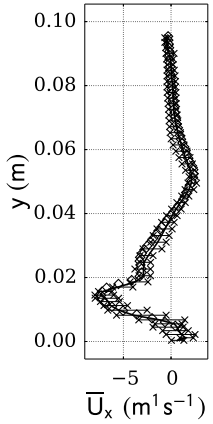
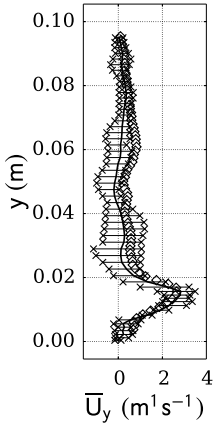
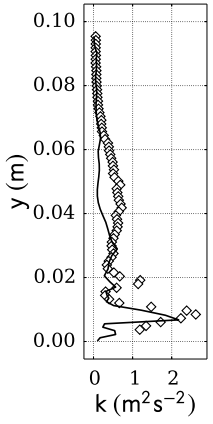
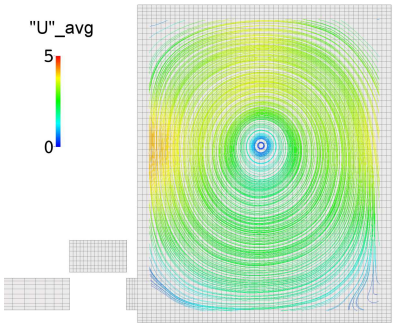




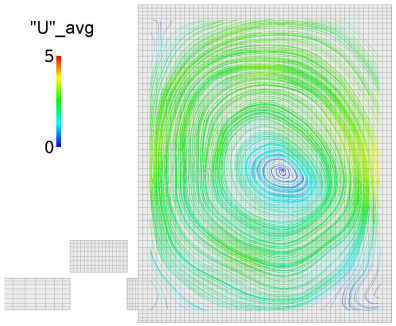


Square piston with guillotine valve

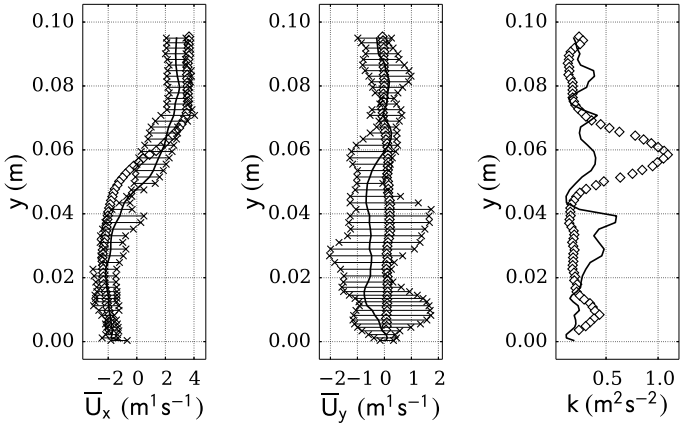
CA = 248 deg



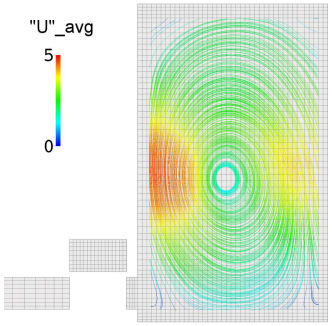
Experiment



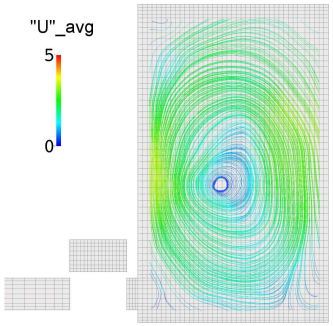
DLRM



CA = 278 deg



Experiment



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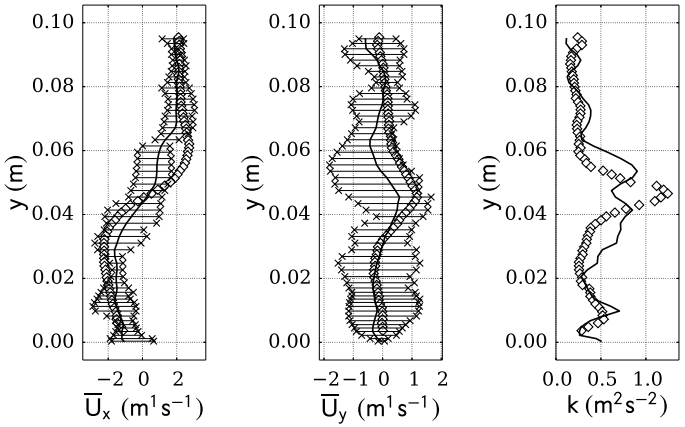
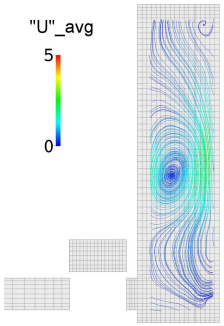
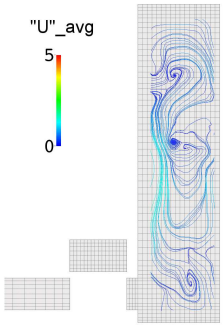


Square piston with guillotine valve

CA = 361 deg



Experiment



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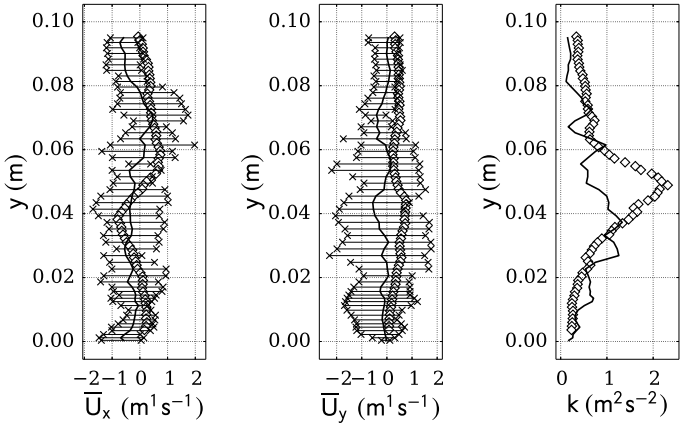
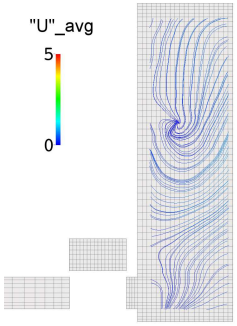
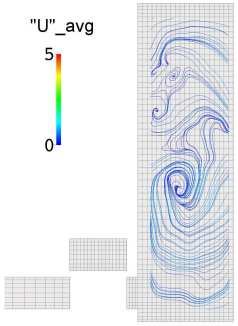


CA = 391 deg



Experiment



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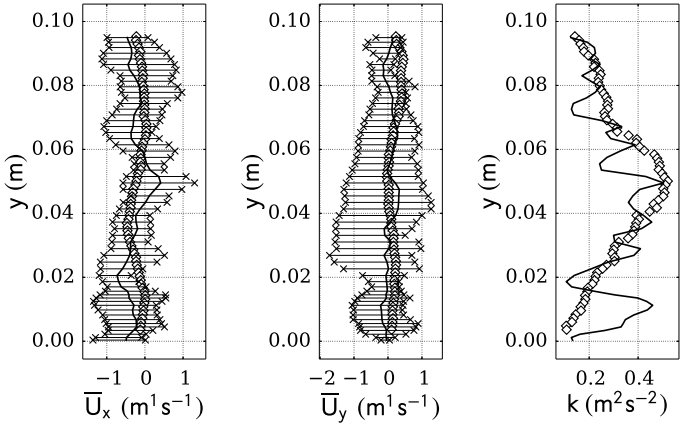
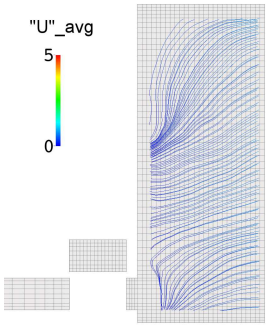
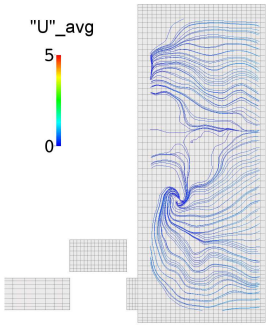


Square piston with guillotine valve

CA = 418 deg



Experiment



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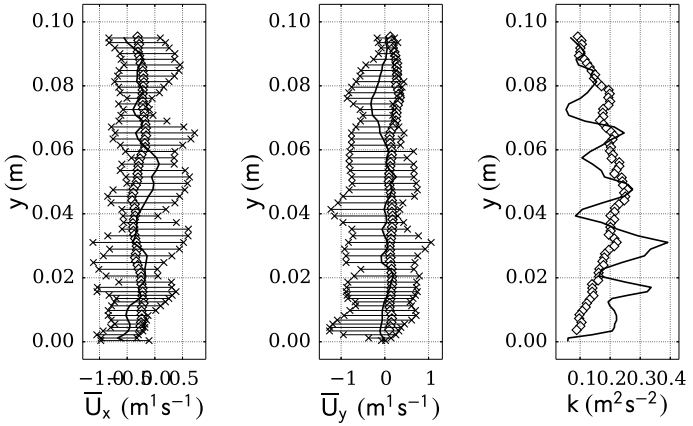
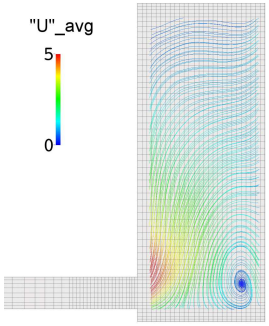
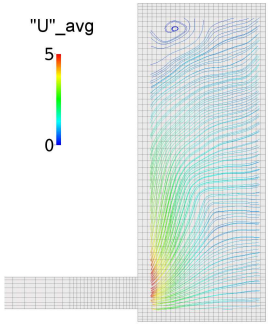


CA = 669 deg



Experiment



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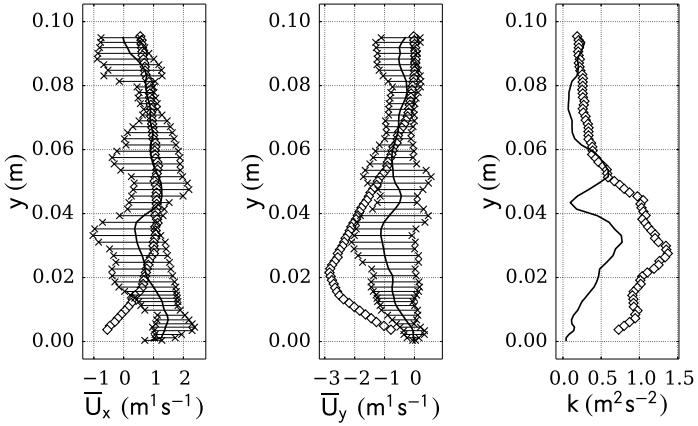
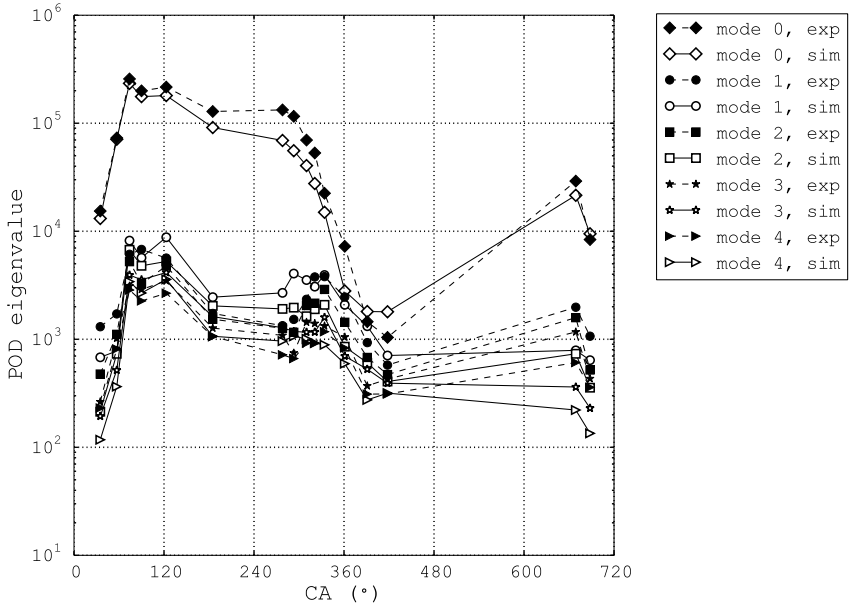
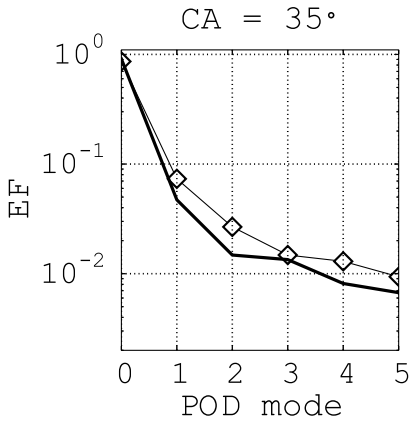
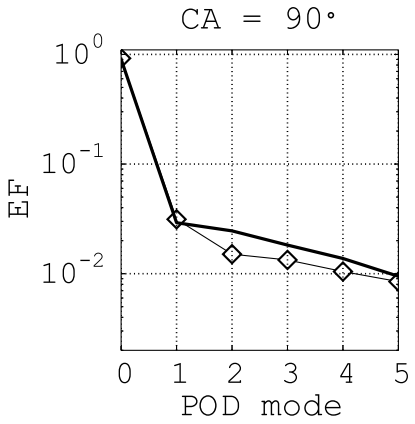


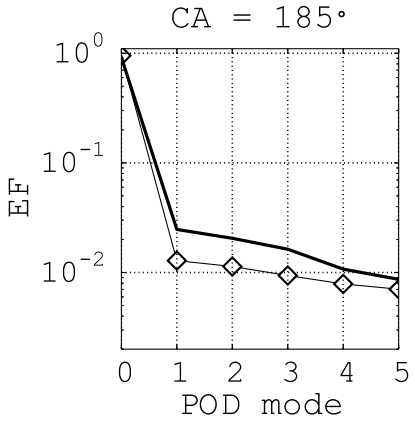
POD – eigenvalues

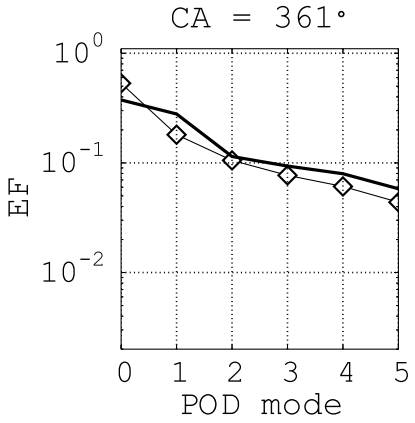
Proper Orthogonal Decomposition of simulated vs. experimental results: Eigenvalues.





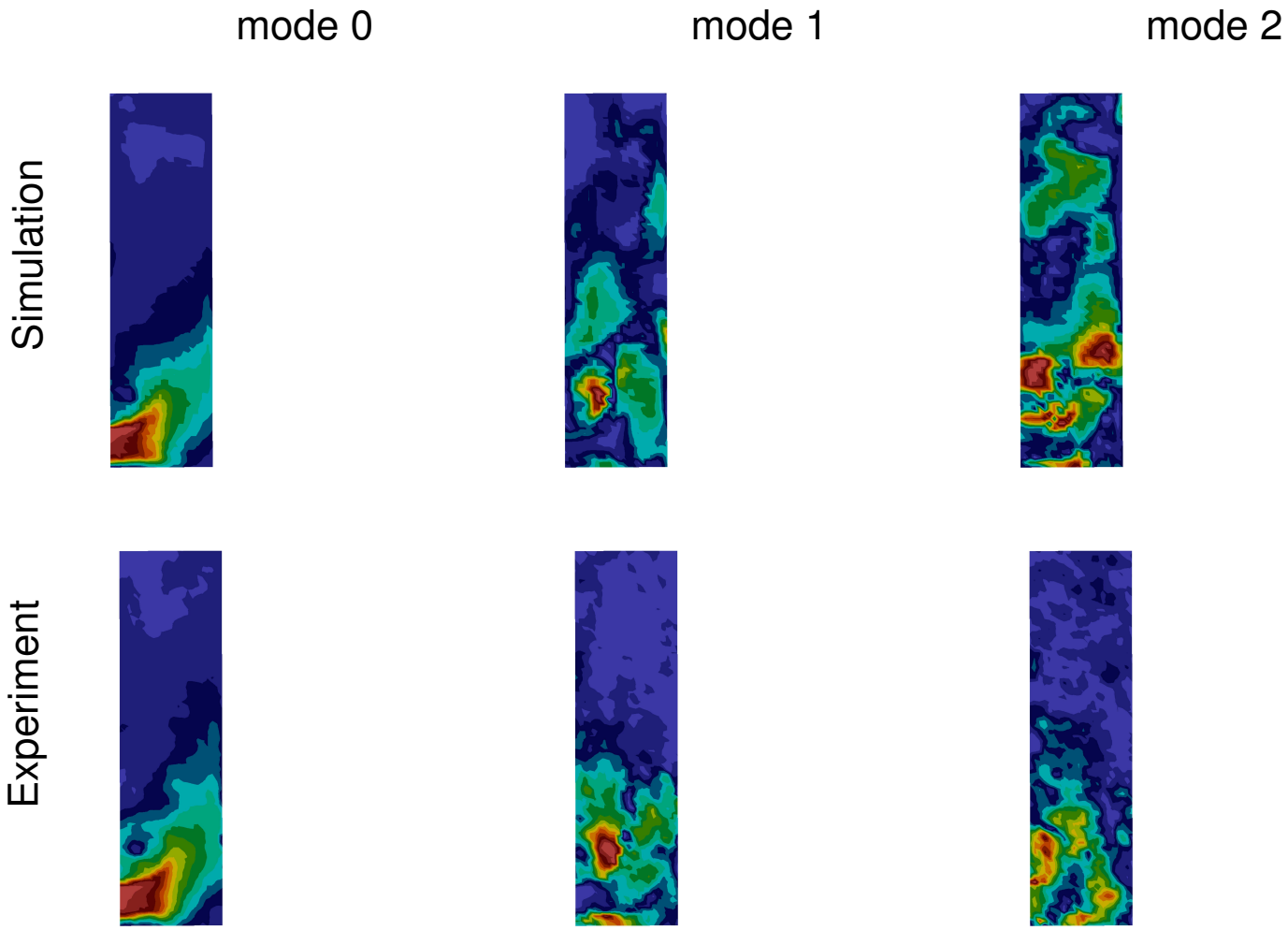






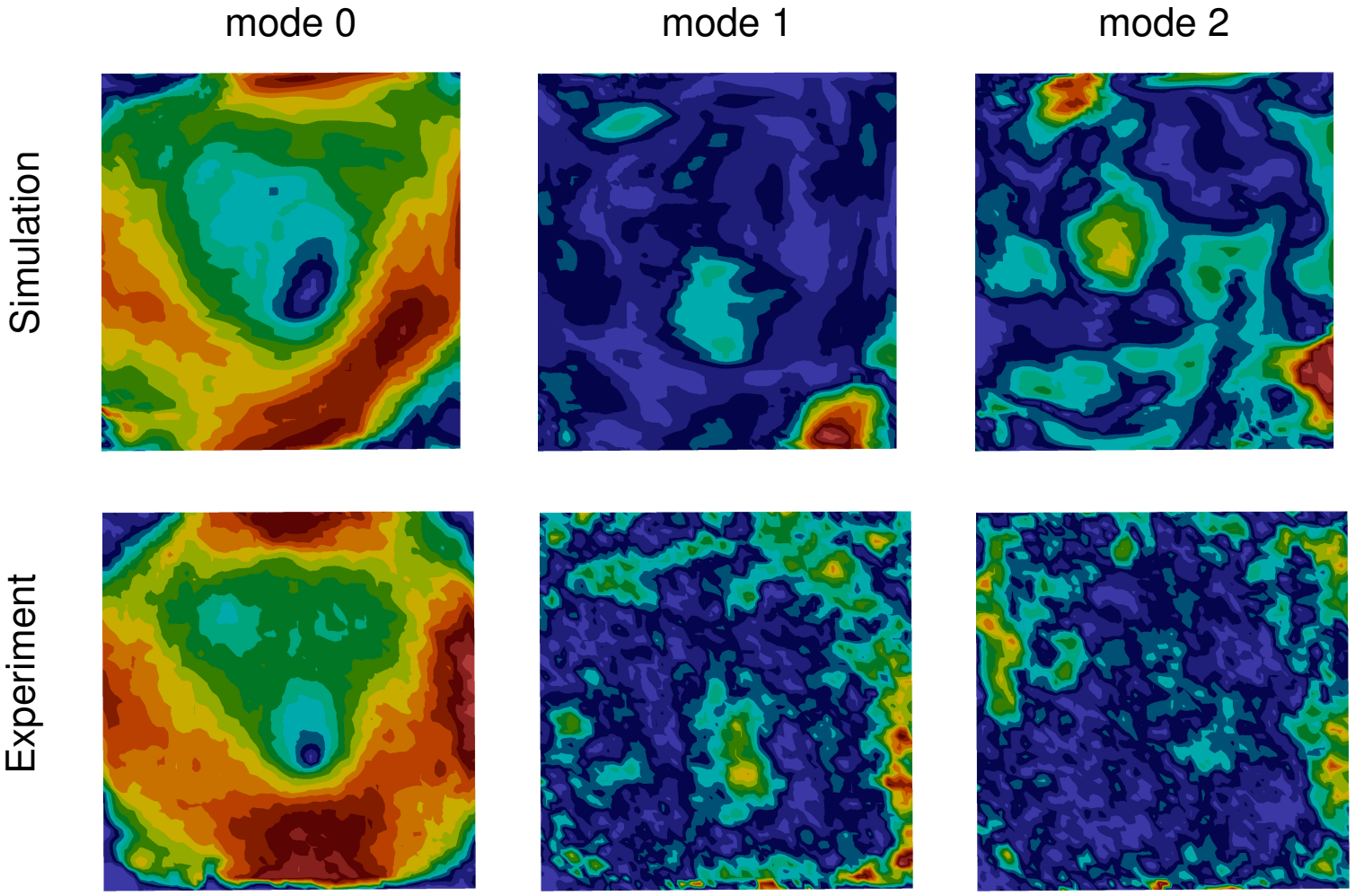
POD – eigenvectors

Crank Angle = 35° ATDC



POD – eigenvectors

Crank Angle = 185° ATDC



Conclusions

dynamicMesh library:

- fully general, completely transparent to OpenFOAM® solvers;
- `topoManager` class handles topological changes at low level
- fully compatible with OpenFOAM®-dev family branches
- very easy to extend

Turbulence library:

- dynamic local filtering ($\neq$ zonal approach) $\rightarrow$ automatic switch between RANS and LES
- possible to combine *ANY* RANS and LES model (**Templatized according to OF-3.0.x**)

Validation on square piston:

- Very good accuracy on averaged quantities ($\mathbf{U}$, k)
- Good prediction of turbulence dynamics (seen in POD)
- allows to a significant speed up in time-resolved simulations

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Prof. Jacques Borée (*ISAE-ENSMA*, Futuroscope Chasseneuil, France) for providing the very detailed set of experimental data that were used for model validation.

Thank you for your attention!

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Post-doc Researcher

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