EFC Topic 4.4
Exploring CCV origin

Presented by Cecile PERA (IFPEN)

Objectives of the 4.4

Summarize: CCV understanding & modeling

Contributions

1. Motored operation

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2. Fired operation,

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3. New tool modeling,

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4. Perspective, — **All**

1. Motored operation

Instantaneous Flow Field (SIDI TU Darmstadt)

PIV measurements

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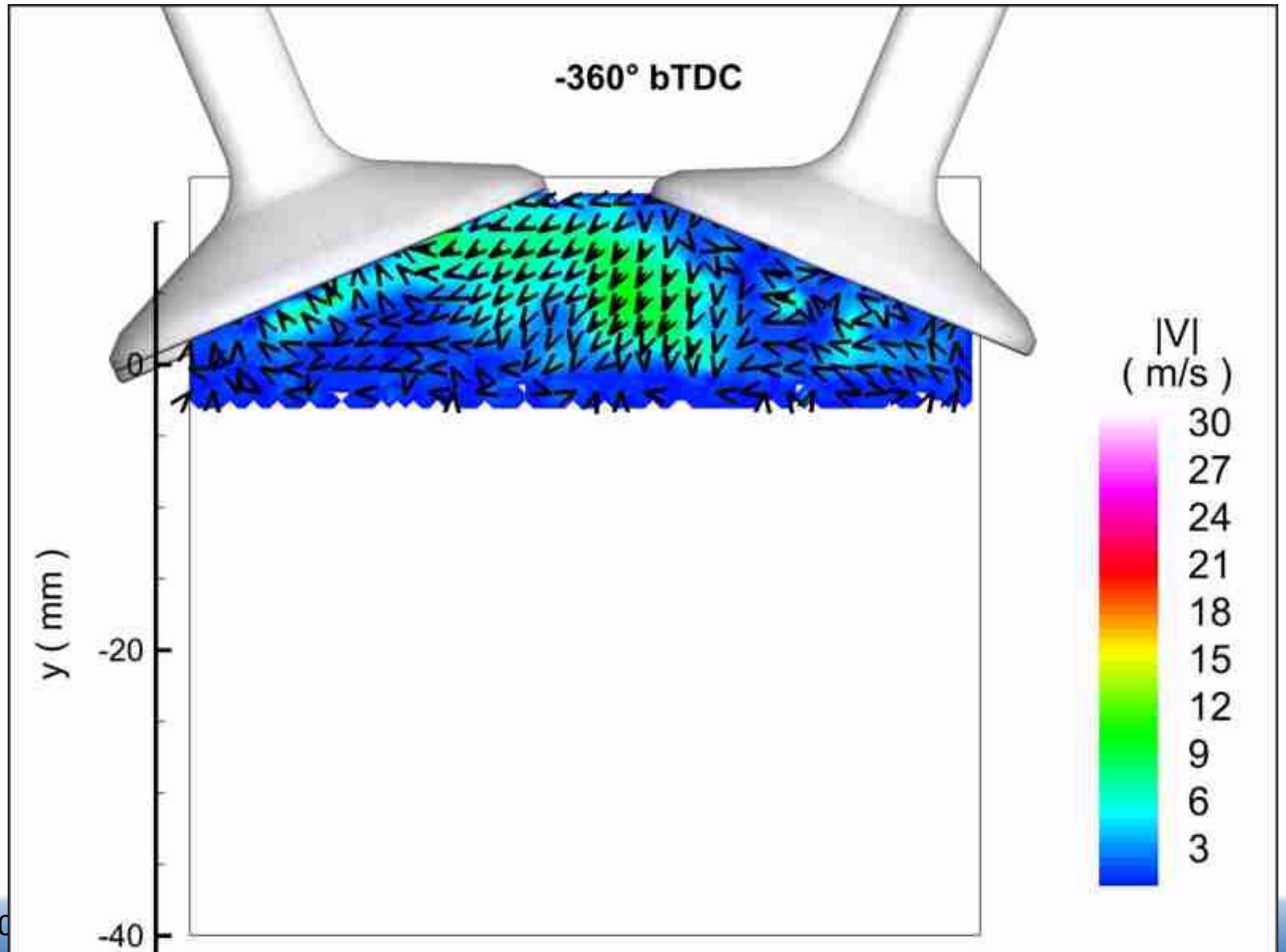

Instantaneous vs. Ensemble-Avg Flow Field

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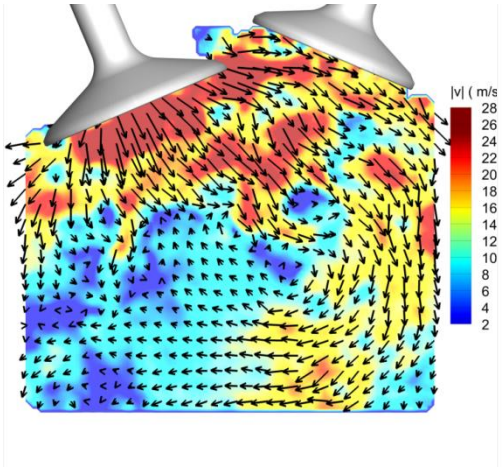
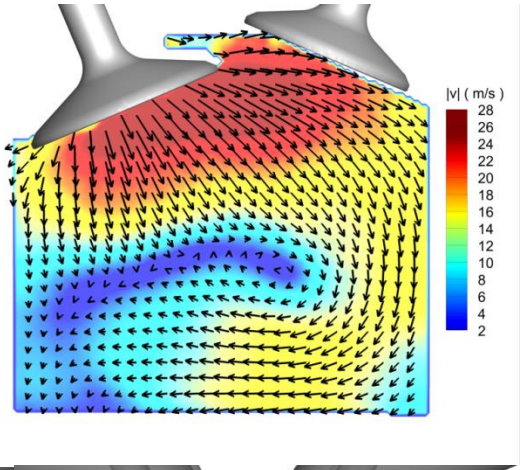
IFP Energies nouvelles

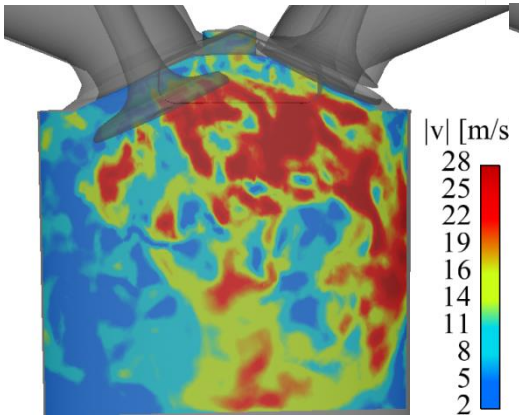
Instantaneous **Ensemble-Avg**

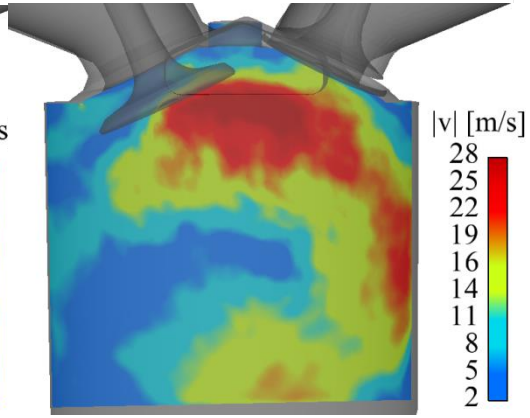
Exp -TUD





LES - SGEmac



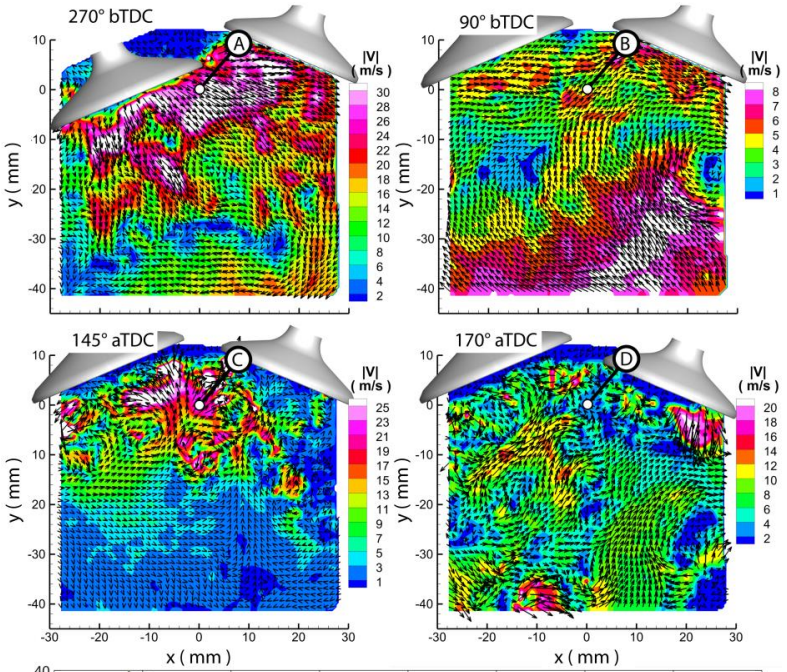


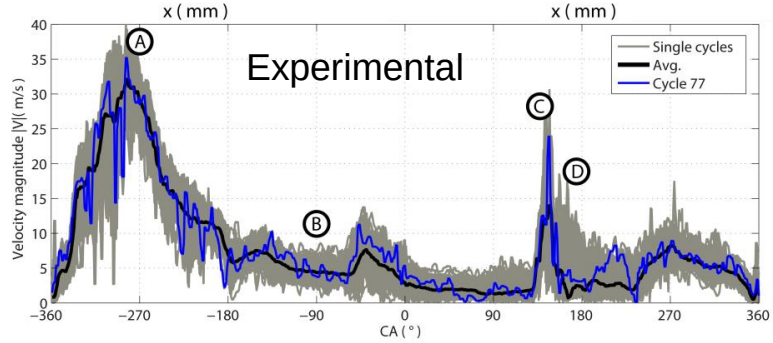
- How can we understand motored-CCVs?
- What is defined CCVs.
- Differences and roles of:
  - Large scale flow pattern
  - Turbulence

Velocity fluctuations

- Extract velocity at single point
- Entire engine cycle
  - High-speed PIV
- Deviations of inst. velocity from ensemble-average
- Large fluctuations throughout entire cycle

SIDI TUD

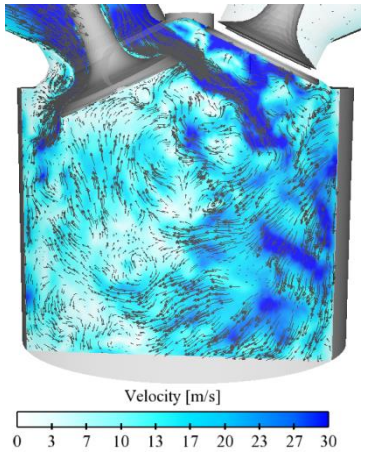




Baum et al.: *Flow Turbulence Combust.* 92 269-297 (2014)

SGEmac LES IFP

-250 CAD



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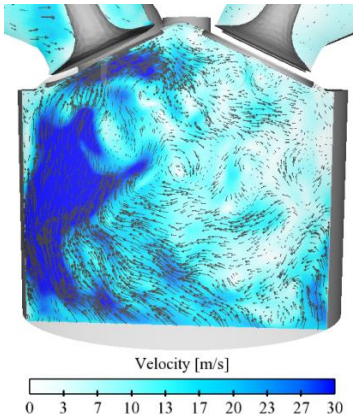
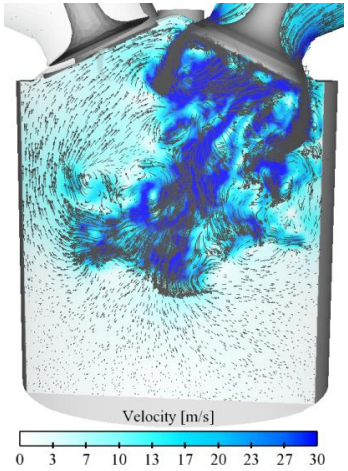


145 CAD



Fluctuation of Large-Scale Flow Structures

PIV measurements

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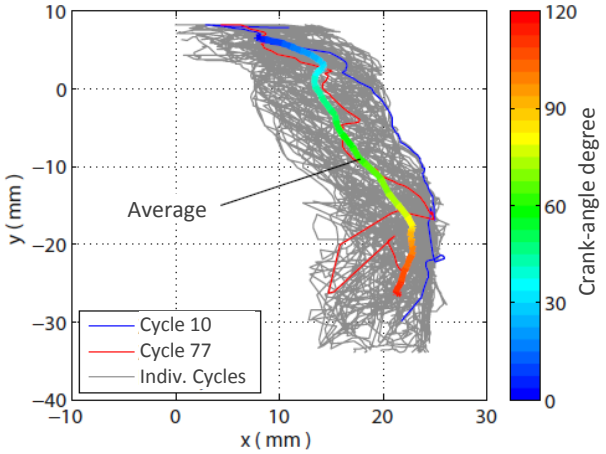
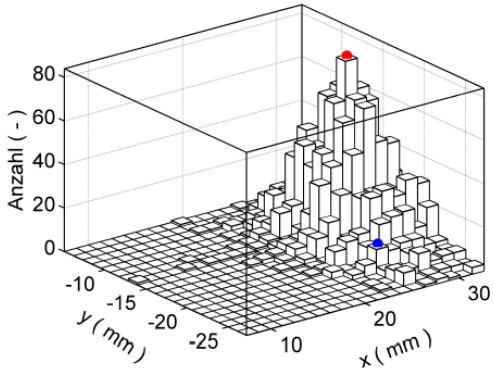
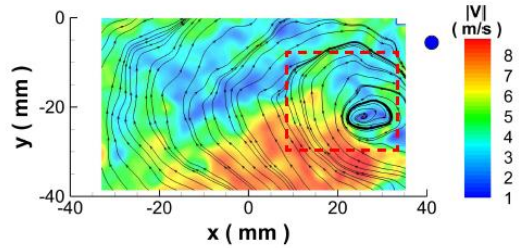
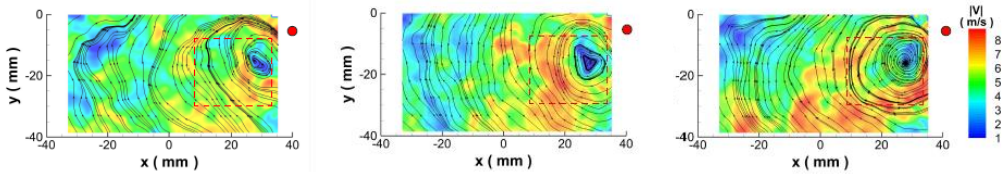
- **Identify tumble vortex**
  - Instantaneous images
- **Location of maximal occurence**
- **Conditional sampling**
  - Formation of flow structures
  - Cause of flow deviation
  - High statistic needed
  - Time history needed



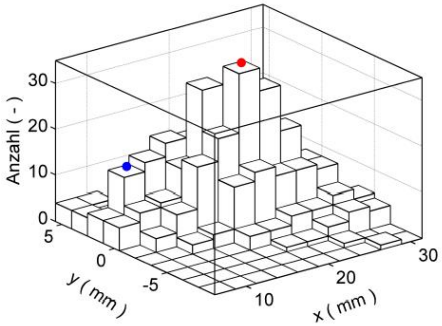
90° bTDC (compression)

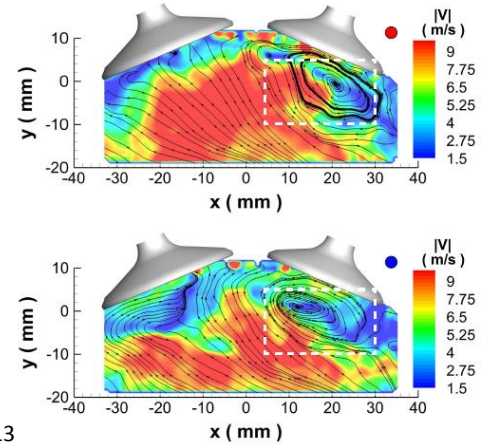






45° bTDC (compression)



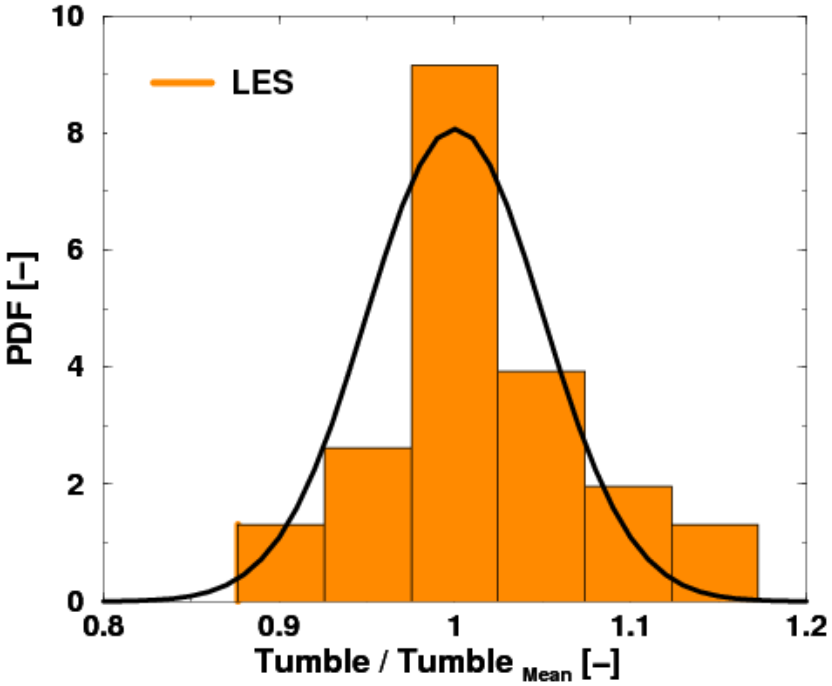


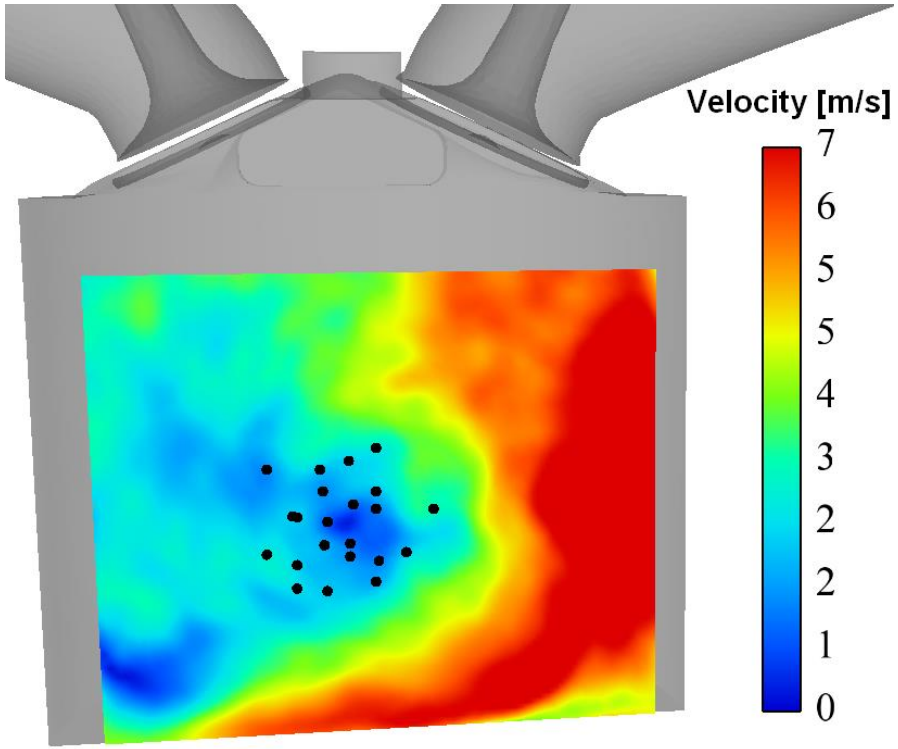
Elias Baum, PhD Dissertation TU Darmstadt 2013

Fluctuation of Large-Scale Flow Structures (SGEmac IFP)

LES computations

- CCVs in spatial location of tumble motion
- CCVs in intensity of tumble motion





Turbulence Fluctuations vs Flow Variation

Tomographic PIV

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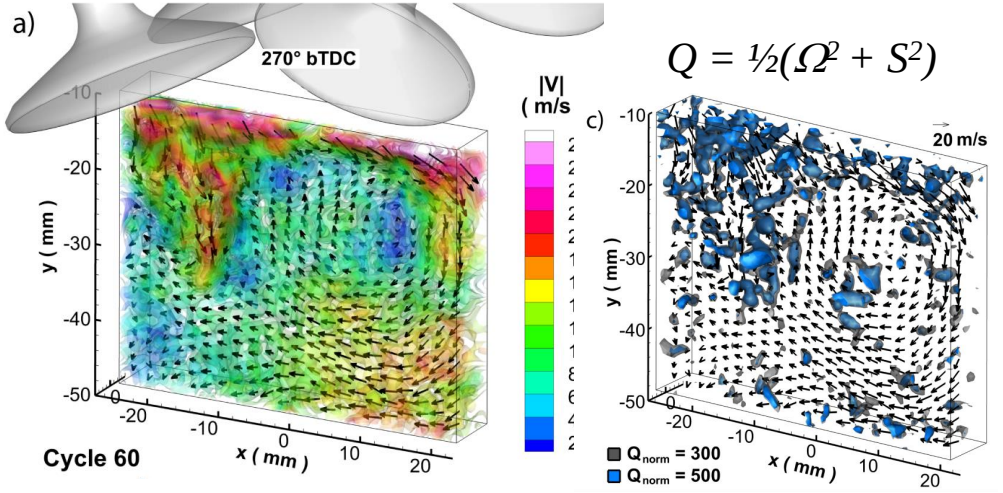
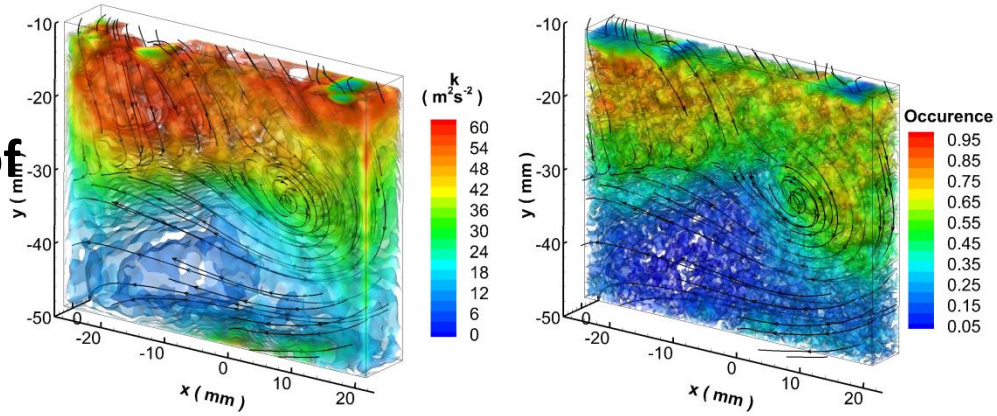
- Tomographic PIV
- Identify 3D vortical structures
  - Q-criterion: $Q=1/2\ (\Omega^2+S^2)$
- Probable location of 3D vortical structures
  - Topology
- Comparison to 3D TKE topology
  - Agreement: large influence of 3D vortical structures on TKE
  - Differences: TKE influence

Tomographic PIV, Instantaneous cycle 270° bTDC

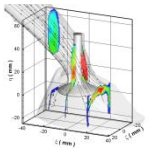


$Q = \frac{1}{2}(\Omega^2 + S^2)$

Baum et al.: *Flow Turbulence Combust.* 92, 269-297 (2014)



Influence of Intake Flow Magnetic Resonance Velocimetry (MRV)



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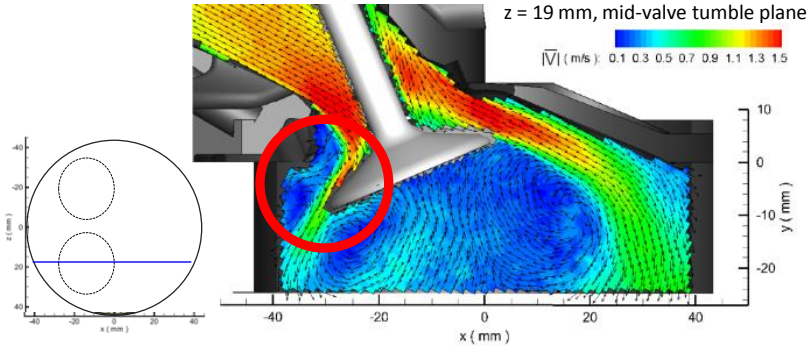
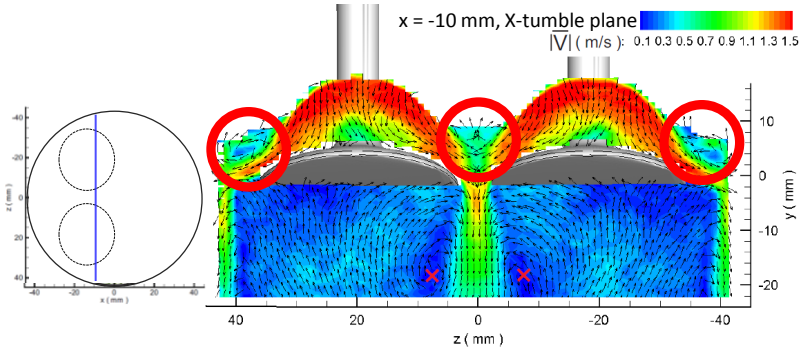
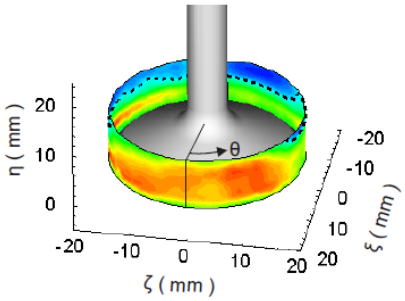
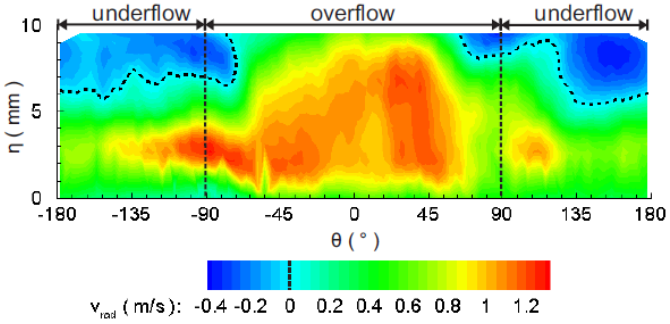
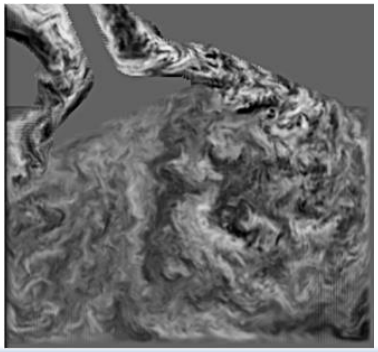
- **Ensemble-average volumetric flow**
  - Intake system & cylinder
- **Recirculation zones**
  - Intake geometry
  - Valve flow through valve curtain
  - Volumetric efficiency csq
  - Cyclic flow behavior
- **Improve understanding of intake flow**
  - Simulation efforts underway
  - Fine grid spacing in intake geometry









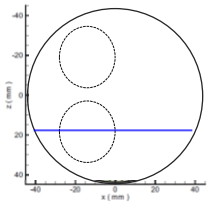


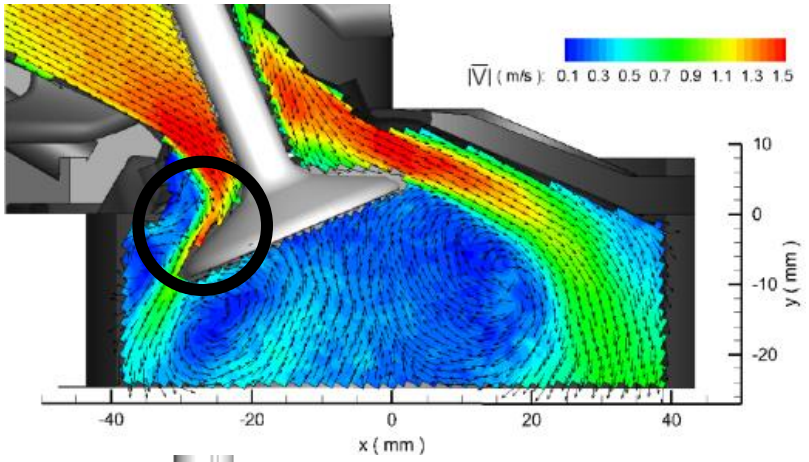
Intake Flow Simulation Velocity magnitude

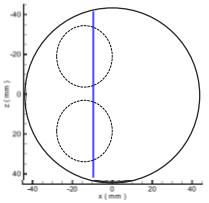
T. Nguyen, A. Kempf, PsiPhi 0.3 mm
U. Duisburg-Essen

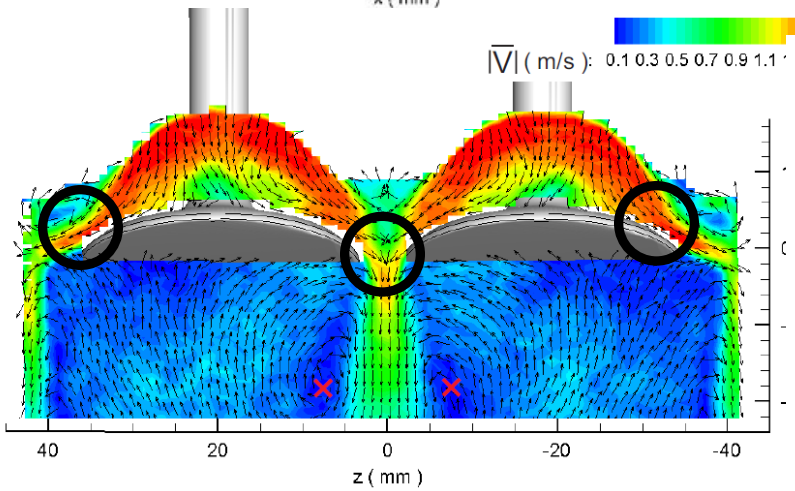
Influence of Intake Flow

Exp -TUD

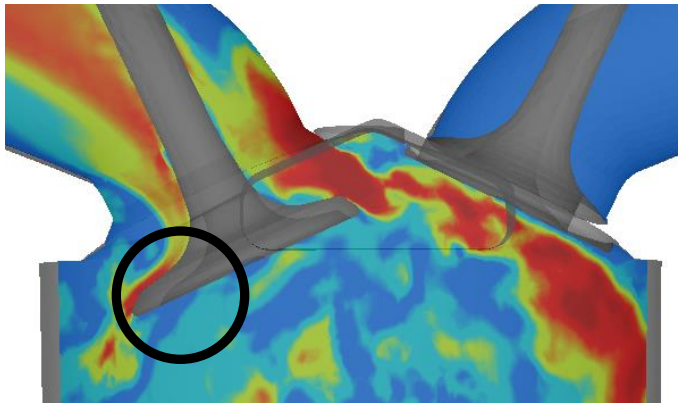


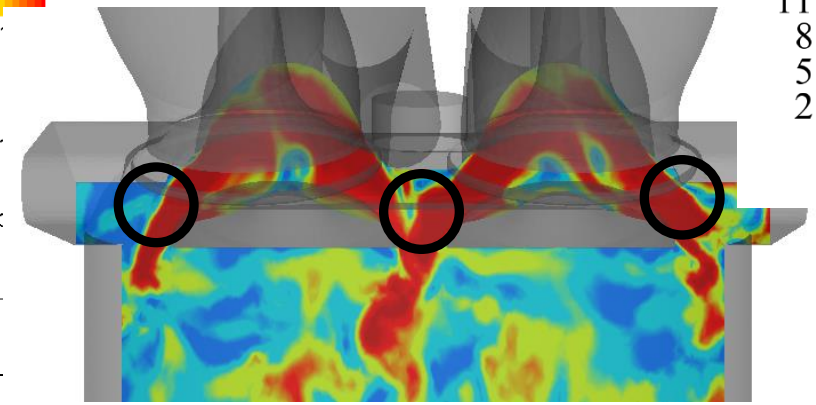


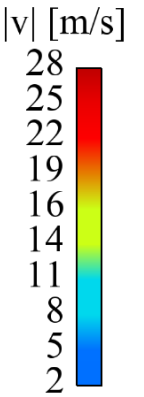




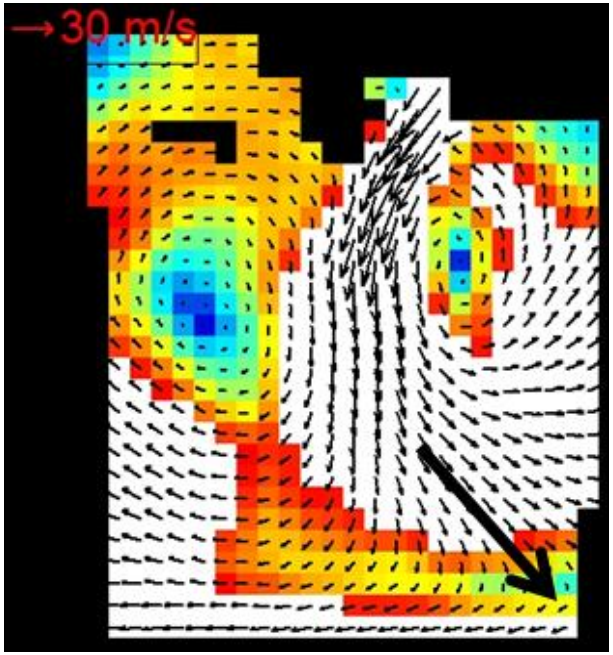
LES - SGEmac

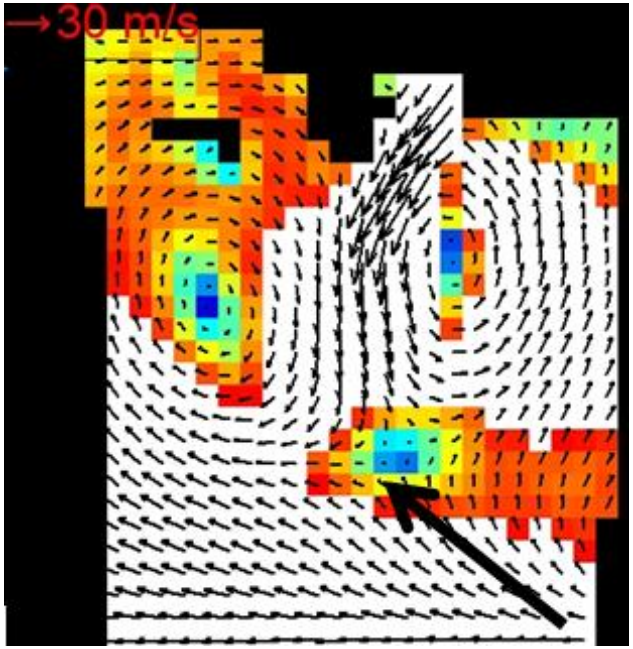


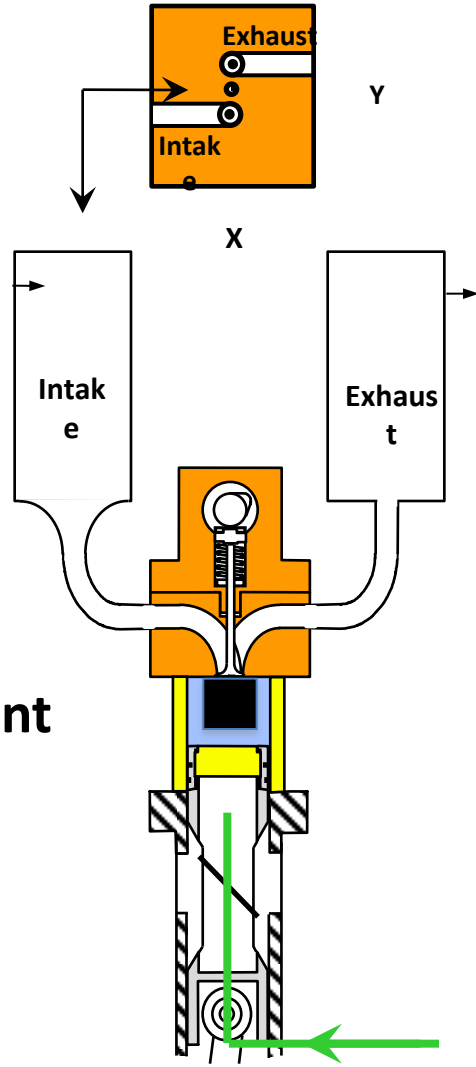




Flow Pattern (TCC – Univ Michigan)





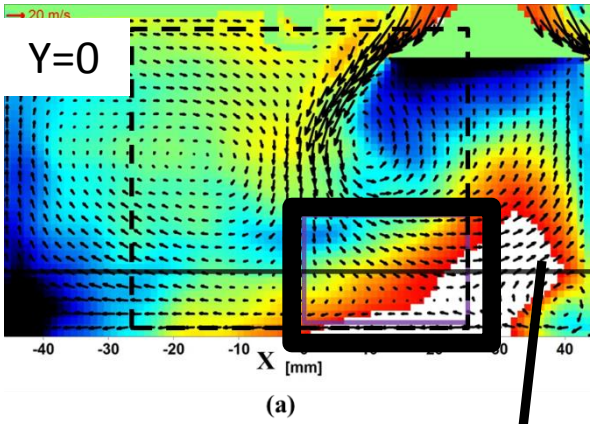


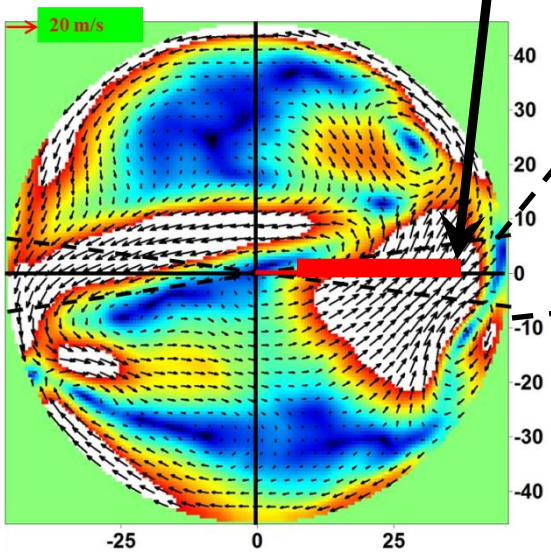
- At mid-intake stroke, ensemble-averages from different 70-cycle samples show flow structures with opposite direction
- Measurements show both flow patterns exist
  - Appearance is sample dependent

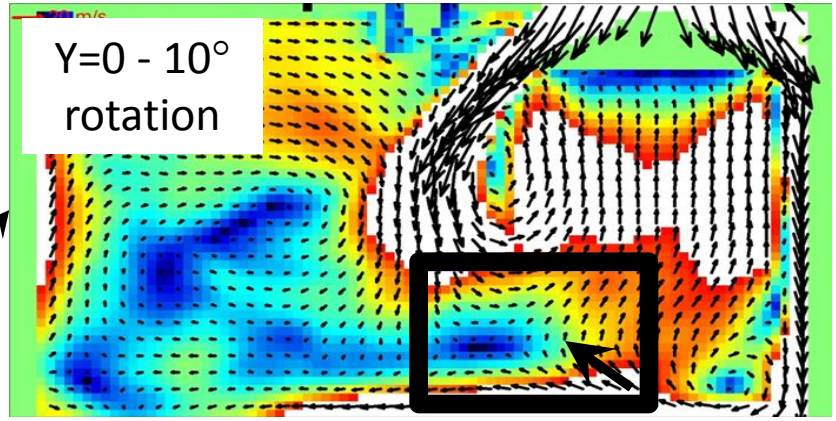
•"Effect of Boundary Conditions on Intake Flow Patterns in a Motored Spark Ignition Engine", Abraham et al. submitted to IJER, 2014

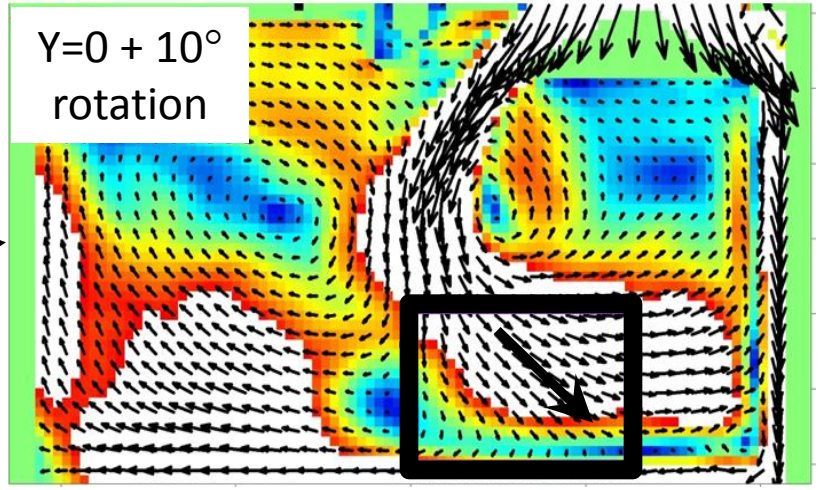
Flow Pattern (TCC – Univ Michigan)

Use 3-D LES data, sampled at rotated planes, to identify the reason for flow CCV







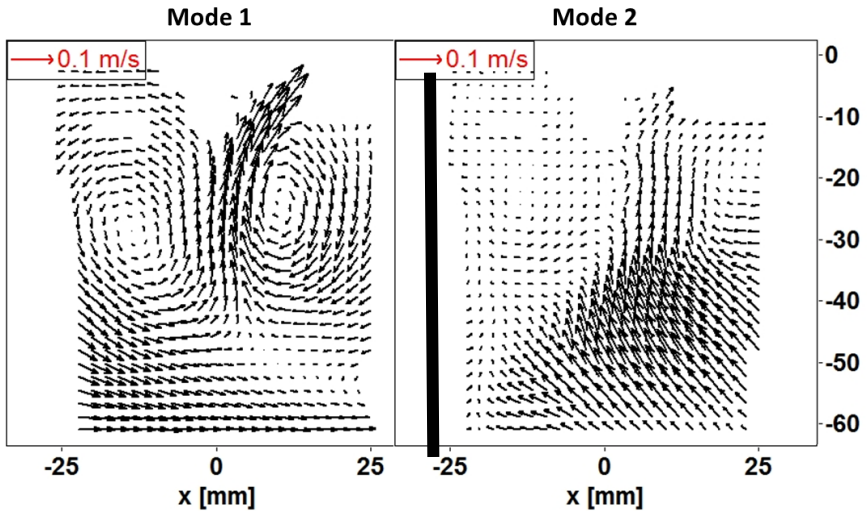


40 cycle Ens-Averaged

Flow Pattern (TCC II – Univ Michigan)

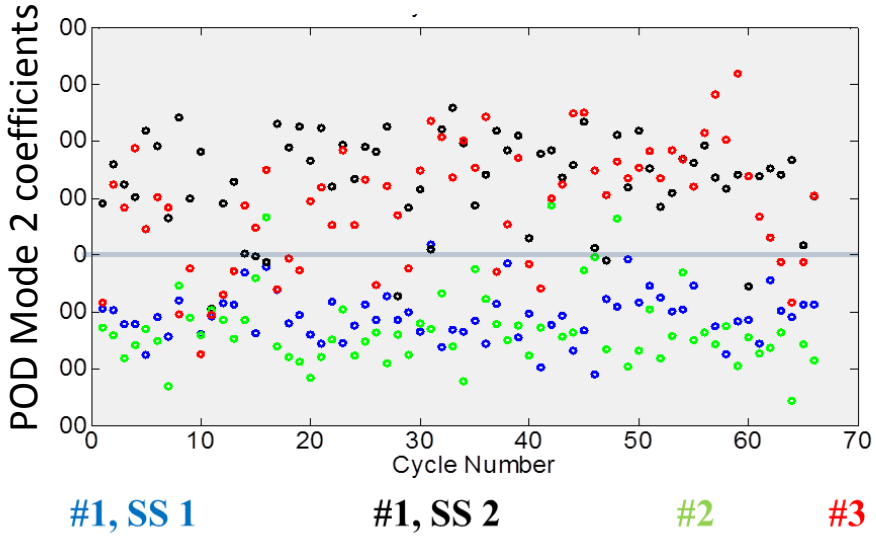
Use conditional sampling of POD modes to correlate flow structure with:

- **Intake Port Pressure** → **No Correlation**
- **Lateral valve oscillation** → **Very weak correlation**
- **RPM changes** → **Inconclusive**



POD Mode 1 dominated by intake jet & entrainment vortices

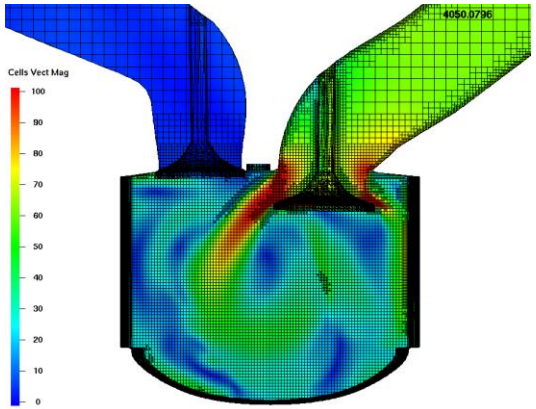
POD Mode 2 dominated by Lower Right-Hand, flow structure



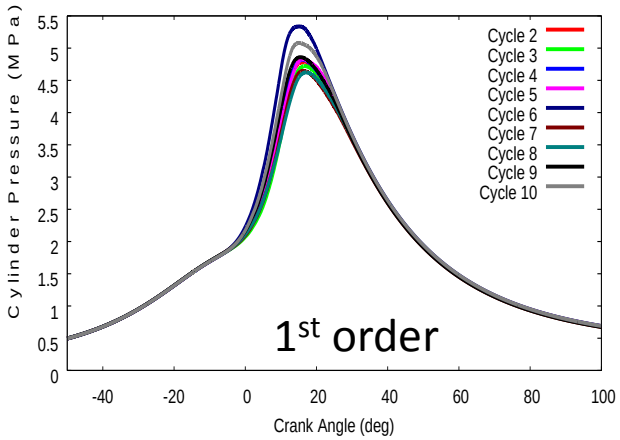
Mode 2 coefficients correlate with direction of LRH flow structure

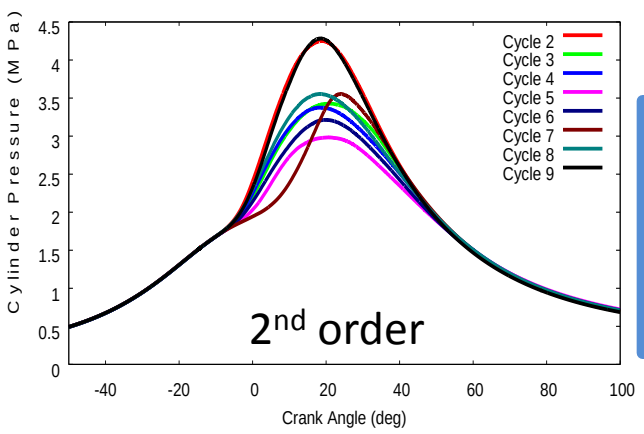
2. Fired operation

Direct-Injection Spark Ignited Example



Bore	101.6 mm
Stroke	100.0 mm
Connecting Rod	180.0 mm
Compression ratio	9.2:1
Number of Valves	4
Start of Injection	-220 deg. ATDC
Spark Timing	-15 deg. ATDC
Engine Speed	3000 RPM
Equivalence Ratio	1



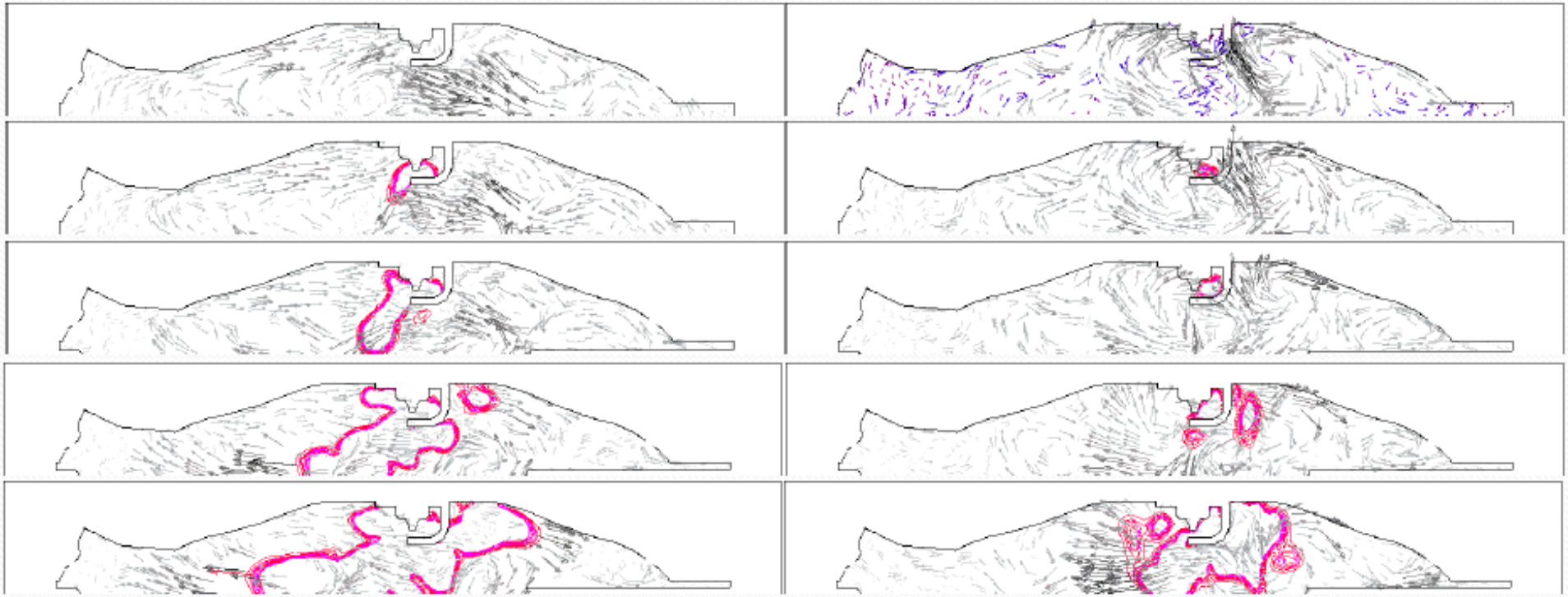


CCV exist in RANS simulations if the numerical viscosity is sufficiently minimized

	First Order	Second Order
IMEP (bar)	9.9	9.2
COV of IMEP	1.8	3.9

Combustion progress (UNIMORE)

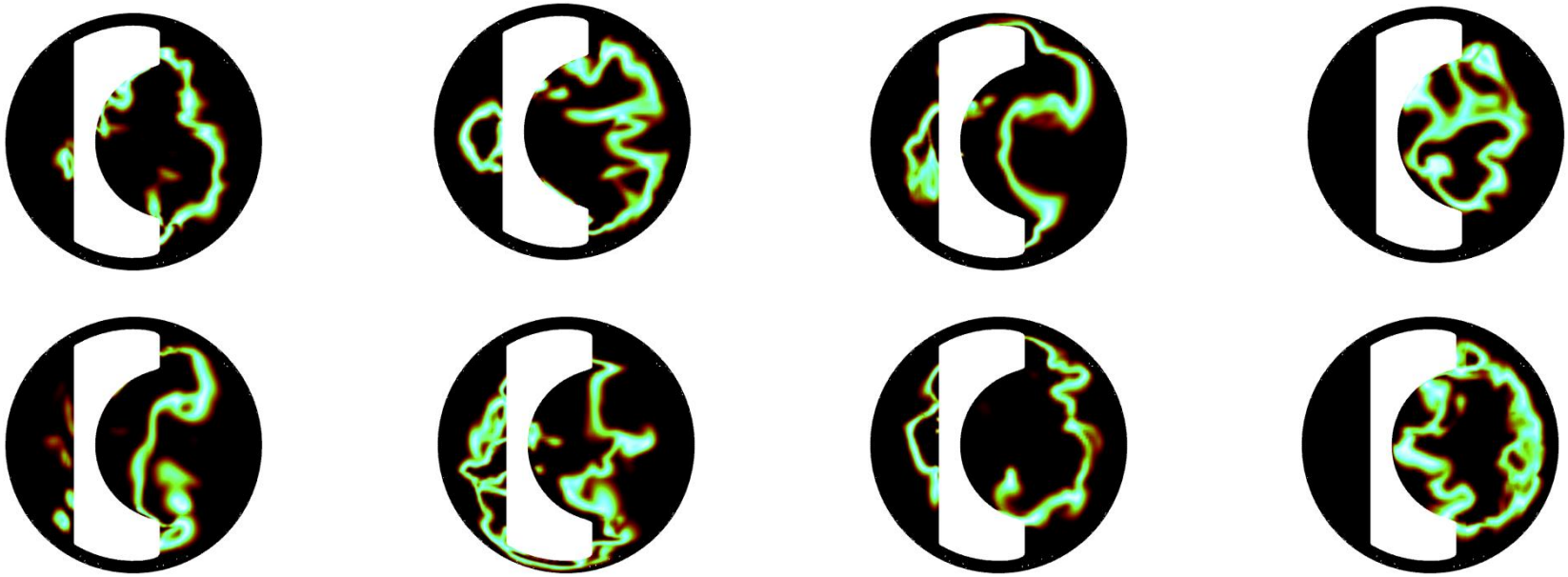
LES computations



Difference in flame propation between the flastest cycle (left) and slowest one (right)

Combustion progress (CTU Prague)

LES computations

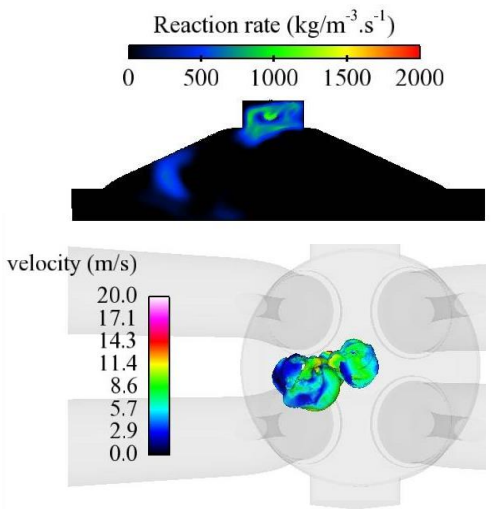


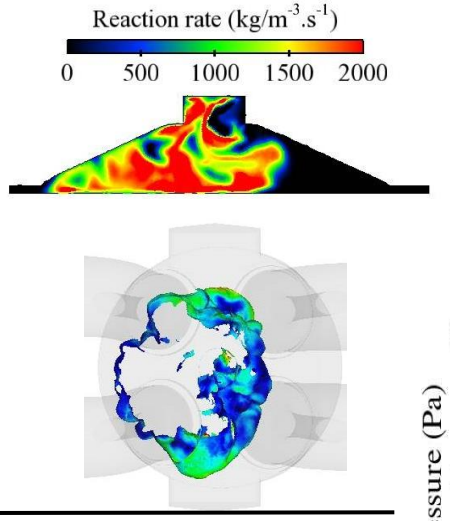
- Difference in flame propagation
- Critical parameters are:
  - combustion speed - driven by turbulence level
  - Ignition delay – initial flame kernel development

Combustion progress (SGEmac IFP)

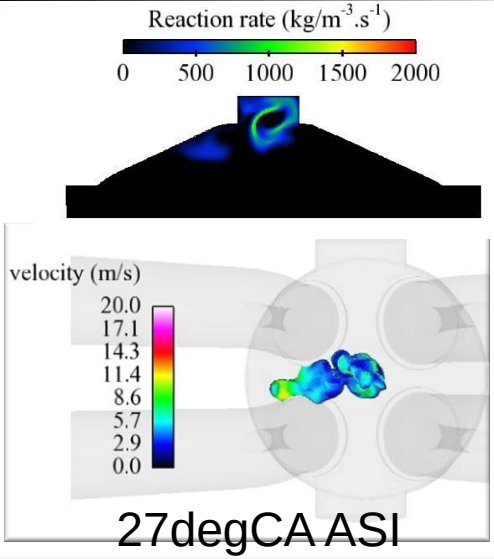
LES computations

Fast Cycle

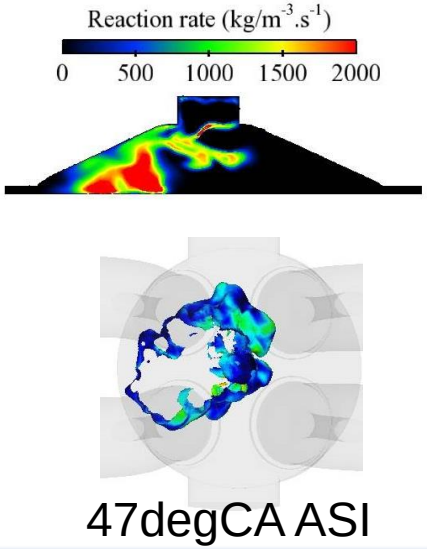




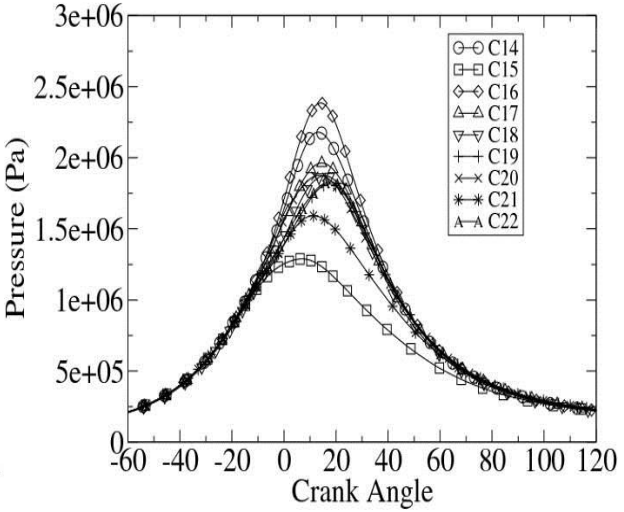
Slow Cycle



27degCA ASI

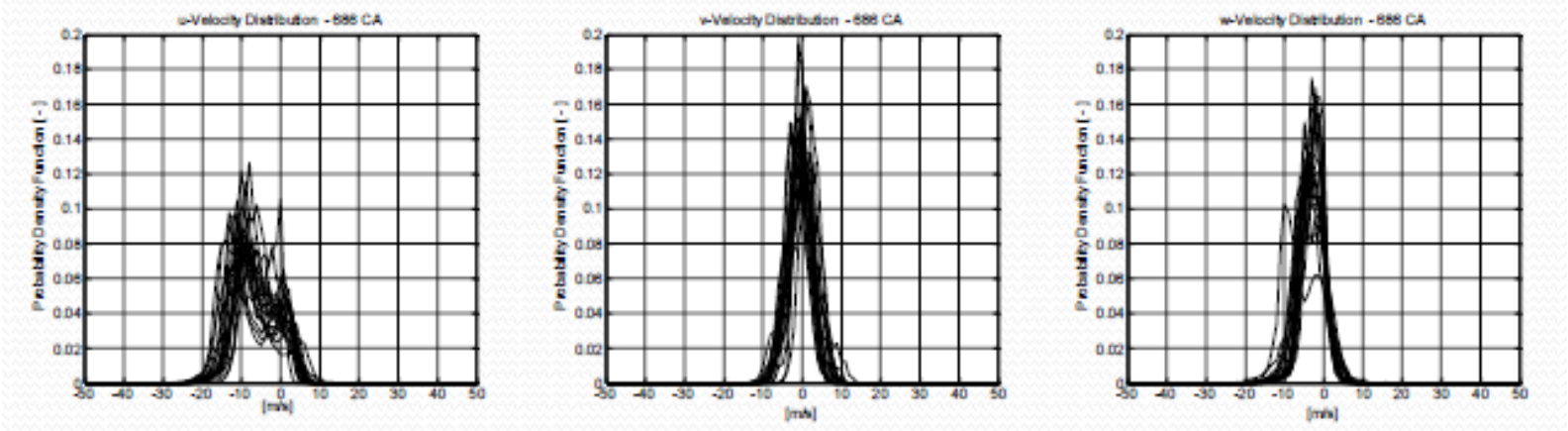


47degCA ASI

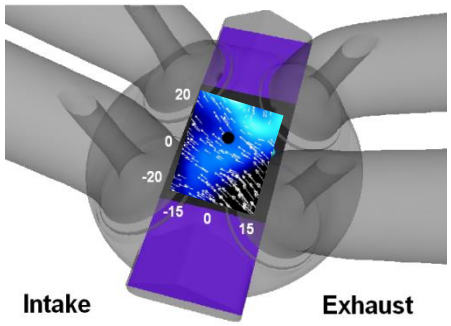


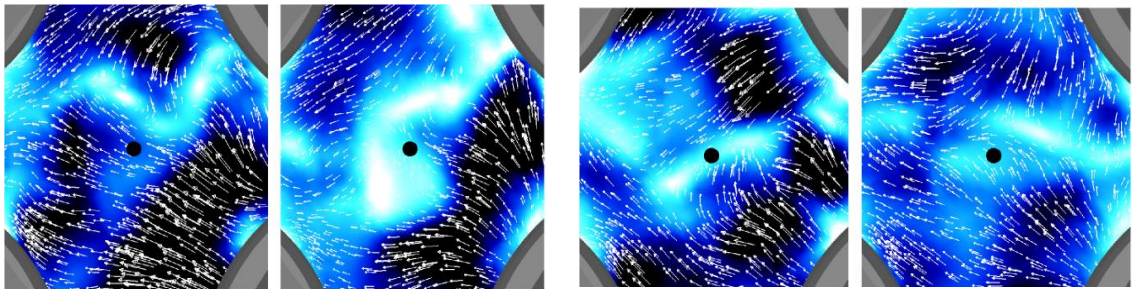
Flow fluctuations close to the spark plug @ spark timing (LES IFP, LES UNIMORE)

PDF of flow component around the spark during ignition



Velocity statistic around the spark during ignition

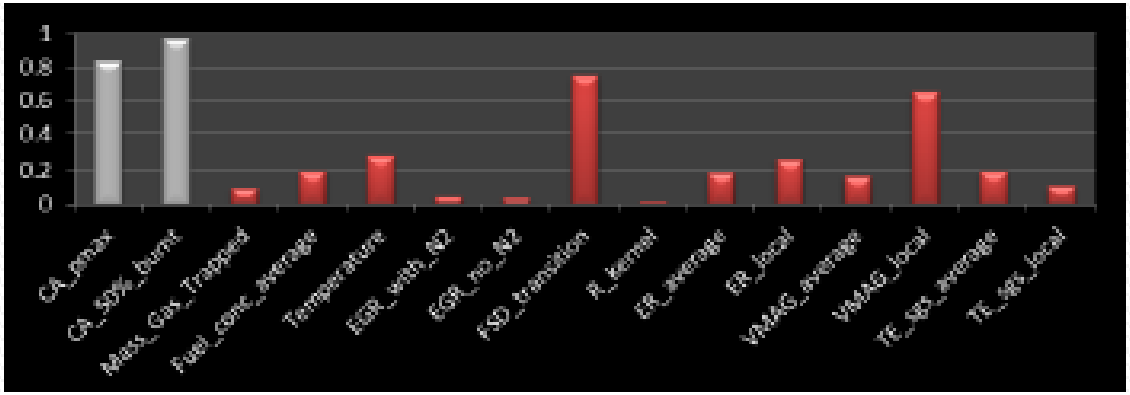




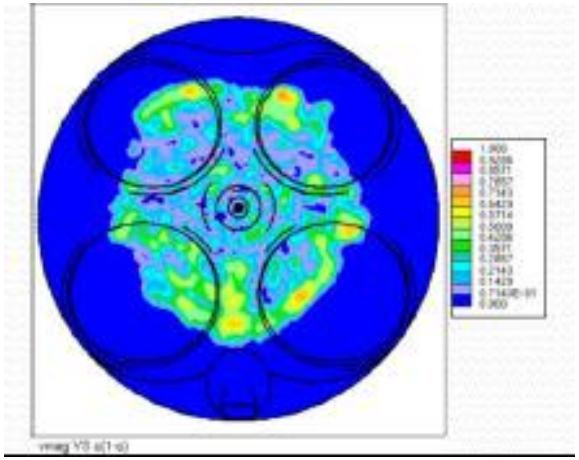
Cycle10 Cycle11 Cycle12 Cycle13

Cross-correlation coefficient – Both 0D and Fully 3D (UNIMORE) LES computations

Correlation Coefficient (Pmax, Yj)



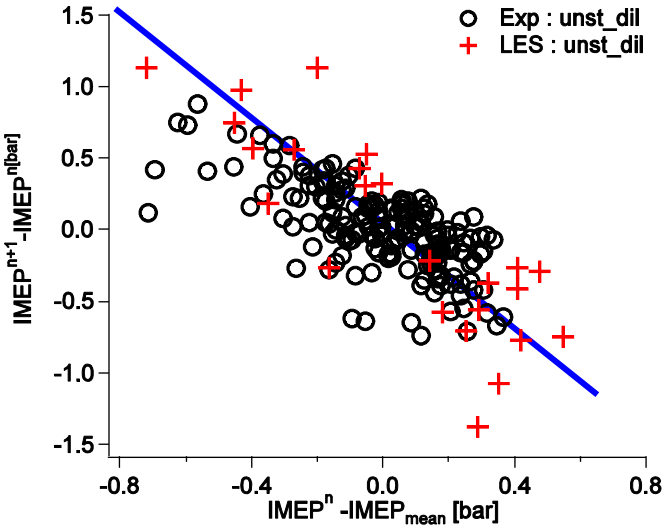
Correlation Coefficient spatial distribution



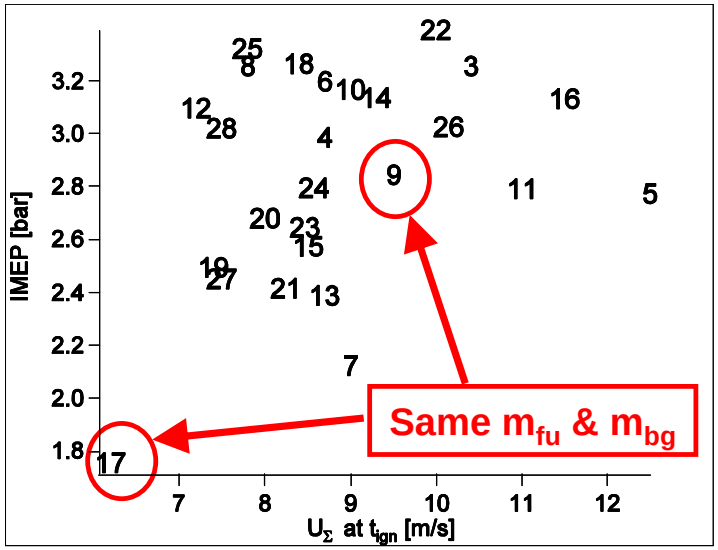
IMEP correlation (IFP)

LES computations

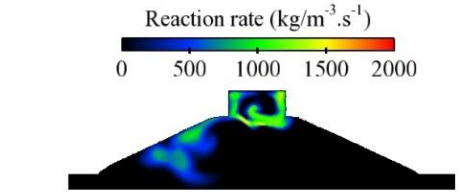
Variations of IMEP from C to C

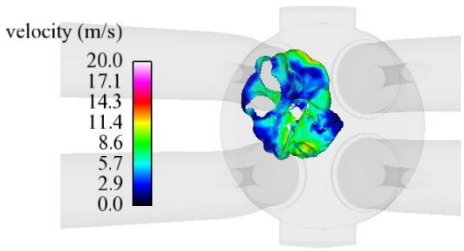


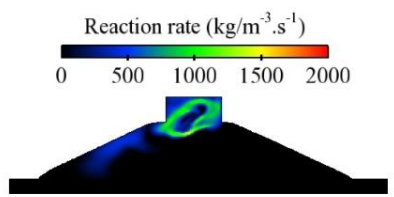
IMEP vs convection at spark plug

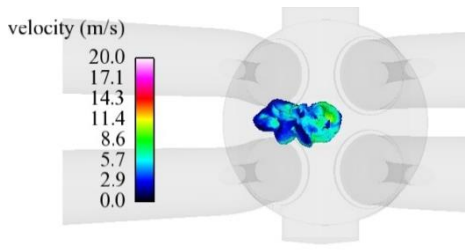


- **Important effect of the flow properties on the flame development and so on CCVs**
  - **Turbulence structure**
  - **Turbulence intensity**
  - **Turbulence scales**









3. New modeling tools

How to introduce CCV in 1D modeling

Naturally described by codes (@ 1st order)

Variations of:

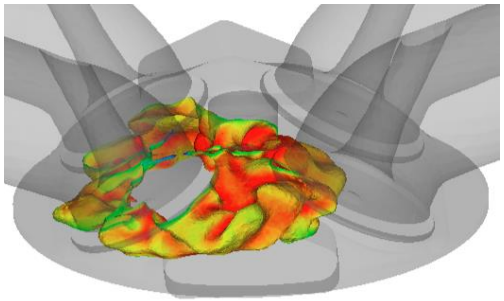
Intake system
- Turbulence
- Acoustics
- Op. conditions

⇔

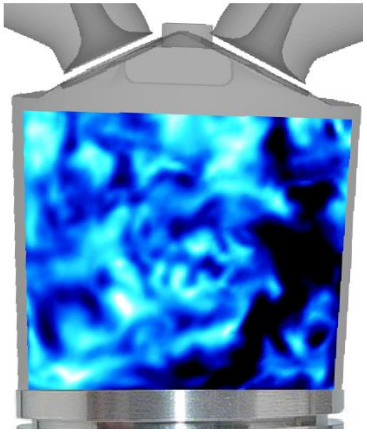
- Trapped mass
- EGR rate, temperature
- Fresh mixture composition

⇔

Exhaust system
- Turbulence
- Acoustics
- Op. conditions



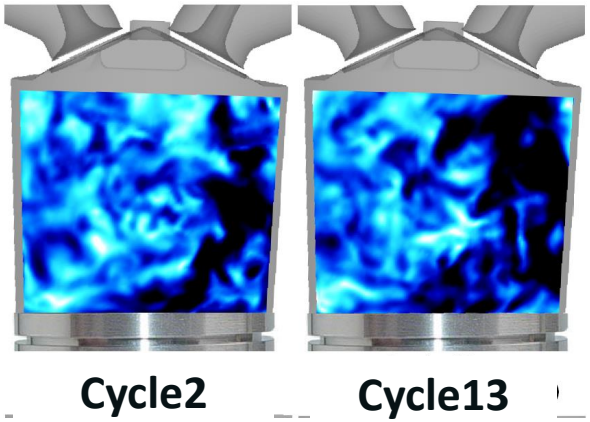
- Large scale flow patterns
- Small scale turbulence
- Conditions at spark plug
- In-cylinder temperature

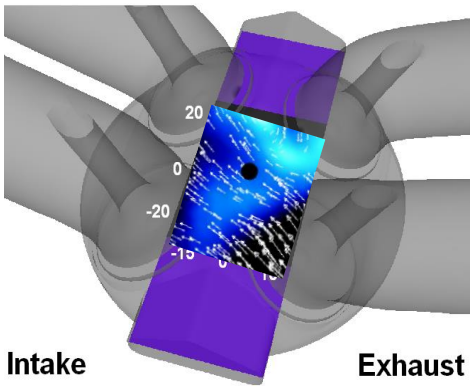


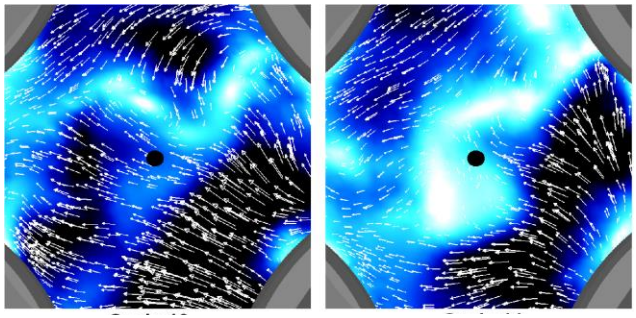
Needs in-cylinder phenomena details

Strategy

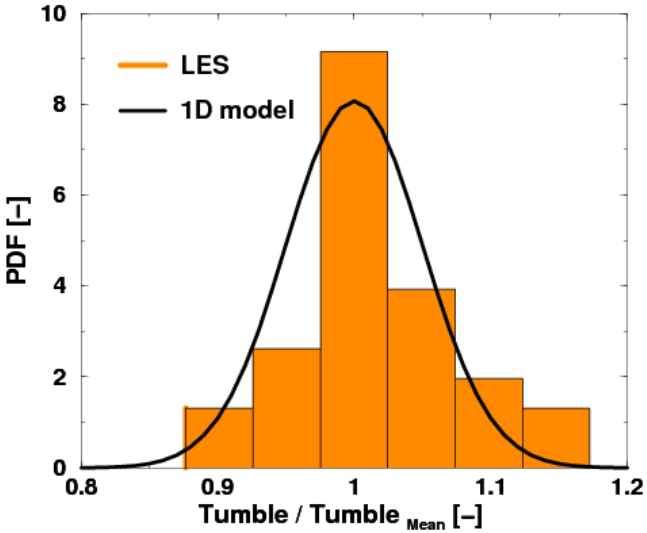
- **Dedicated post-processing of cold flow LES**
  - Turbulent scales @ spark timing (l_t)
  - Tumble number @ IVC (large scale kinetic energy – K)
  - Velocity fluctuations close to the spark plug @ spark timing







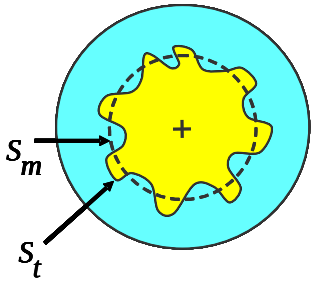
- **Tumble motion study**
  - Gaussian shape of the probability density function (LES) @ IVC

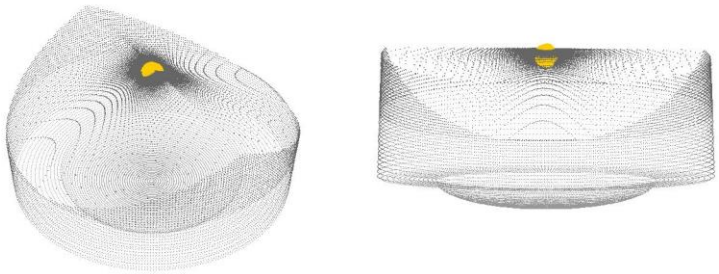


The CFM-CCV 1D model[1]

- **Two-zone model (fresh/burnt gases)**
- **Based on CFM 1D model[2]**
- **Flame surface:**

$$S_t = \Xi S_m$$





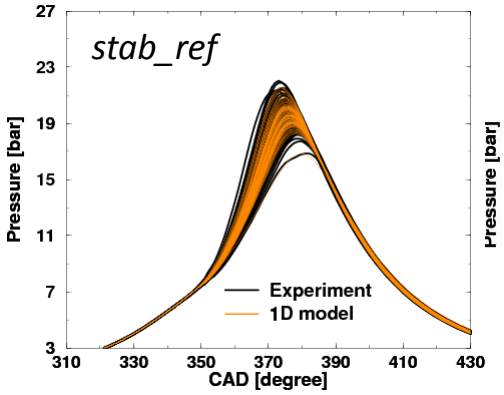
$$\frac{1}{\Xi}\frac{d\Xi}{dt} = \Gamma\left(u'/U_l, l_t/\delta_l\right)\frac{u'}{l_t}\left(\frac{\Xi_{equ}-\Xi}{\Xi_{equ}-1}\right) - \frac{2}{r_{bg}}(1+\tau)(\Xi-1)U_l$$

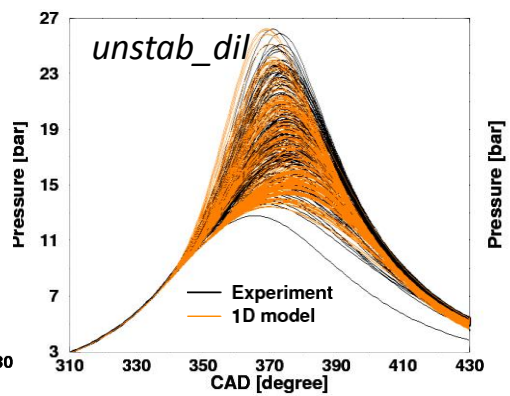
- **Turbulence model for**
  - **u': turbulence fluctuations**
  - **l_t : turbulence integral length scale**

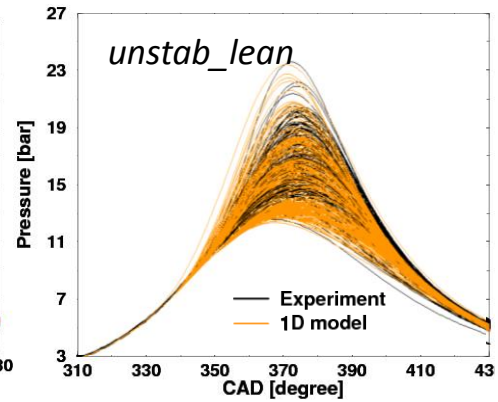
[1] Pera et al. SAE 2012-01-0127
[2] Richard *et al.* (2009) Oil Gas Sci Technol 64(3)

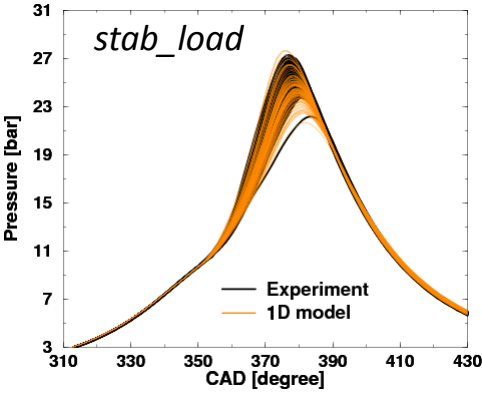
The CFM-CCV 1D model[1] – Validation on the SGEmac database

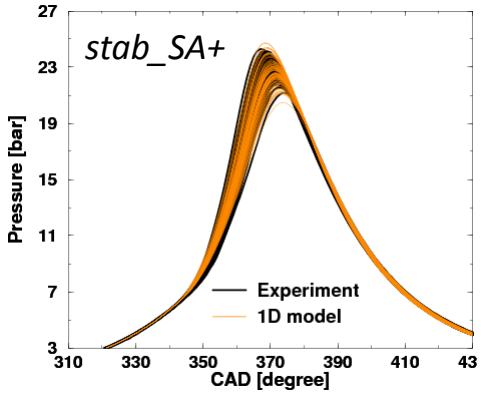
- **Cylinder pressure envelop results**
  - **Simulation of 100 cycles for stable 200 cycles for unstable conditions**
  - **The same relative perturbations are used for all engine speed/load**

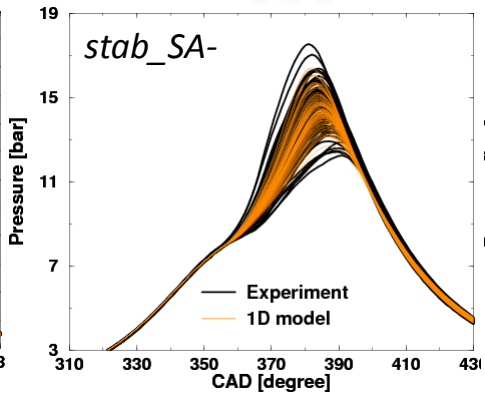


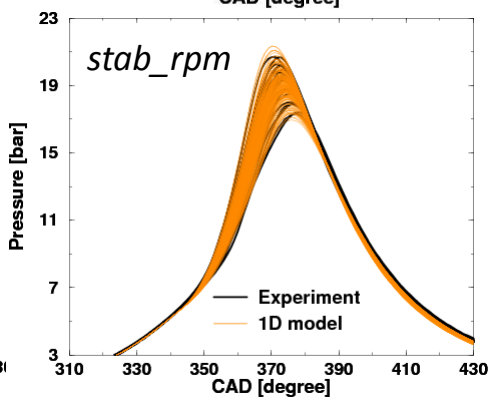






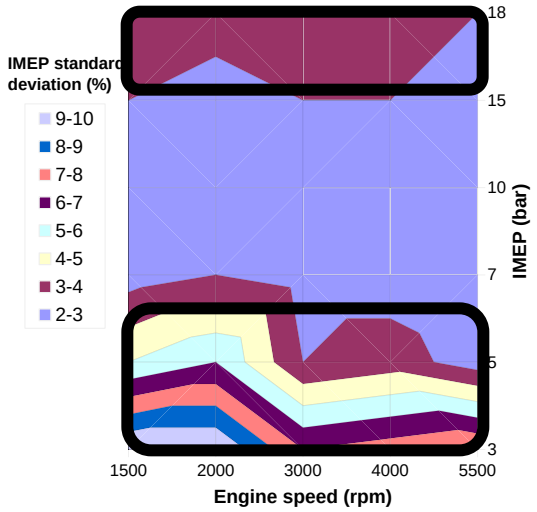






Engine operation stability map

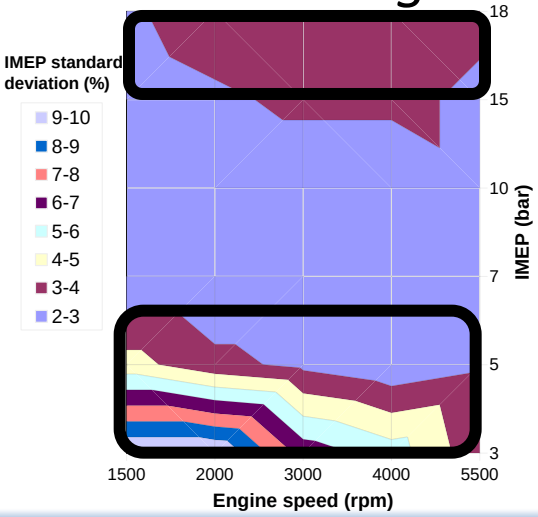
Experimental map



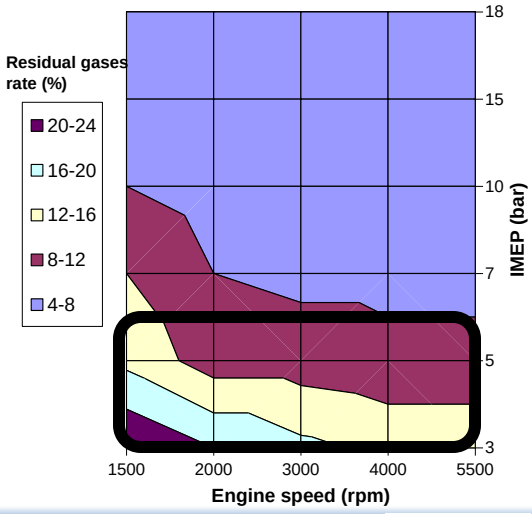
Stable and unstable zones are predicted for all conditions

Instability may be linked to chemistry modification : dilution or high enrichment

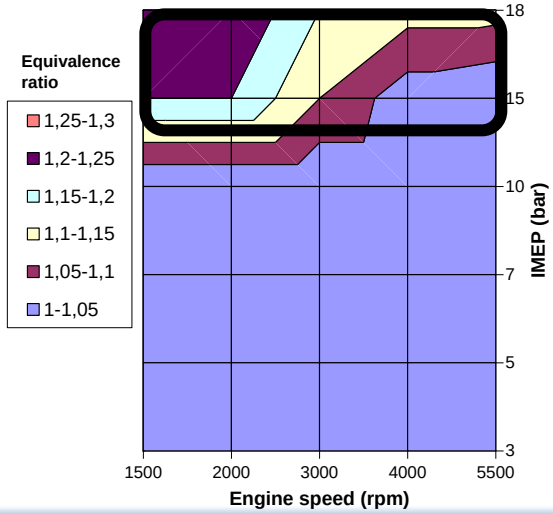
Modeling



IGR rate (%)



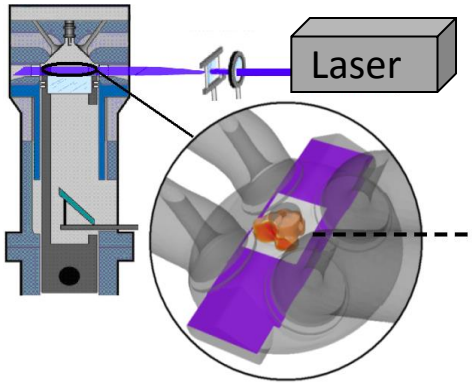
Equivalence ratio

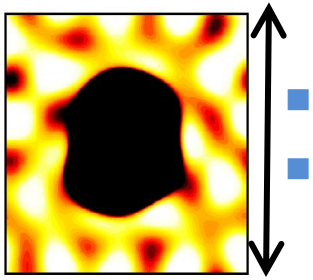


4. Perspectives

DNS of early flame propagation for CCV understanding[3]

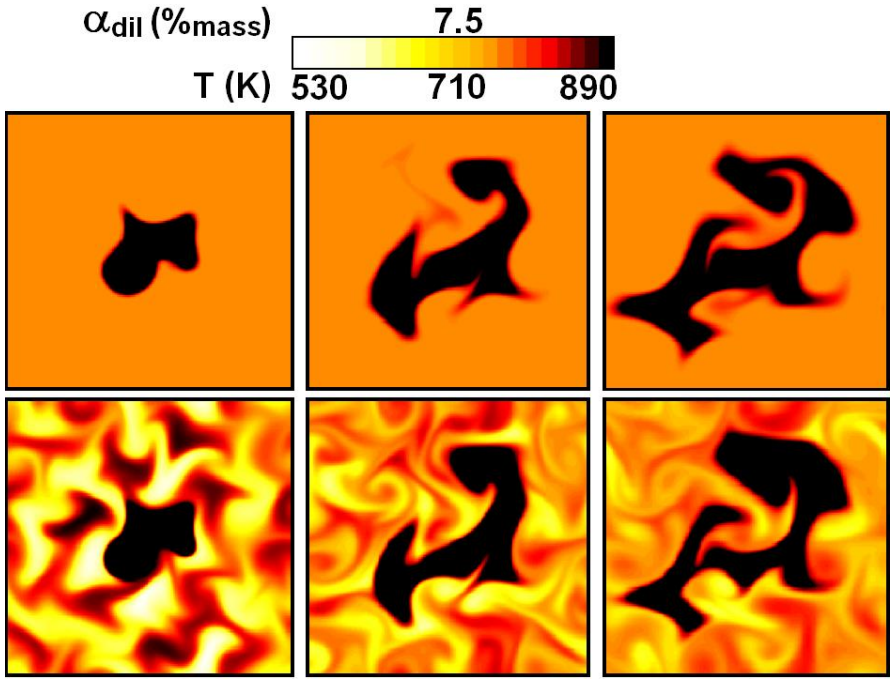
[3] Pera et al. , FTaC 2014



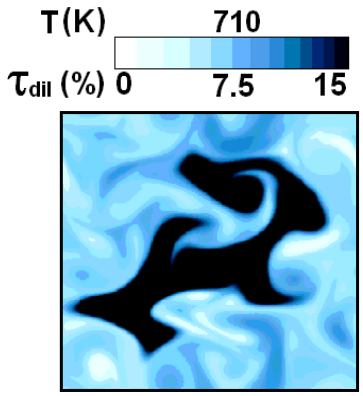


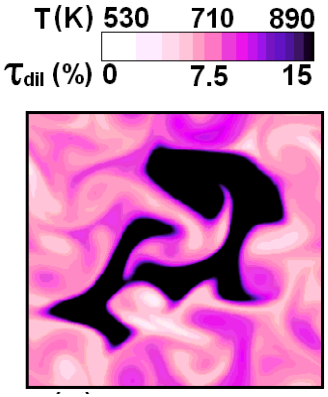
- 4 mm
- Δx = 14 µm

- **Temperature heterogeneity could highly modify flame shape**
- **Effect of temperature is dominant over that of dilution**



Based on SGEmac exp. (Unstab-Lean op. pt)



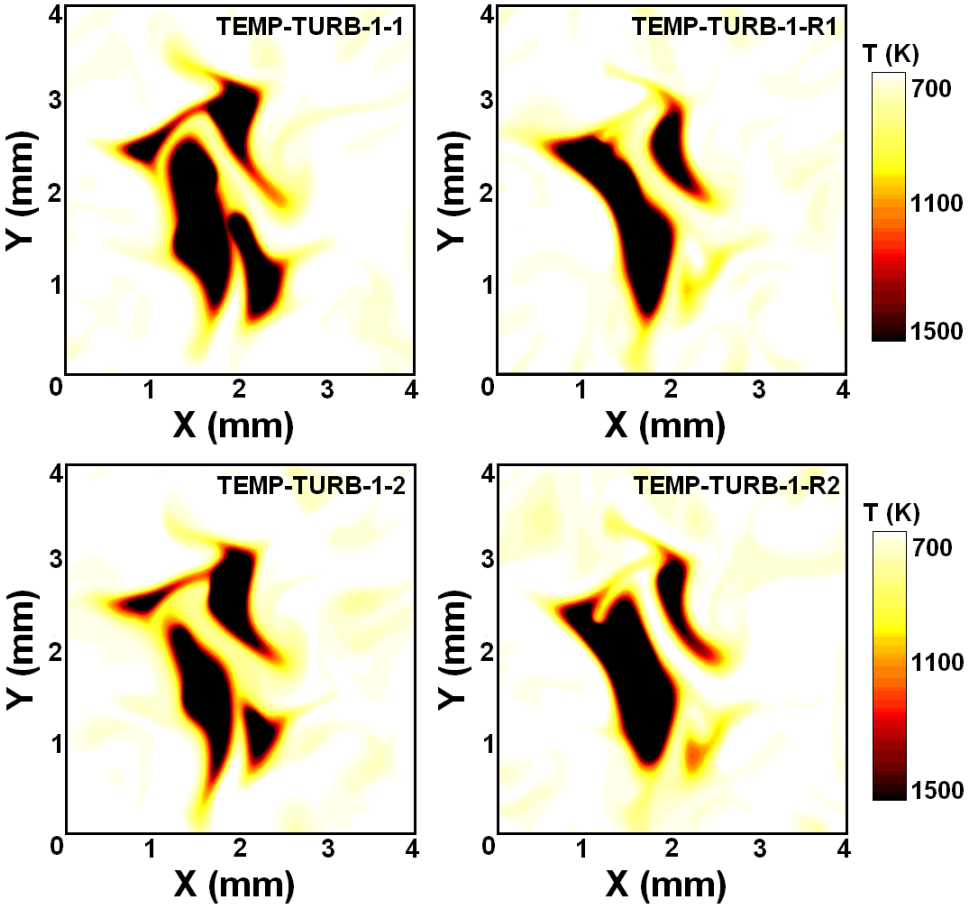


DNS of early flame propagation for CCV understanding[3]

4 realizations ≈ 4 engine cycles

Ensemble average (4 cycles)

Modeling (RANS or LES)



- Error in flame shape if heterogeneities (temperature / dilution) are not explicitly accounted for
- RBG Heterogeneities contribute to quench the flame
  - Modelling?

[3] Pera et al. , FTaC 2014

Contributions

1. Motored operation

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3. New tool modeling,

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4. Perspective, — **All**