HIGH EFFICIENCY ENGINE DESIGN USING IFPEN COMBUSTION MODELING

OUTLOOK

- IFPEN Introduction
- CSI-IFPEN COLLABORATION
- IFPEN model portfolio
  - Compression Ignition engine modeling (EFM3Z – TKI)
  - Spark Ignition engine modeling (ECFM – ISSIM – TKI)
  - Large Eddy Simulation for ICE (ECFM-LES and ISSIM-LES)
- High efficiency engine design
  - Lean Burn engine (prechamber ignition)
  - Spark Assisted Compression Ignition engine (SACI)
- Future of ICE modeling

IFP ENERGIES NOUVELLES

IFPEN is a french research institute on energy and environment management

3 research axes

SUSTAINABLE MOBILITY	NEW ENERGIES	RESPONSIBLE OIL AND GAS
Developing effective, environmentally-friendly solutions for the transport sector	Producing fuels, chemical intermediates and energy from renewable sources	Proposing technologies that meet the demand for energy and chemical products while improving energy efficiency and reducing the environmental impact

Fundamental research, the bedrock supporting the development of our innovations

WOMEN, MEN AND RESOURCES

1,622
(total full-time equivalent workforce)

1,119 engineers and technicians dedicated to research

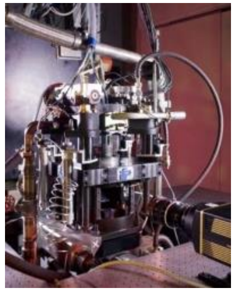
2 facilities:
Rueil and Solaize

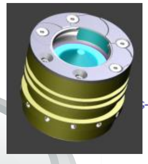
€280M
budget allocation in 2018 + own resources in 2018

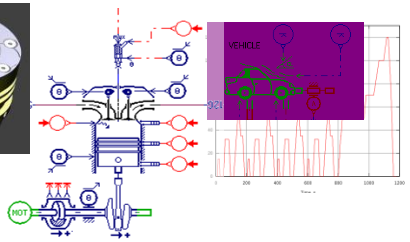
50%
of the IFPEN budget devoted to NETs

One of the only French public research bodies to self-fund **over 50%** of its budget

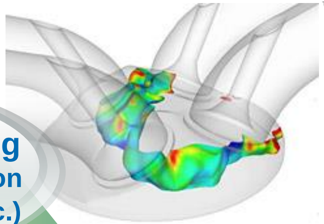
FROM INNOVATING CONCEPT TO VEHICLE DEMONSTRATOR



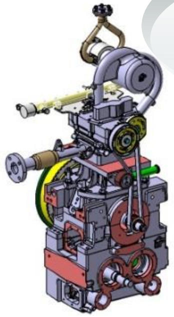




Innovative concept proposal and pre-dimensioning (simulation and advanced diagnostics)



Engine optimisation using numerical tools (combustion systems, air and fuel loop, etc.)

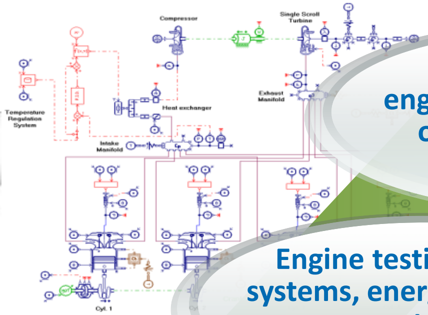


Single-cylinder engine testing

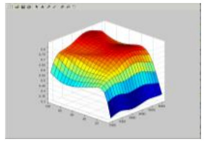
Complete manufacture of the engine prototype

Validation : proof of concept, robustness

Engine testing tuning : systems, energy, emissions control…

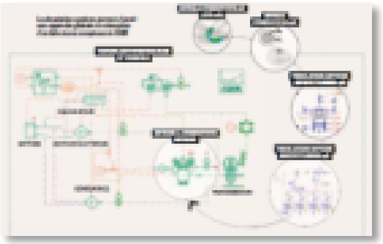


Calibration of the engine control : prototype or industrial vehicule



From definition…

>> with IFPEN tools and CONVERGE

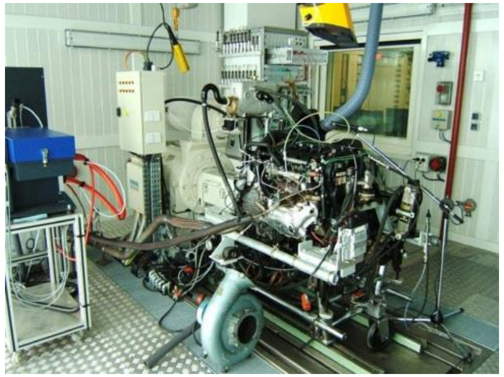


… to prototype

INSTITUT CARNOT IFPEN Transports Energie

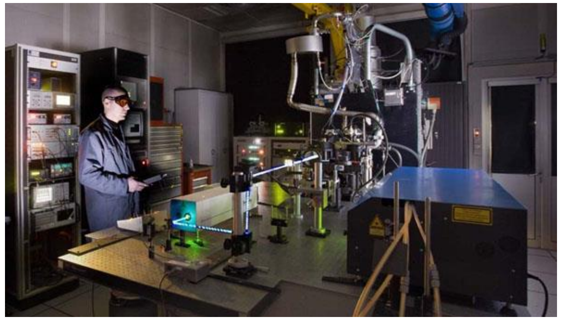
IFP Energies nouvelles

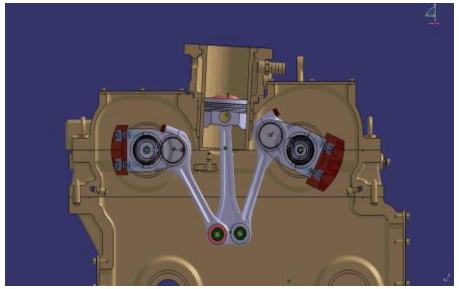
ENGINE TESTING FACILITIES AND LABORATORIES

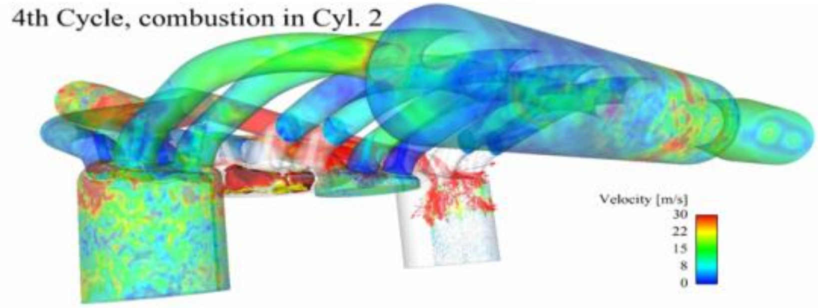


- Located in Rueil Malmaison (Paris) and Solaize (Lyon)
  - **13 multicylinder Engine Test Cells** (HIL, from Light Duty to Heavy Duty… with gas capabilities)
    - 1 cold-start test cell
    - 1 high-dynamic "climatic" test cell
  - **6 monocylinder** Engine Test Cells fully automatic
  - **3 optical engine test cells**
  - **3 optical diagnostics laboratories** (high P / high T vessels)
  - 2 chassis dynamometer (1 Euro 6)
  - **1 injector test bench**
  - 1 flow bench (permeability, aerodynamics measurements…)
  - CFR engine laboratory (octane – cetane measurements)
  - Catalysis and after-treatment Laboratory

  - Engine Design Office
  - High computing capability (110 Teraflops)







INSTITUT CARNOT IFPEN Transports Energie

IFP Energies nouvelles

IFPEN / CSI COLLABORATION FOR ICE

IFPEN has developed 3D modeling for ICE for more than 25 years. In 2015, IFPEN has signed a collaboration with Convergent Science Inc to develop CONVERGE. The original collaboration has been extended in 2018 for 5 years.

Since 2016, CONVERGE solver contains IFPEN model for ICE simulation and are intensively used by the automotive customers.

2015

RANS model development for ICE Simulation
(ECFM, ECFM3Z,TKI, ISSIM)
SCR system – Adblue Deposit

First collaboration

2018

LES ans RANS model development for ICE Simulation
(ECFM-LES, ISSIM-LES, Soot Sectionnal model, TFM-AMR)
Spray impact / Liquid film evaporation on boiling conditions
SCR system – Adblue Deposit

Extended collaboration

2022…

CSI IFPEN COLLABORATION

SUSTAINABLE MOBILITY

24 peoples including
13 Research engineers and 11 PhD developing new modeling for CONVERGE

+

15 Research engineers using every day CONVERGE for collaborative research project using 3D simulations

Internal project
Collaborative research project(GSM...)
European / National research pr
CONVERGE development

CONVERGE

IFPEN has 90% of the CONVERGE source files and is directly connected to the development team via a common concurrent version system (GIT). Bi-monthly meeting with the development team are organized. Daily contact with CSI team.

IFPEN is able to manage beta version (with the most up to date modeling) for collaborative research project (industrial or academic partner).

INSTITUT CARNOT IFPEN Transports Energie
IFP Energies nouvelles

IFPEN RESEARCH USING CONVERGE

Since 2015 and our new collaboration, IFPEN has switched the PhD work from in-house code IFP-C3D to CONVERGE and since 2018 from AVBP to CONVERGE (LES, GT).

PhD starting year:

2017 – 1 PhD (Hybrid LES – HTLES)

2018 – 5 PhD (GT, Soot Modeling, Knock – fuel sensitivity, LES Abnormal combustion, LES advanced data analysis – Flash boiling) – 1 Post-Doctoral student.

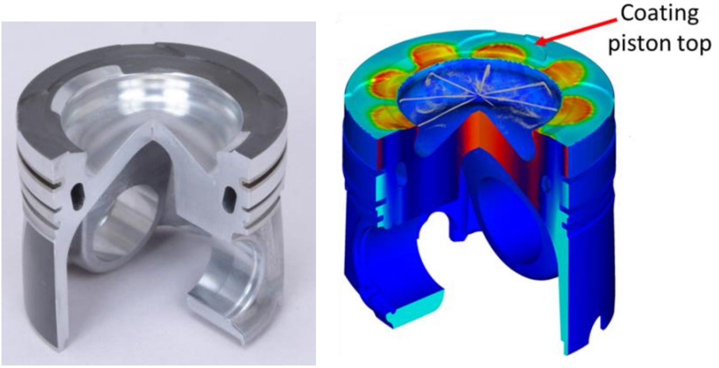
2019 – 2 PhD (GT ignition modeling, machine learning of CFD)

2020 – About 5 PhD proposals / 1 Post-Doctoral position.

PhD at IFPEN are supervised by IFPEN academic combustion network (Ecole Centrale Paris, Université Marseille, CORIA, Prisme Orléans university Lab, Cambridge…)

Thanks to this intensive research work, IFPEN will be able to improve ICE modeling using CONVERGE.

In 2020, more than 10 PhDs will develop CONVERGE at IFPEN.



Compression Ignition Engine :

- **ECFM3Z** - **TKI** and simplified chemistry for burned gases
- SAGE and **IFPEN Soot Sectional Modeling** (coming next in V3.0.x)

Spark Ignition Engine :

- **ECFM - ISSIM – TKI** with simplified chemistry for burned gases
- **ECFM - ISSIM –TKI + SAGE coupling** with Soot Sectionnal modeling (Coming next in V3.0.x) for pollutant emissions
- **ECFM-LES - ISSIM-LES -- TKI** Large Eddy Simulation version for CCV and abnormal combustion

Spark Assisted Compression Engine (SACI)

- **ECFM3Z – ISSIM – TKI** with simplified chemistry

 |

IFPEN MODEL PORFOLIO
TABULATED KINETIC IGNITION MODEL - **TKI**

SUSTAINABLE MOBILITY

New fuel composition → Fuel Surrogate (Spray modeling)

(Chemistry)

chemical kinetic mechanism

direct

Kinetic reducing method

undirect

Kinetic table generation into Converge Studio

Remark : auto-ignition and pollutant emissions is computed

Homogeneous Chemistry (**SAGE**) using reduced kinetic scheme

Multi-zone, adaptive kinetic mechanism method + (G-equation)

Tabulated chemistry combustion Model
Tabulated Kinetic Ignition

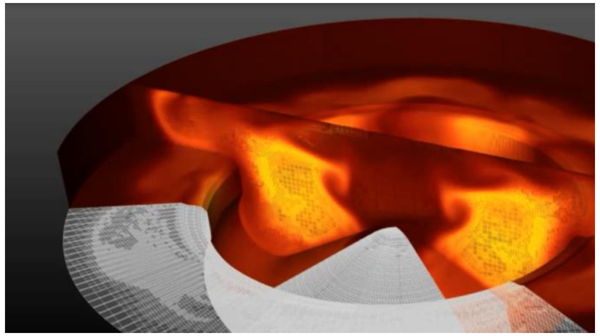
+
ECFM3Z or **ECFM**

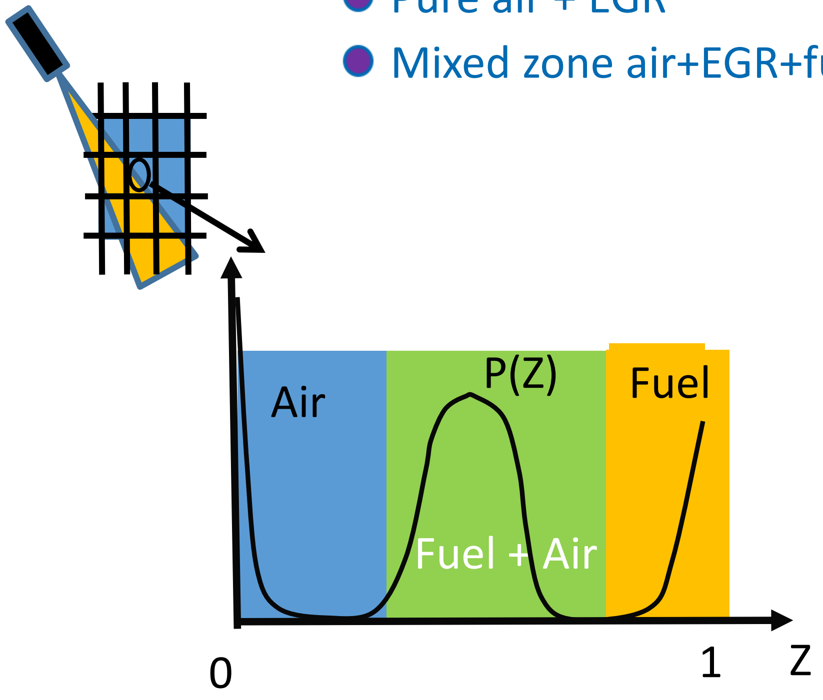
Remark : Just auto-ignition is tabulated

CONVERGE CFD SOFTWARE

THE ECFM3Z COMBUSTION MODEL

- General purpose model developed at IFPEN the last 20 years
  - Based on premixed flame propagation model (ECFM) for gasoline engines
  - Combustion: three mixture fraction description
    - Pure gaseous fuel (from evaporating liquid spray)
    - Pure air + EGR
    - Mixed zone air+EGR+fuel



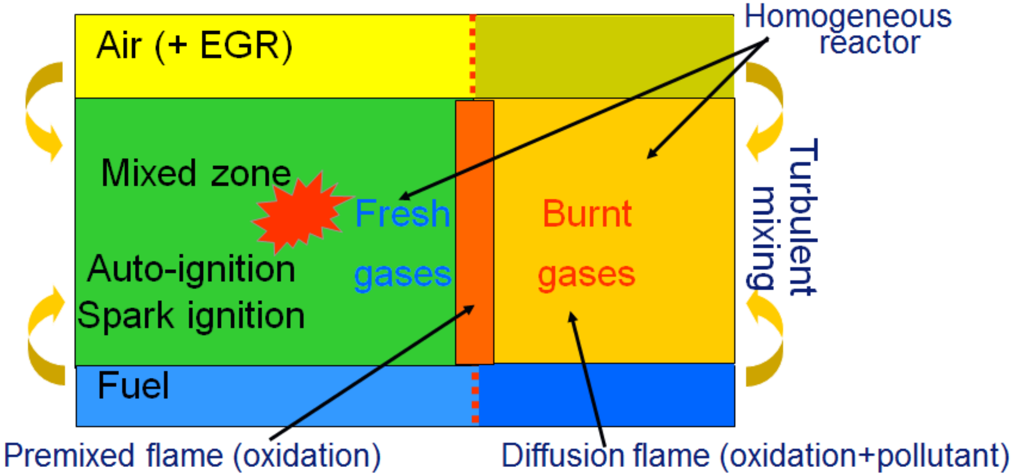


ECFM3Z model assumes:

Fresh gases / Burn gases zone

Mixing zone in fresh gases where premixed combustion occurs

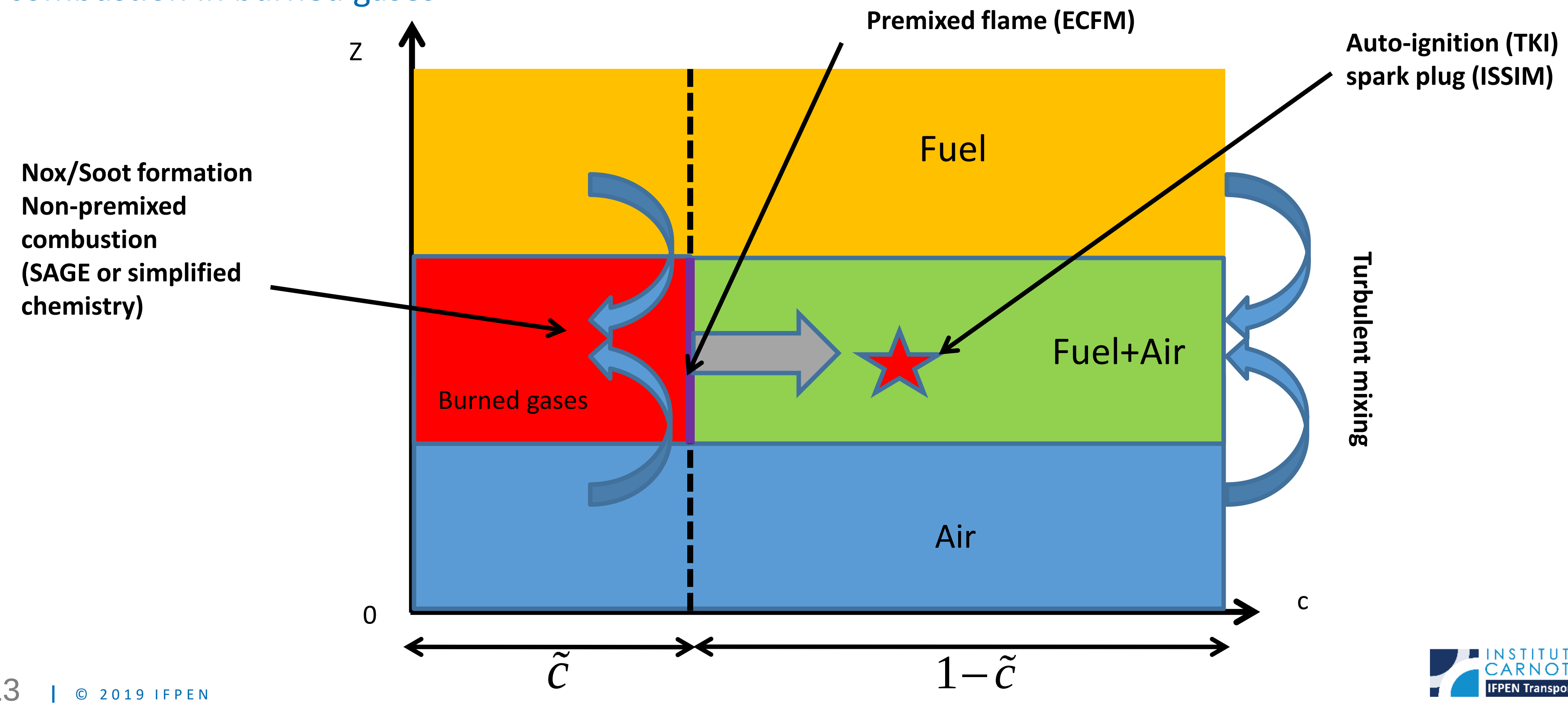
ECFM3Z scheme



THE ECFM3Z COMBUSTION MODEL

SUSTAINABLE MOBILITY

- Mixed zone keeps growing
- Burned gases are formed due to auto-ignition and/or spark plug ignition (c>0)
- Fuel and air going to burned zone lead to diffusion controlled combustion in burned gases
- NOx and soot start to form in burned gases
- Propagative flame surface is formed between unburned and burned gases

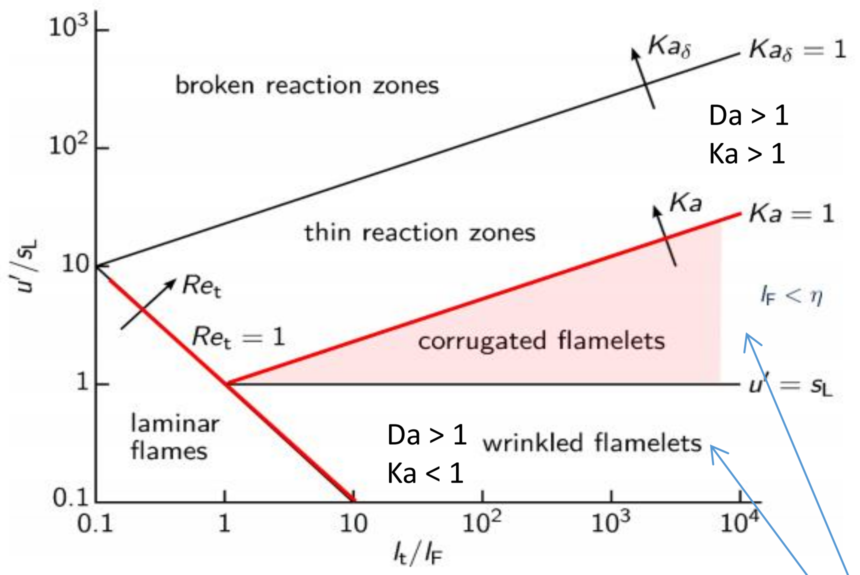


- ECFM : model for **premixed combustion (Extended Coherent Flame Model)**
  - **Flamelet assumption: flame thickness is smaller than Kolmogorov scale**
  - Reaction rate is the product flame surface (flame surface density Σ) by laminar flame speed (Sl):

Reaction rate of the progress variable ← [1] $\dot{\omega}_{FP} = S_l \Sigma$

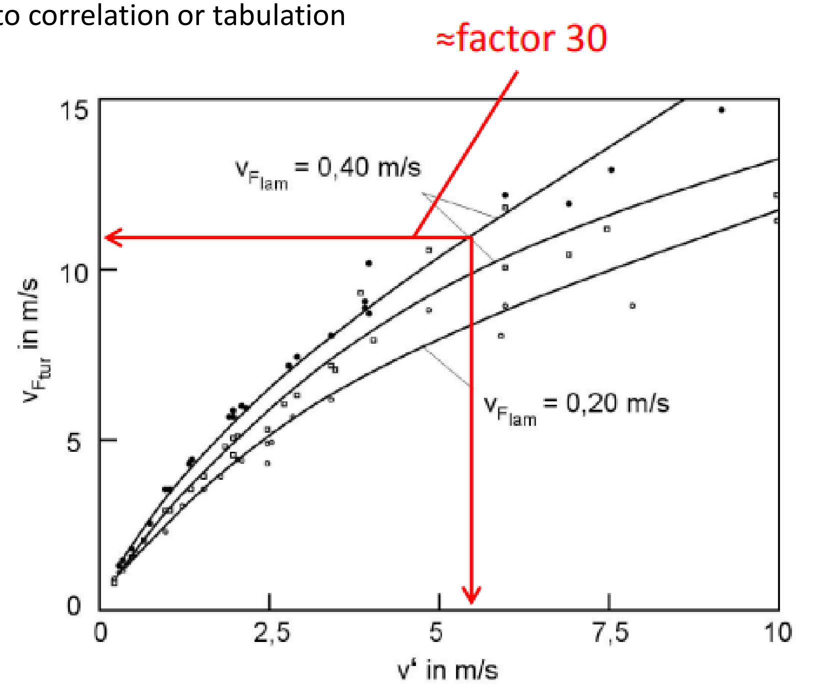
Flame surface density :
- Accounts for turbulent effect
- Is obtained resolving a transport equation

Laminar flame speed :
- Accounts for chemical effect
- Is obtained thanks to correlation or tabulation



Turbulent

ECFM zone



Measured Burning velocity vs Laminar flame speed

ECFM PRESENTATION

[1] Candel and Poinsot (1990)

[2] Colin and Benkenida (2004)

- ECFM : model for **premixed combustion**
  - Progress variable “c”
    - A combustion tracer
    - c = 0 in fresh gases and 1 in burnt gases

$1 - c_{FP}$ Fresh gases

c_{FP} Burnt gases

Need an efficiency function used to mimic sub-cell turbulence effect

  - Flame surface density

$$\frac{\partial \Sigma}{\partial t} = -\nabla.(\tilde{u}\bar{\Sigma}) - \nabla.\left(\frac{\tilde{\mu}_t}{Sc_t}\frac{\partial \Sigma}{\partial X}\right) + \frac{2}{3}\frac{\partial \tilde{u}}{\partial X} + \alpha\frac{\varepsilon}{k}\Gamma_k\left(\frac{u'}{S_L};\frac{L_t}{\delta_f}\right) + \frac{2}{3}S_L\frac{1-\tilde{c}}{\tilde{c}}\Sigma^2 - \frac{\beta_0 S_L}{1-\tilde{c}}\Sigma^2$$

[2]

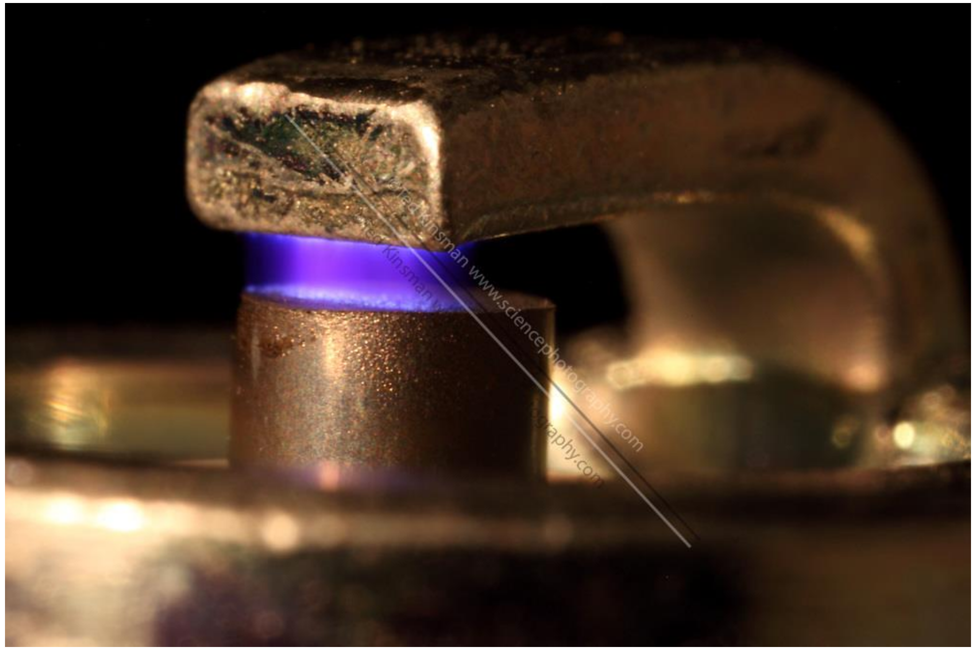
Time evolution / **Averaged transport** / **Turbulent transport** / **Mean strain rate** / **Turbulent strain rate** / **Normal propagation and curvature**

  - Laminar flame speed

S_l=f(Fuel,Temperature,Pressure, IGR, FAER)

SPARK IGNITION MODELING / ISSIM MODEL

- Its goal is to initiate the ECFM equation (generate flame surface)
- It accounts for various phenomena :
  - Local mixture stratification at the spark plug
  - Aerodynamic effects (initial kernel could be convected or stretched by the fluid motion)
  - Flame quenching

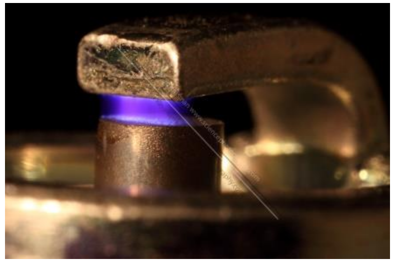


- What the ISSIM model is predicting ?

  - ✓ Is the spark plug able to breakdown ?
  - ✓ Spark size and displacement due to flow velocity
  - ✓ Is spark enough powerful to ignite the mixture?
  - ✓ Physical burnt mass deposit ➔ corresponding to the fuel mass burnt with E_{ign} energy
  - ✓ ECFM variable initiation

SPARK IGNITION MODELING / ISSIM MODEL

Breakdown
$V_{spk} > V_{bd}$



Spark formation
Size : l_{spk}=f (Spark plug size, local fluid motion)

Spark energy evaluation
E_{ign} = f (l_{spk},V_{spk},I_{spk})

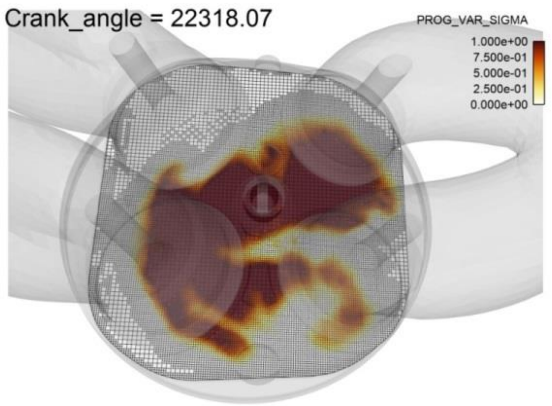
Check if ignition is successful
$E_{ign} > E_{crit}$
E_{crit}=f(FAER,T,P)

yes

Burnt mass deposit :
$m_{bg}{}^{in} = f(l_{spk}, E_{ign})$

Progress variable initialization
$\bar{c}_{ign} = f(m_{bg}{}^{in})$
Ξ_{ign}★ Initial flame wrinkling

ECFM COMBUSTION



★ Initial flame wrinkling is a modeling parameter
It allows to calibrate the start of the combustion

TKI AND COUPLING WITH ECFM MODEL FOR KNOCK MODELING

- **TKI : model for Auto-Ignition**
  - Tabulated approach
  - Accounts for detailed chemistry with low computational cost

$$\dot{\omega}_{AI} = f(T,P,\phi,\%_{EGR},cAI)$$

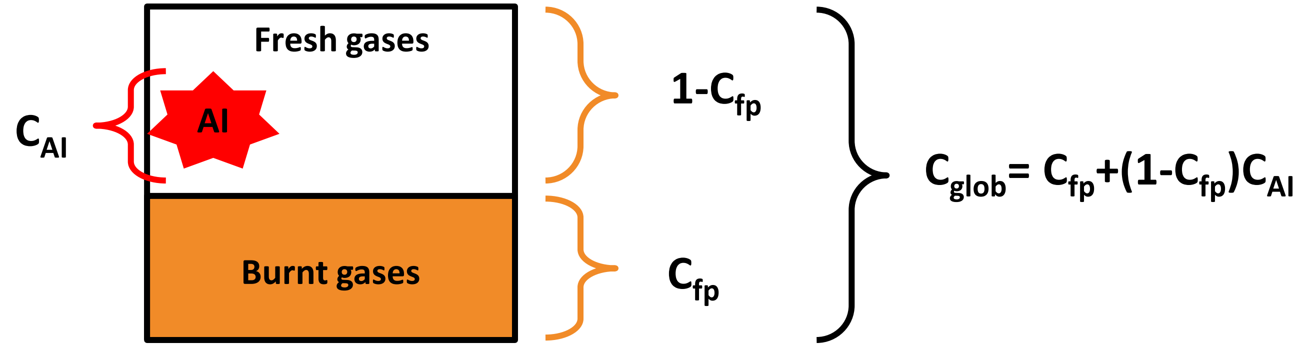
Reaction rate of the progress variable ← $\dot{\omega}_{AI}$

T,P: Thermodynamic conditions

$\phi, \%_{EGR}$: Mixture

cAI: Progress variable

- **Interaction with ECFM**
  - Performed thanks to progress variable
  - This formalism allows **a <u>complete decoupling between these phenomena</u>**



LARGE EDDY SIMULATION FOR ICE

SUSTAINABLE MOBILITY

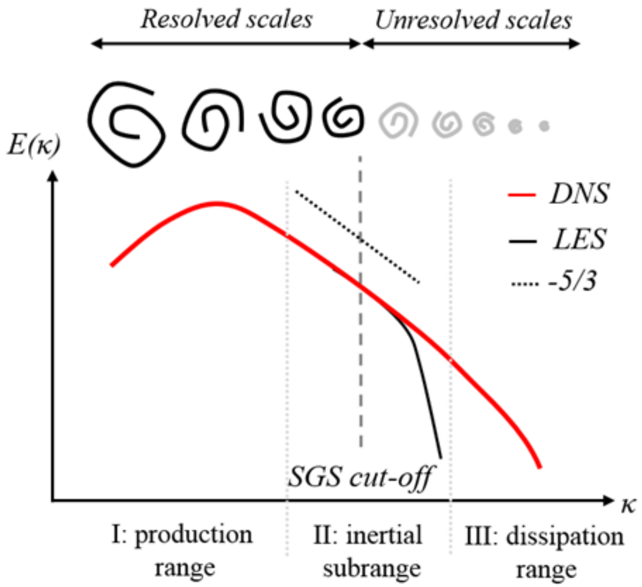
- High efficiency engine design and new combustion processes will need to integrate in the design loop Large Eddy Simulation calculations (problem of mixing jet, high dilution…)

- IFPEN will add to CONVERGE all his knowledge and feedback it has developed for last 20 years on LES simulation.

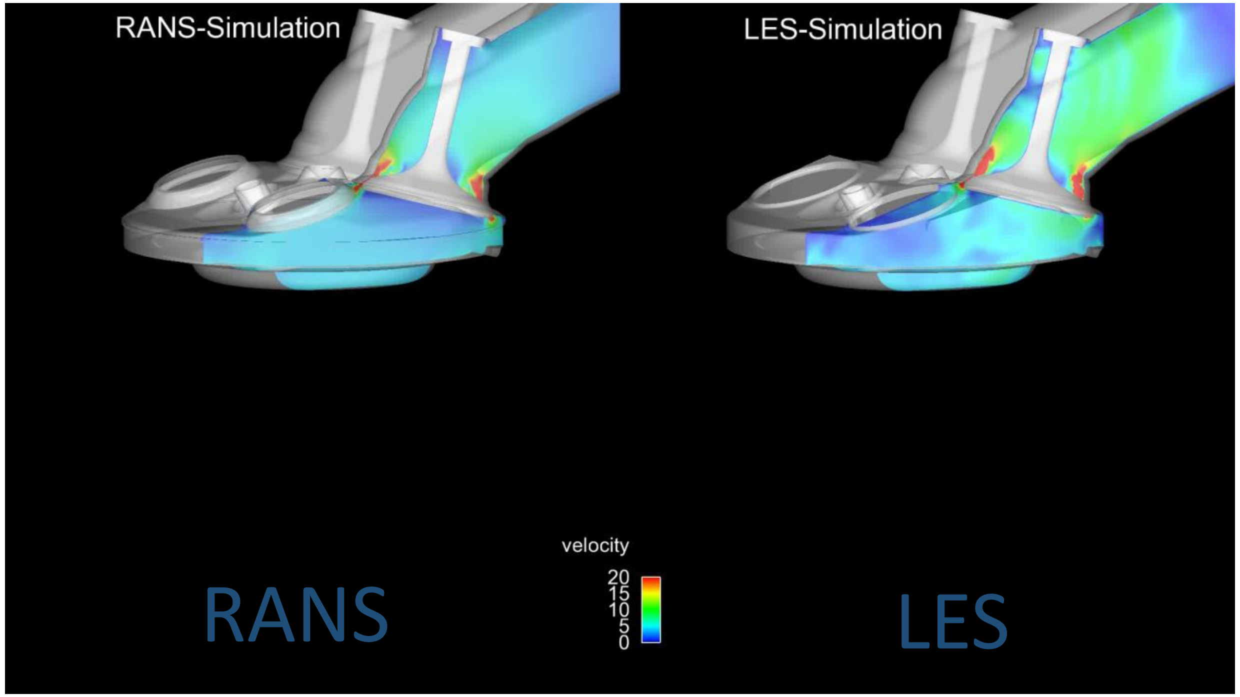
- Thanks to high parallel efficiency of CONVERGE 3.0, the LES will become a new feature available for ICE design.

- IFPEN models have been adapted to LES :

ECFM-LES for combustion and ISSIM-LES for spark ignition.



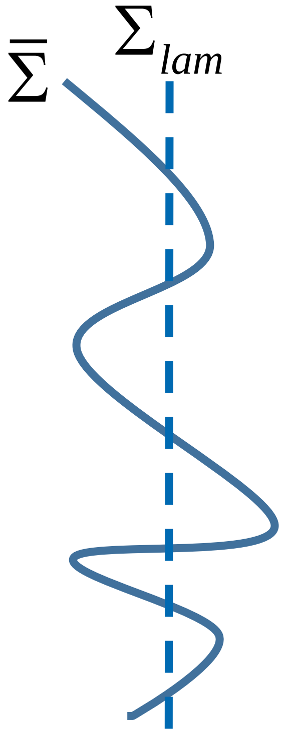
RANS & LES IN SHORT



- **Predicts a statistical average cycle**
  - Few cycles for convergence
- **All flow scales are modelled**
  - Yields average flow & turbulence

- **Predicts a spatially filtered individual cycle**
  - Requires multiple cycles to yield statistics
- **Only unresolved flow scales are modelled**
  - Largest scales resolved &
    Small (subgrid-) scale turbulence modelled

DIFFERENCES BETWEEN ECFM FOR RANS AND ECFM-LES



LES formulation (Richard et al, PCI,2007): (available in CONVERGE 3.0)

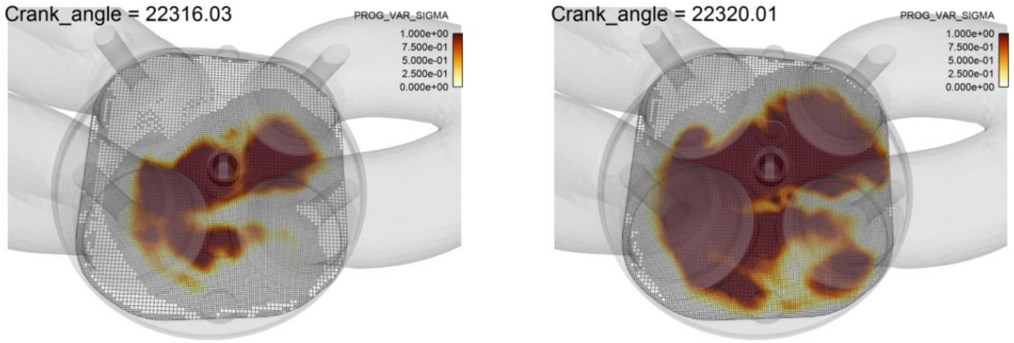
- Wrinkling is much lower than in RANS calculation
- Laminar propagation cannot be neglected like in RANS

Done through addition of resolved Flame Surface Density source terms

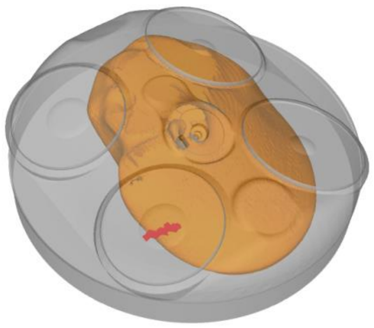
$$\frac{\partial\bar{\Sigma}}{\partial t}+\nabla.\left(\tilde{u}\bar{\Sigma}+S_d N\bar{\Sigma}\right)=\nabla.\left(\mu_t\nabla\bar{\Sigma}\right)+a_T\bar{\Sigma}+\left[\frac{2(1+\tau)}{3\bar{c}}-\frac{1}{1-\bar{c}}\right]S_l\bar{\Sigma}(\bar{\Sigma}-\Sigma_{lam})+S_d(\nabla.N)\bar{\Sigma}+A_T\bar{\Sigma}+S_{\Sigma}^{issim}$$

P_{res} | T_{sgs} | S_{sgs} | C_{sgs} | C_{res} | S_{res} | **Initial ISSIM FSD source term**

Resolved part in LES



ECFM / ISSIM LES simulation



ECFM – ISSIM RANS Simulation

DIFFERENCES BETWEEN ISSIM FOR RANS AND ISSIM-LES

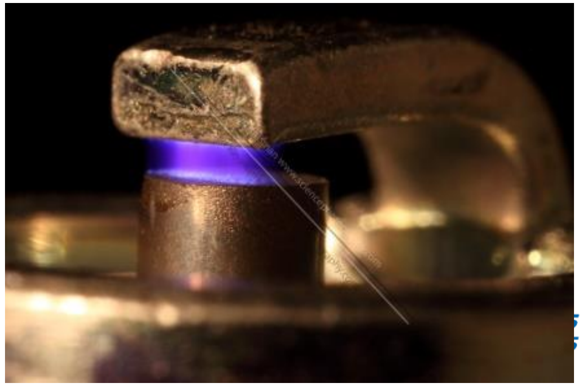
- Same electrical circuit model and initial flame kernel deposition than in RANS.
- But in LES:
  - Initial flame front not fully resolved (i.e. ctilde_max <1)
  - Growth rate of FSD not correctly predicted by resolved FSD source terms (P_{res}, C_{res} , S_{res})
  - Replaced by model source term during ignition

$$S_{ign} = \frac{2}{r_b}(1+\tau)S_l\overline{\Sigma}$$

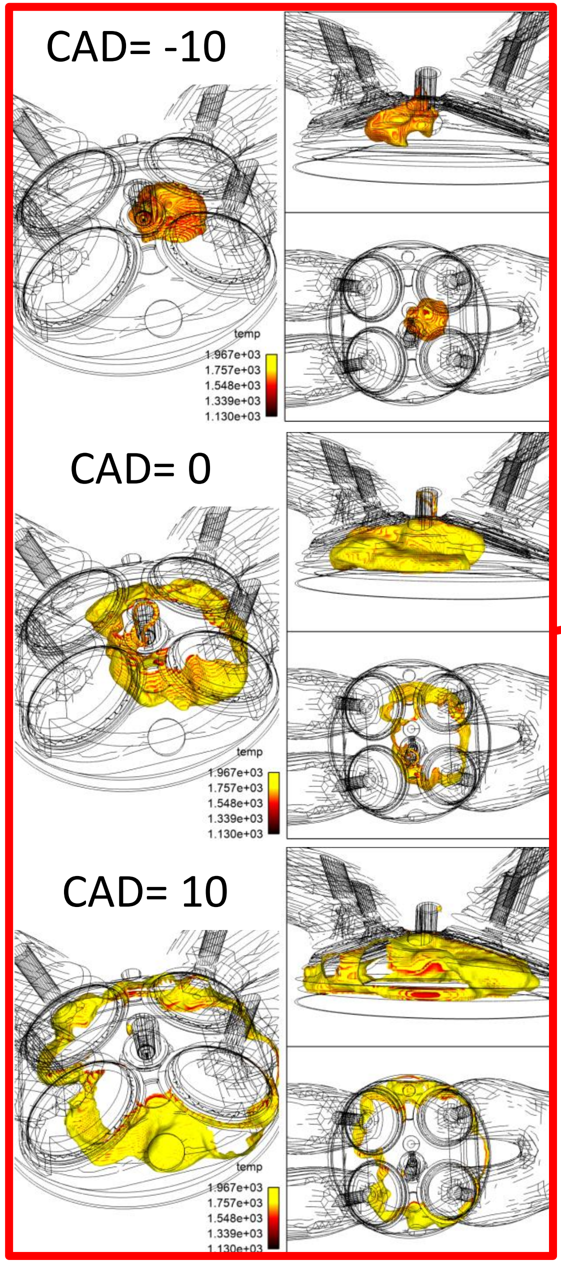
ISSIM stretch term

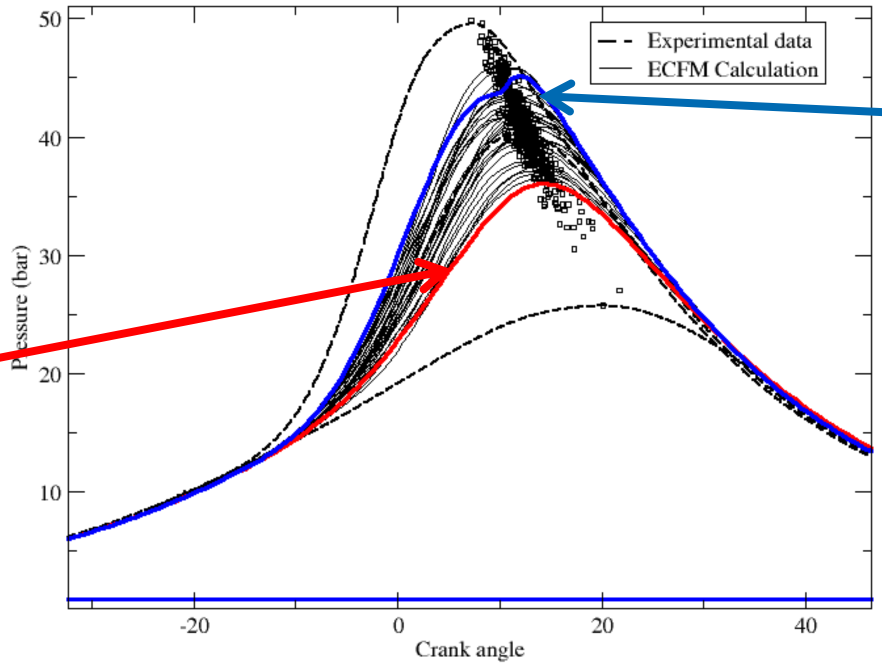
$$\frac{\partial\overline{\Sigma}}{\partial t} + \nabla.\left(\tilde{u}\overline{\Sigma} + (1-\alpha)P_{res}\right) = T_{sgs} + S_{sgs} + C_{sgs} + (1-\alpha)\left(C_{res} + S_{res}\right) + \alpha S_{ign} + S_{\Sigma}^{issim}$$

Transition factor:
- α=1 during ignition
- α=0 after transition

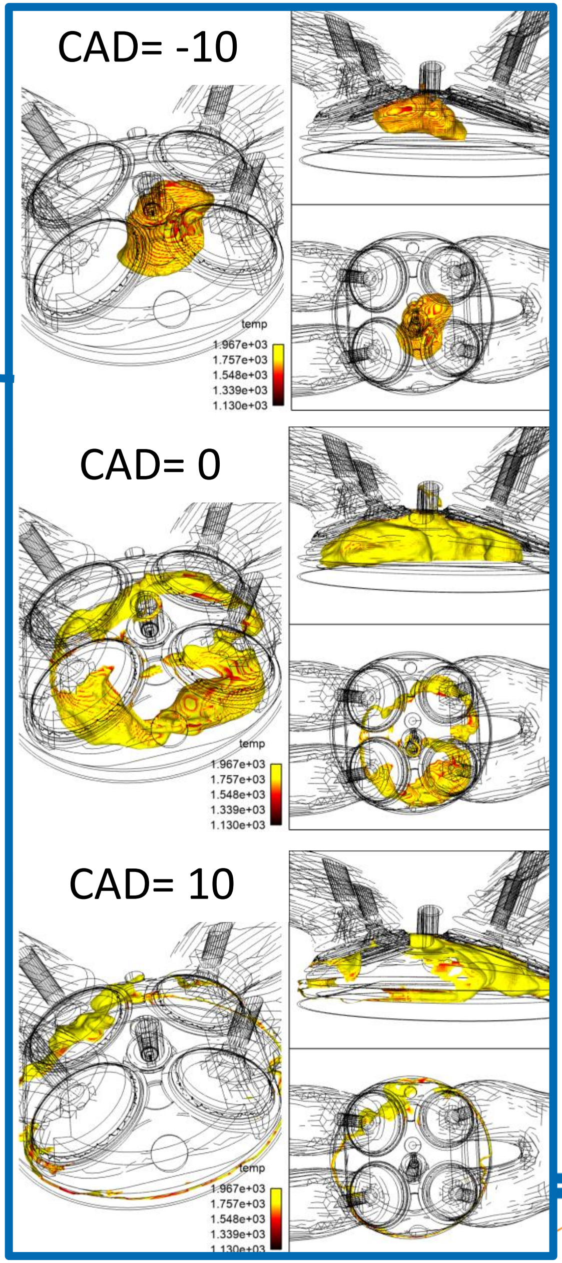


Slow cycle





Fast cycle



- The aerodynamic field at the spark plug is mainly responsible for the combustion velocity of each cycle

HIGH EFFICIENCY ENGINE DESIGN USING CONVERGE AND IFPEN PORTFOLIO

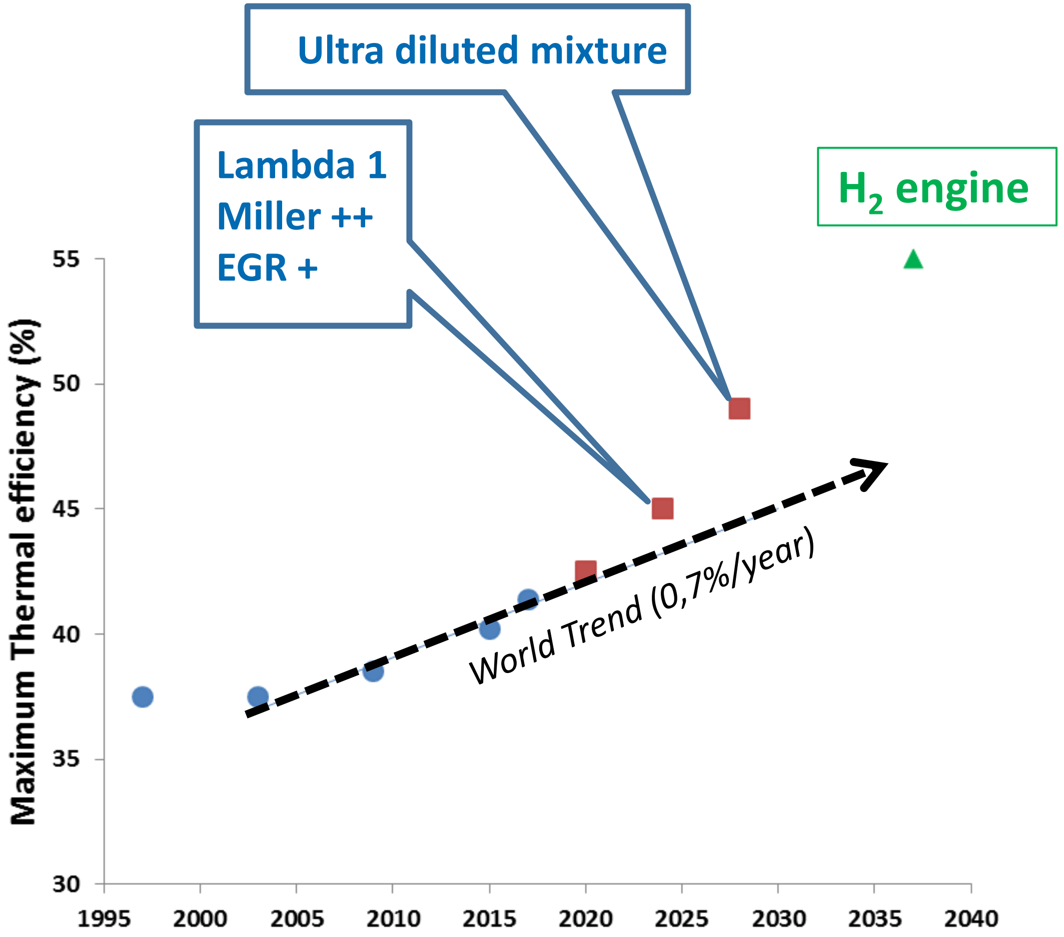
- High contribution of ground transportation to greenhouse gas and pollutant emissions

  …Global warming and health issues…
  …More and more stringent regulations in Europe
  …Electrification of the vehicles…

- The internal combustion engine should gain in efficiency to remain one of the solutions for the powertrain for future mobility

HIGH EFFICIENCY ENGINE DESIGN USING CONVERGE AND IFPEN PORTFOLIO

SI ENGINE ROADMAP TOWARDS 2025+



Lambda 1, Miller ++, EGR+

- IFPEN Swumble™ engine
- Stroke to Bore increase – upsizing
- **Passive prechamber ignition system**

Ultra diluted mixture

- Lean burn Eagle concept and further development
- **SACI IFPEN Combustion System**
- Stoichiometric ultra EGR diluted concept

H_2 engine as an alternative to fuel cell

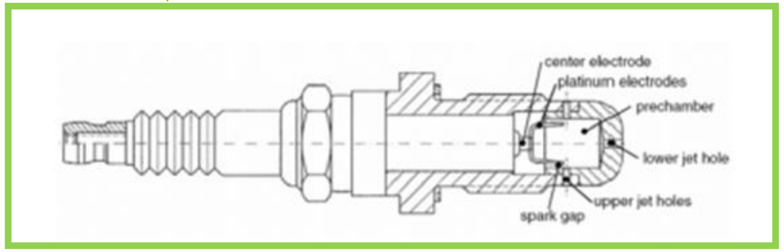
(*) International Summit on Internal Combustion Engines and Fuels
TOYOTA MOTOR CORPORATION, Koichi NAKATA, 21 August, 2018

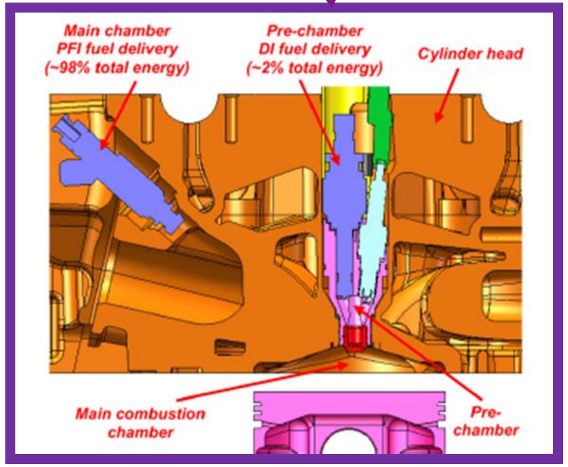
HIGH EFFICIENCY ENGINE – PRECHAMBER IGNITION SYSTEM

Two different compromises of system cost / packaging / global efficiency

Active prechamber: fueled using a dedicated (at least fuel) injection device

Passive prechamber: un-fueled/no internal injection device





Study focussed on Passive Pre-chamber

- Easy to implement: can replace directly a conventional spark plug
- Should be improved and adapted to the combustion system to be considered
- Sensitive to several parameters and dedicated strategies have to be implemented

➡ **Need for a comprehensive understanding of the physics involved**

HIGH EFFICIENCY ENGINE DESIGN – PRECHAMBER DESIGN

OPTICAL ENGINE

	IFPEN Optical Engine
Type	Single cylinder, 4 valves
Displacement	400cc
Flow motion	Tumble 1.5
Fuel	Gasoline E10
Injection	Port fuel

Low load/low RPM

Net IMEP (bar)	6.0
Engine speed (rpm)	1200
F/A ratio (-)	0.9
Qair (kg/h)	10.2

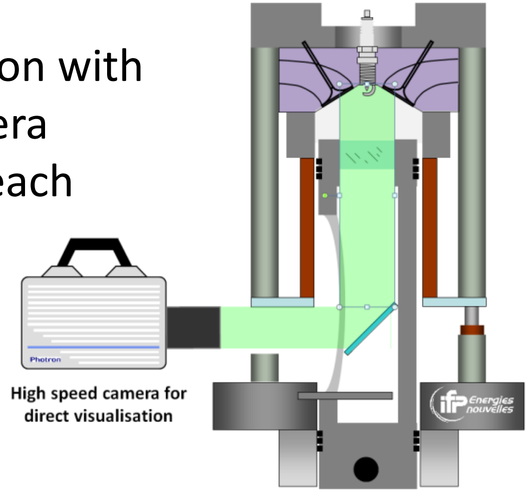
3 pre-chamber configurations

	Holes	Diameter
6-hole PC	6 identical	Ref
8-hole PCa	4 larger	Ref
	4 smaller	Ref/2
8-hole PCb	4 larger	Ref
	4 smaller	Ref/3

+ conventional spark plug

Optical diagnostics

- Direct visualization through piston with high speed high sensitivity camera
- During 20 cycles (statistics) for each configuration.

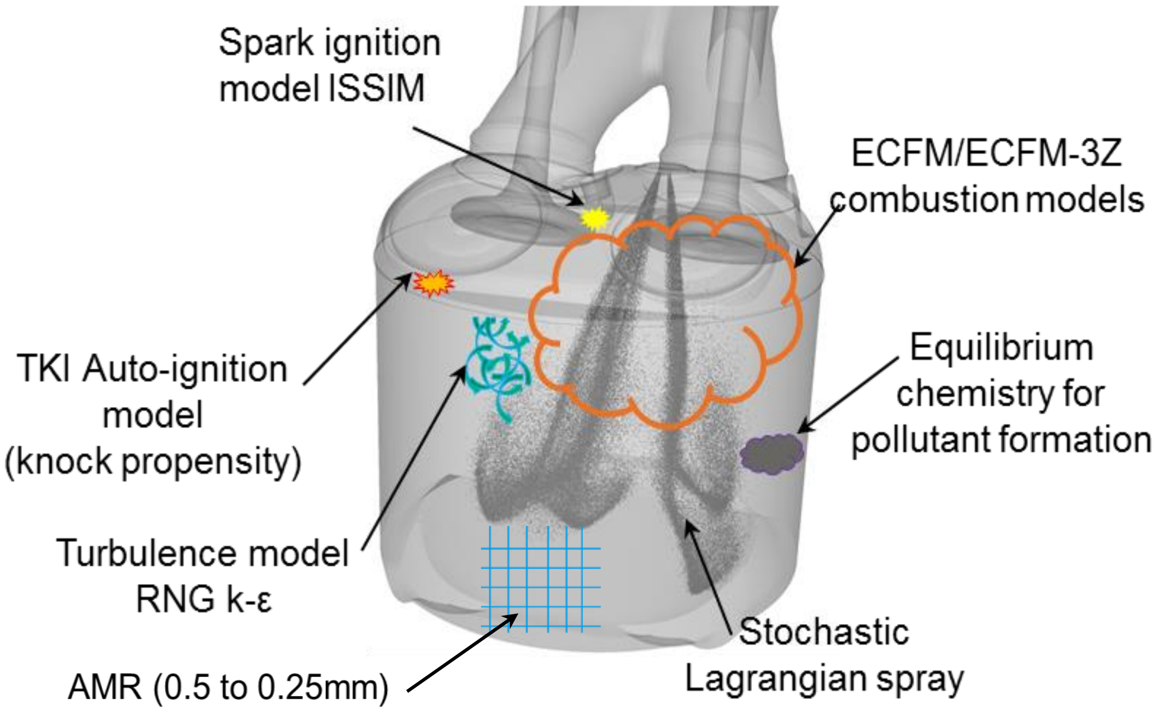


Objectives

- **Identification of the phenomena and main parameters.**
- **Provide measurements for CFD validation**

HIGH EFFICIENCY ENGINE – PRECHAMBER IGNITION SYSTEM

3D CFD RANS COMPUTATIONS

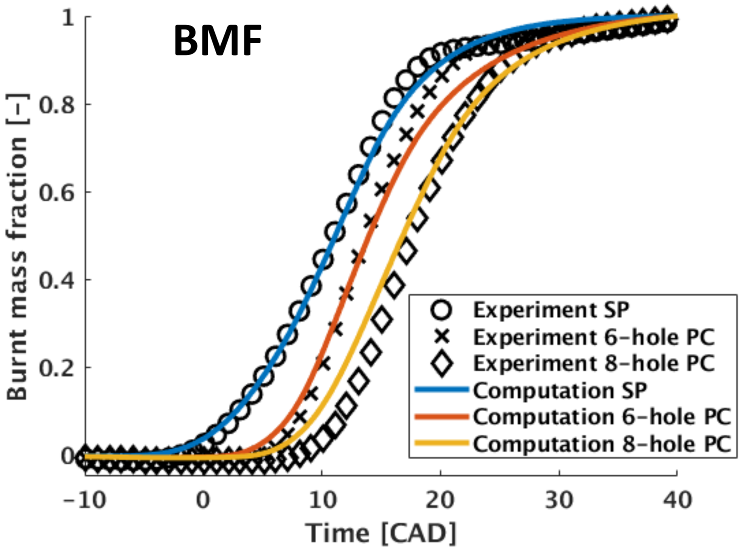


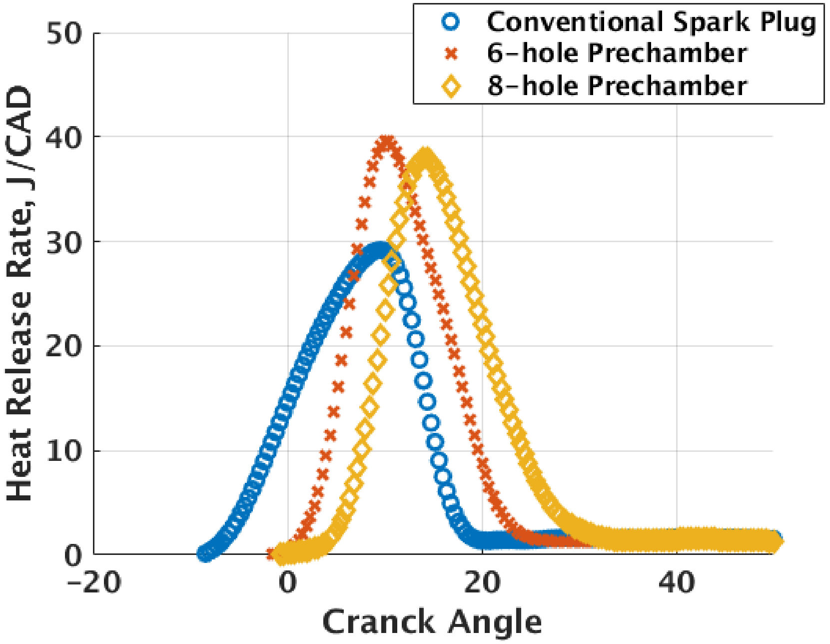
- Boundary Conditions from experiments
- PFI ➔ Fully premixed mixture (Experimental Lambda)
- At least 8 cells in the pre-chamber hole diameter
- Two complete cycles (Analysis of 2nd cycle only)

HIGH EFFICIENCY ENGINE – PRECHAMBER IGNITION SYSTEM

- <u>Comparison of **3 different ignition setups**</u>:
  - O Conventional spark plug
  - X 6 hole Pre-chamber
  - ◊ 8 hole Pre-chamber (PCa)

- Passive pre-chamber → ↗ HRR and combustion speed (max HRR)
- Conv. SP needs larger spark advance (10CAd) for same CA50

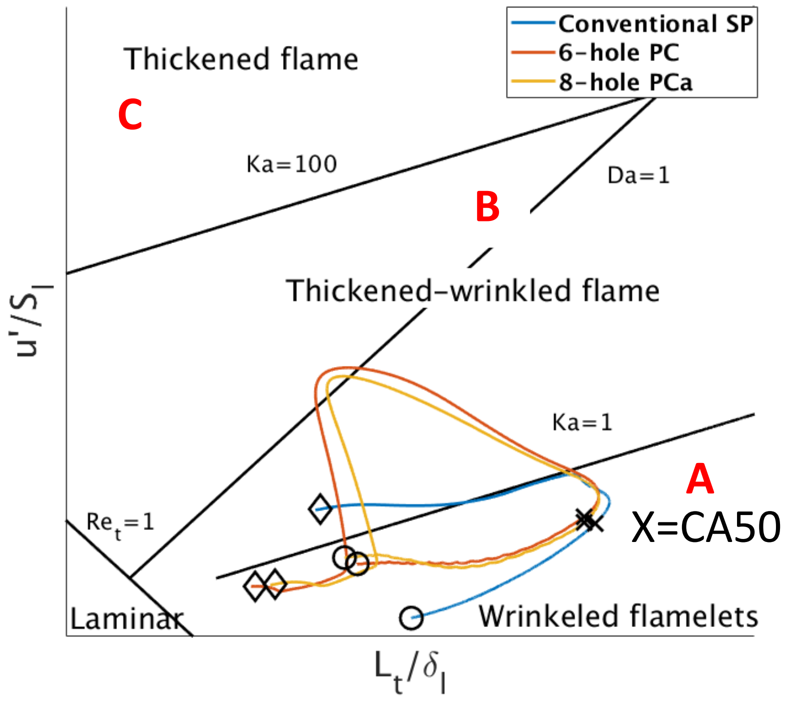




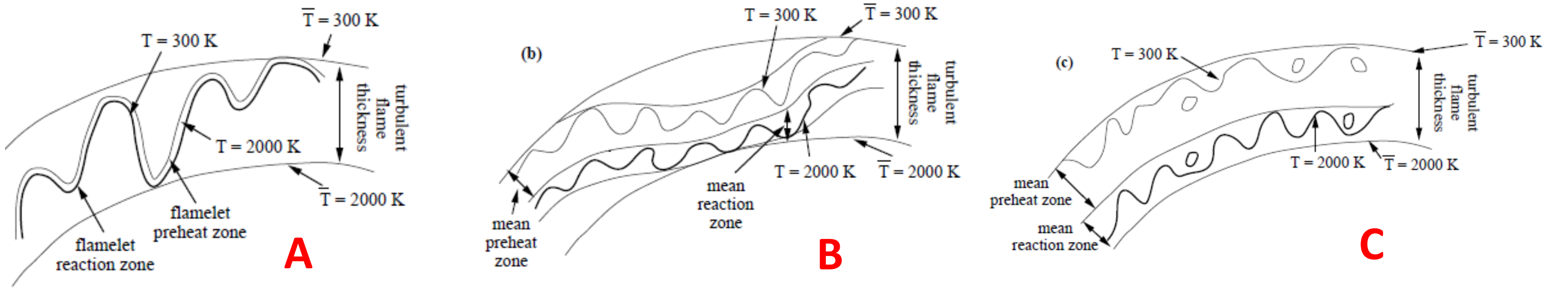
Good agreement between computations and experiments

Note: Different model calibration from Spark Plug to Pre Chambe configuration due to evolution of combustion regime … Borghi Diagram

COMBUSTION PROCESS – ANALYSIS AND DESCRIPTION



Borghi diagram: visualization of the interactions between turbulence and combustion



Wrinkled flamelets | Thickened-wrinkled flame | Thickened flame

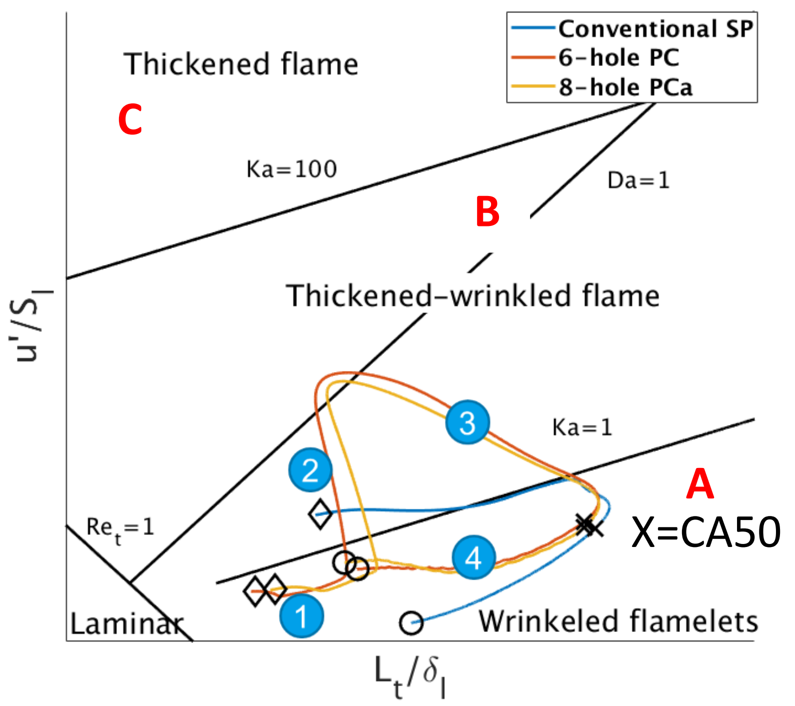
↗ interactions of turbulence on flame

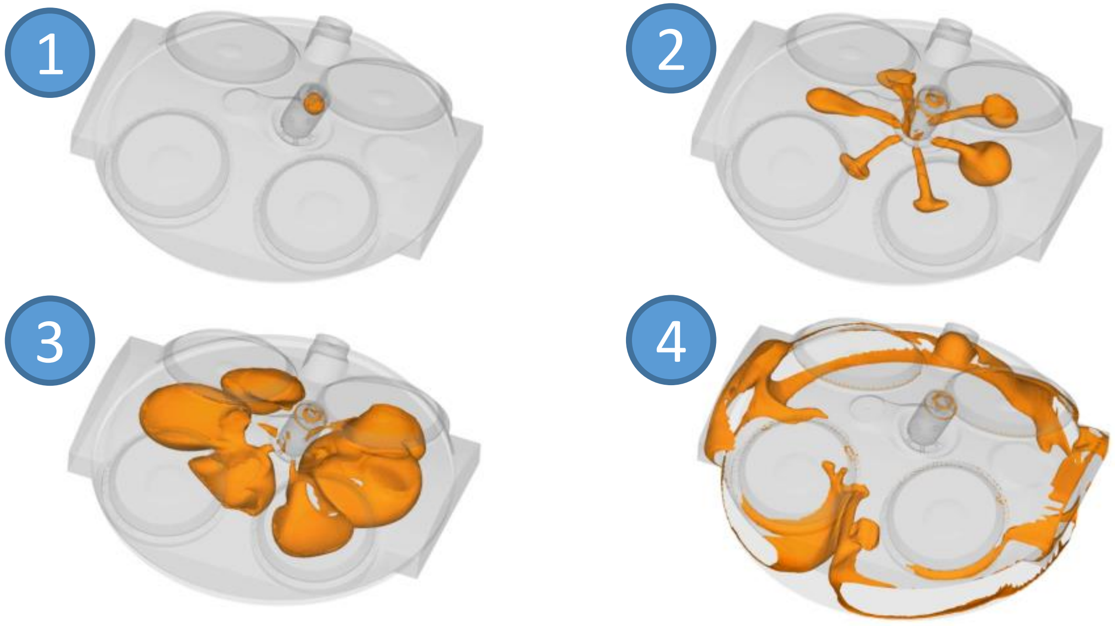
Monitoring (computations) of the conditions encountered by the flame during the combustion from ST (◊) to CA90 (O)

Different evolutions:

- SP: no evolution of u’ before CA50 (L_t increases due to flame propagation)
- PC: strong increase of u’ before CA50 due to high turbulence level

COMBUSTION PROCESS – ANALYSIS AND DESCRIPTION

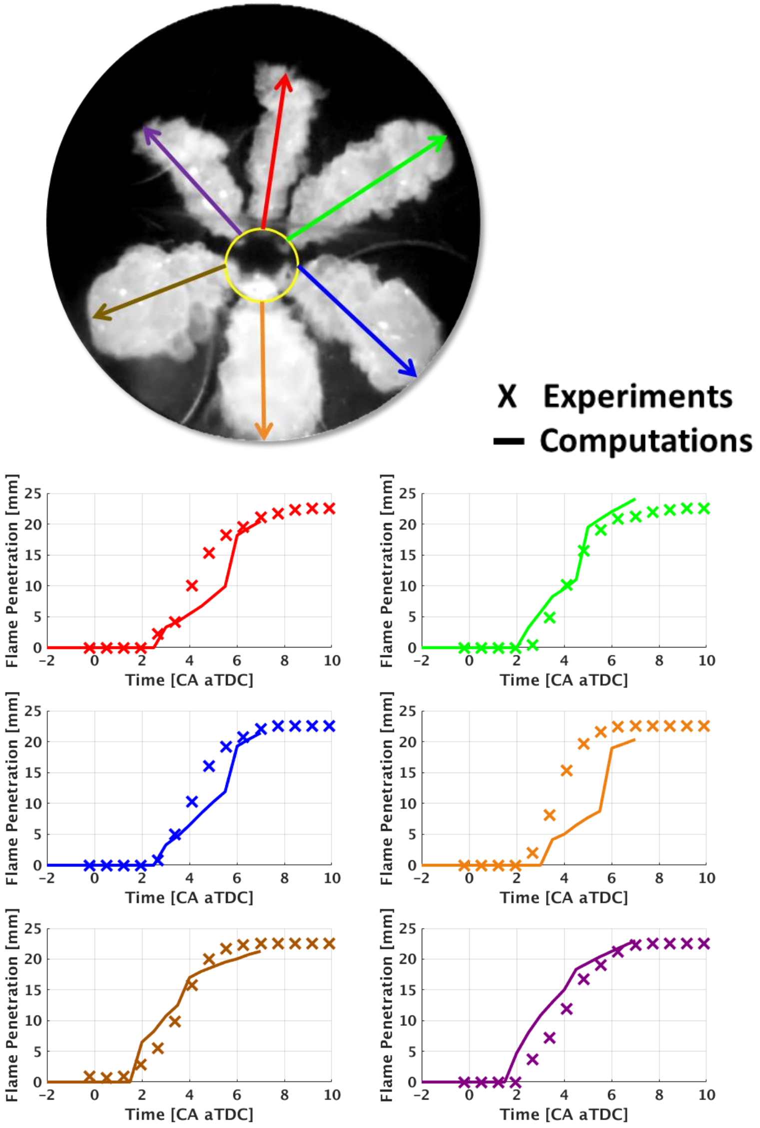




4 different stages can be identified (PC case):

1. Flame propagation (low turbulence) in the PC
2. Jet Flame ejection (strong increase of turbulence), switch the flame regime from **A** to **B**
3. Flame propagation (high turbulence)
4. End of combustion

COMBUSTION PROCESS – JET FLAME DYNAMICS



Jet flame dynamics on 6-hole PC

6 jet flames spreading from the six holes can be observed

Jet flame penetration evolution is monitored

- Experiments: average light threshold
- Calculations: Progress variable threshold 0.3

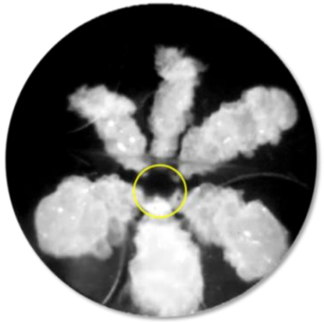
Good representation of jet flame dynamics by the computations:

- Exit timing of jet flame from the nozzle can slightly differ from computations to experiments (different quantity for tracking the flame)
- Same slop of penetration evolution
  ➔ good estimation of the jet flame ejection velocity (36m/s)
- Same penetration/spreading of jet flames can be observed

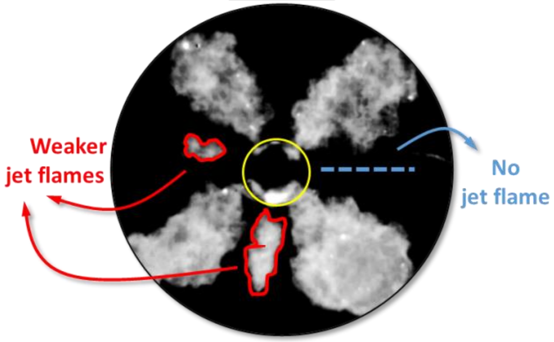
INFLUENCE OF HOLE DIAMETER

3 pre-chamber configurations

	Holes	Diameter
6-hole PC	6 identical	Ref
8-hole PCa	4 larger	Ref
	4 smaller	Ref/2
8-hole PCb	4 larger	Ref
	4 smaller	Ref/3



6-hole PC: Stable cycle to cycle behavior of 6 hole PC (Ref)
➔ 6 consistent jet flames with similar dynamics (see previous slide)

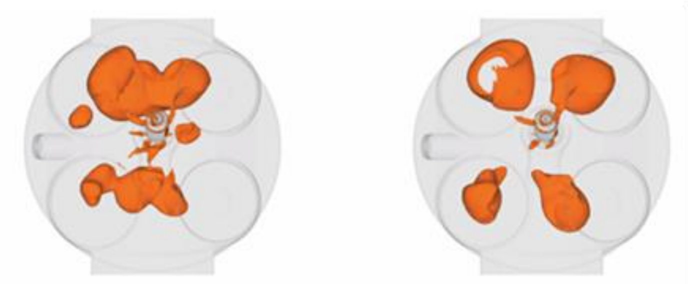


8-hole PCa: Stable behavior of jet flames from large holes but scattered behavior for the small holes (Ref/2):

- Regular size with similar dynamics
- Weaker expansion
- No jet flame

} Influence of hole diameter on jet flame behavior

8-hole PCa 8-hole PCb



8-hole PCb: stable behavior of jet flame from large holes but no jet flame observed from smaller holes (Ref/3) due to **quenching effect**.

➔ Threshold limit in PC hole diameter below which no jet flame is observed (Ref/2)

Same observations from both experiments and calculations

Test on SI engine- description

2 Passive pre-chambers were specifically designed based on 3D CFD calculations for an in-house high efficiency single cylinder SI engine (replacing conventional spark plug without any additional modification)

Design office ⟺ 3D CFD

IFPEN high efficiency engine

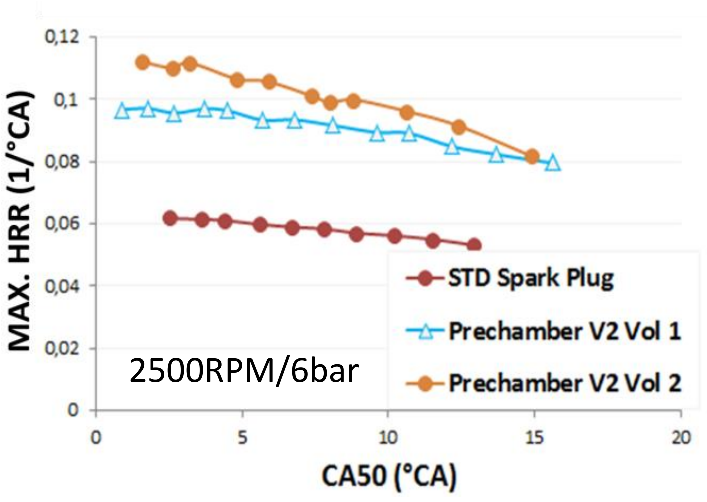
	IFPEN SI engine
Type	Single cylinder, 4 valves
Capacity	410cc
Bore x Stroke	75 x 93 mm
Compression Ratio	14:1
Intake Valve Opening	Miller 140 cad duration
Injection	Central GDI
Flow motion	High Tumble 2
Fuel	Gasoline E10

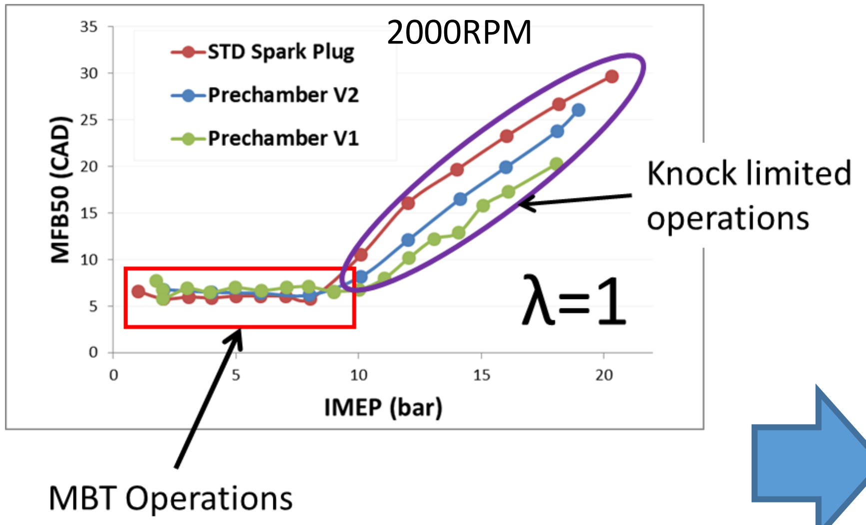
Adaption on knock limited operating condition (2000RPM/18bar), checking the ability at pushing back the knock limit and improving efficiency

- Adaption of PC hole characteristics (number, diameter…)
- Jet flame targeting
- Possibility to vary the PC volume

Tests on SI engine
At λ=1

High efficiency SI engine (high CR, Miller strategy…)



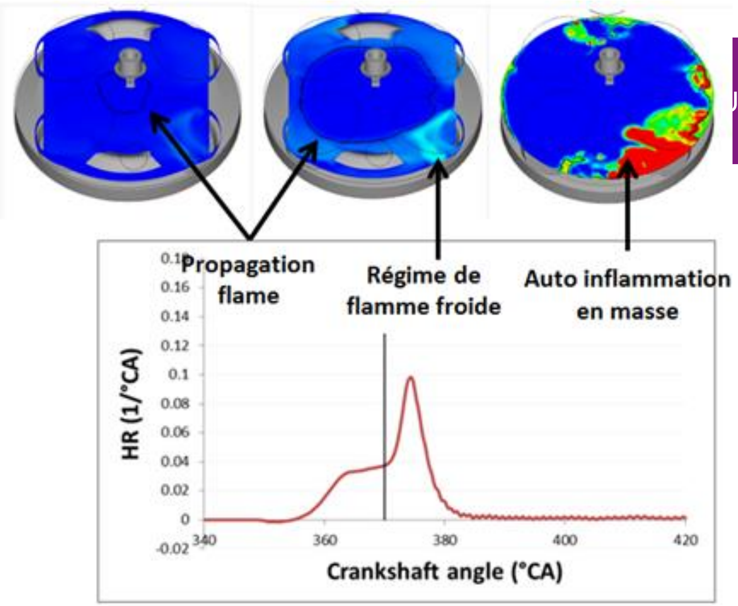


Operation at λ=1:

- Use of PC allows to increase the combustion speed
- Internal volume of PC has significant impact on combustion speed (in agreement with the literature)
- Allows to push back the knock limit and to improve the combustion phasing on the whole engine map (-7CAd @2000RPM) ➔ gains in efficiency
- @5500 RPM and λ=1: IMEP=23.5bar (107kWi/l)

Significant improvements thanks to passive pre-chamber during λ=1 operations

SACI COMBUSTION SYSTEM



- Principle of the **S**park **A**ssisted **C**ompression **I**gnition
  - Spark ignited propagation combustion
  - Controlled Auto Ignition of the end gas without destructive knock
- Expected benefits
  - Remedying the limitations of highly diluted conventional combustion
    - Unburnt HC Emissions, Cyclical dispersions, delayed combustion phasing
  - High fuel efficiency and very low NOx emissions thanks to high CR and highly diluted mixture

SACI demonstration on a Single cylinder engine

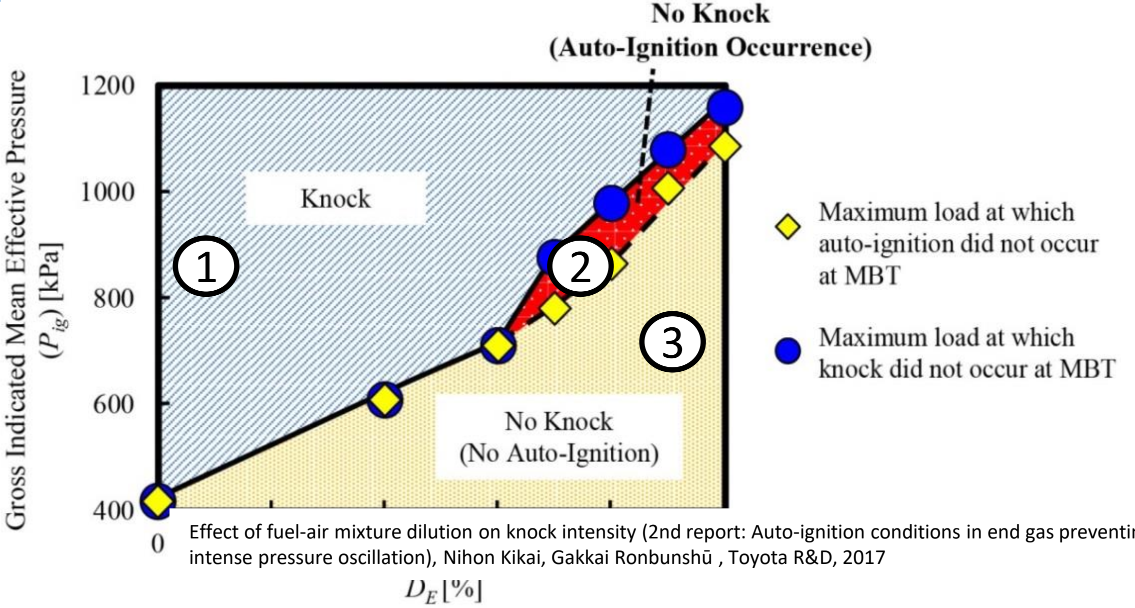
Combustion analysis supported by 3D calculation

IFPEN combustion system development

SACI COMBUSTION SYSTEM

SACI demonstration on a Single cylinder engine

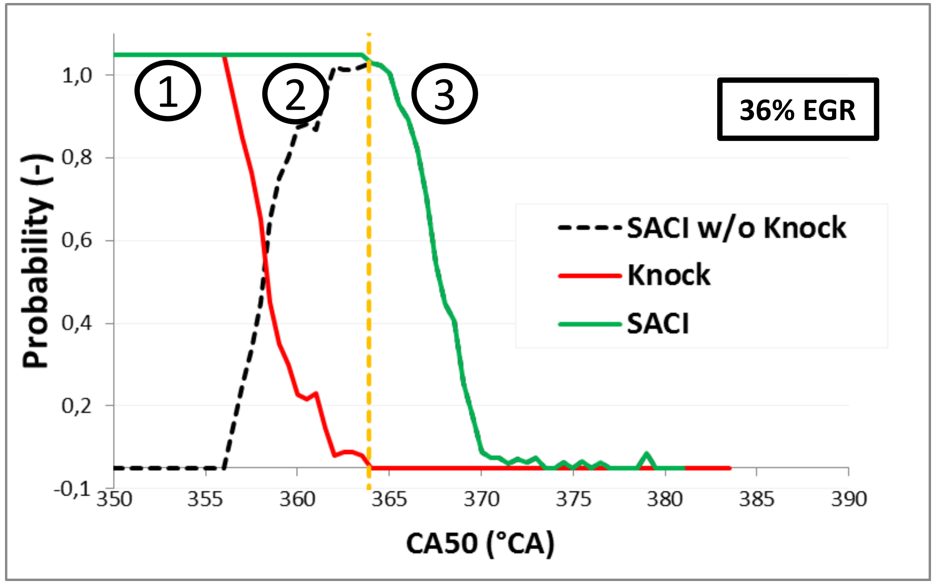
- What is expected for high CRs and mixture dilution
  - Spark timing variation leads to 3 types of combustion
    - Combustion with knock (1)
    - SACI combustion with propagation followed by AI (2)
    - Standard combustion that ends slowly (3)



Effect of fuel-air mixture dilution on knock intensity (2nd report: Auto-ignition conditions in end gas preventing intense pressure oscillation), Nihon Kikai, Gakkai Ronbunshū , Toyota R&D, 2017

Fig.8 Condition of Auto-ignition and Knock (Diluted by Inert Gas).

- What we get on our SCE (RVC 16)



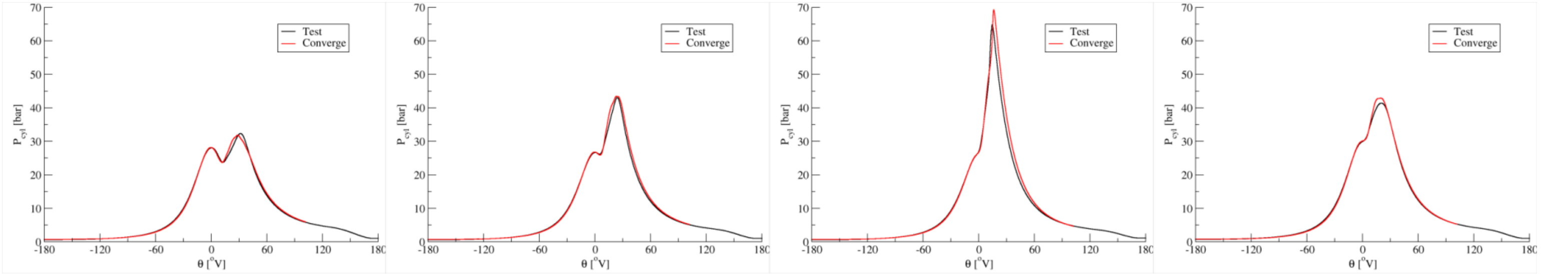
47% fuel efficiency already achieved at λ = 1,6
45% fuel efficiency already achieved at λ = 1 with EGR

1

SACI COMBUSTION SYSTEM

Combustion analysis supported by 3D calculation

- Proven ability to compute such combustion using Converge Software
- Capacity to highlight the phenomenon and processes explaining SACI Combustion
- Use to identify the most promising parameters to control SACI combustion and enhance efficiency

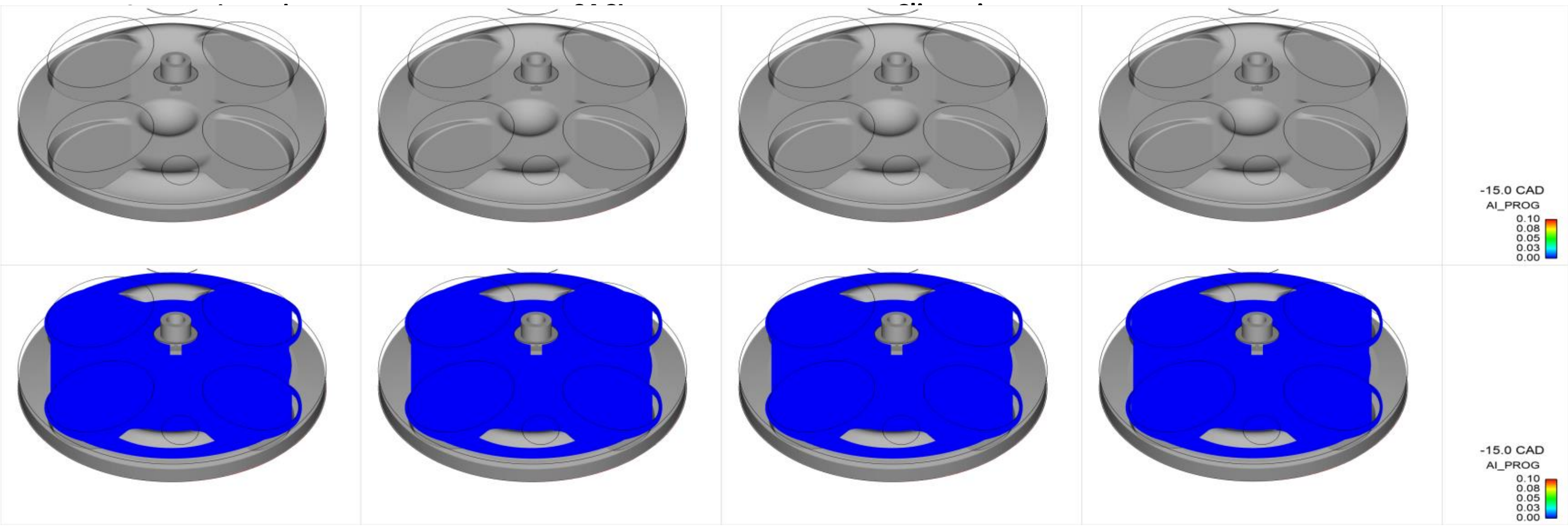


AVA = -6°V – EGR=0%

AVA = -1°V – EGR=0%

AVA = +4°V – EGR=0%

AVA = +4°V – EGR=15%



Thanks to ECFM-TKI model, autoignition and premixed flame reaction rate can be post-processed.

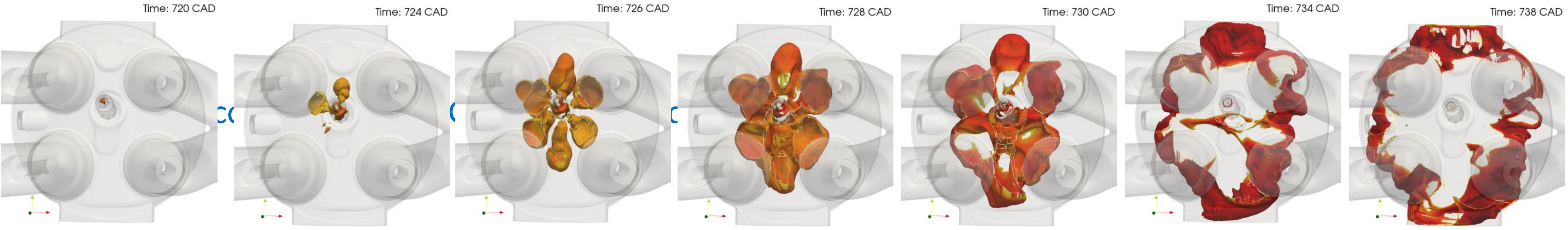
Auto-ignition progress variable

FUTURE OF ICE MODELING AT IFPEN

- Work in progress at IFPEN: Use of LES approach for pre-chamber ignition CCV understanding (ECFM LES, ISSIM-LES and TKI)
  - Push the use of LES as a design tool thanks to CONVERGE-3.0

- Thickned Flame Model for ICE simulation in development (Only LES purpose – no flamelet assumption).

- ECFM coupling with SAGE for detailed chemistry needed for pollutant emissions (RANS and LES) - Soot modeling for SI engine (pool fire…)



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TKI TABLE GENERATION WITH KICGEN AND USAGE

SUSTAINABLE MOBILITY

- Choice of a mechanism
  - Single component (ex: n-heptane)
  - multi-component with fixed composition (ex: 70% n-heptane + 30% iso-octane)
  - Exemples:

	Number of species	Number of reactions
Anderlohr et al. [4]	536	3000
Chalmers [17,18]	42	168
Zeuch et al. [11]	121	593

- Choice of the parameter range
  - Exemple:

	min	max	total number
FAER	0.1	3	9
Pressure (bar)	1	200	12
Temperature	500	1500	56
EGR(%)	0	80	4
Progress variable c	0	1	99

24192 kinetic calculations

Table generator tool
- Kinetic mechanism
- Range of parameters
- Generate input files for SAGE

SAGE 0D Run in parallel
- Full parallel 0-dimensional SAGE homogeneous calculations

Table generator tool
- Check calculations
- Progress variable post-processing
- Write TKI hdf5 table

TKI table ready

CONVERGE
- Reads TKI table at run start
- ECFM3Z interpolates in TKI table in each cell at each time-step

$$\dot{\omega}_c^{ai}(x,t) = \dot{\omega}_c^{TKI}(P,\tilde{T}_u,\bar{\Phi},X_{dil},c_{ai})(x,t)$$

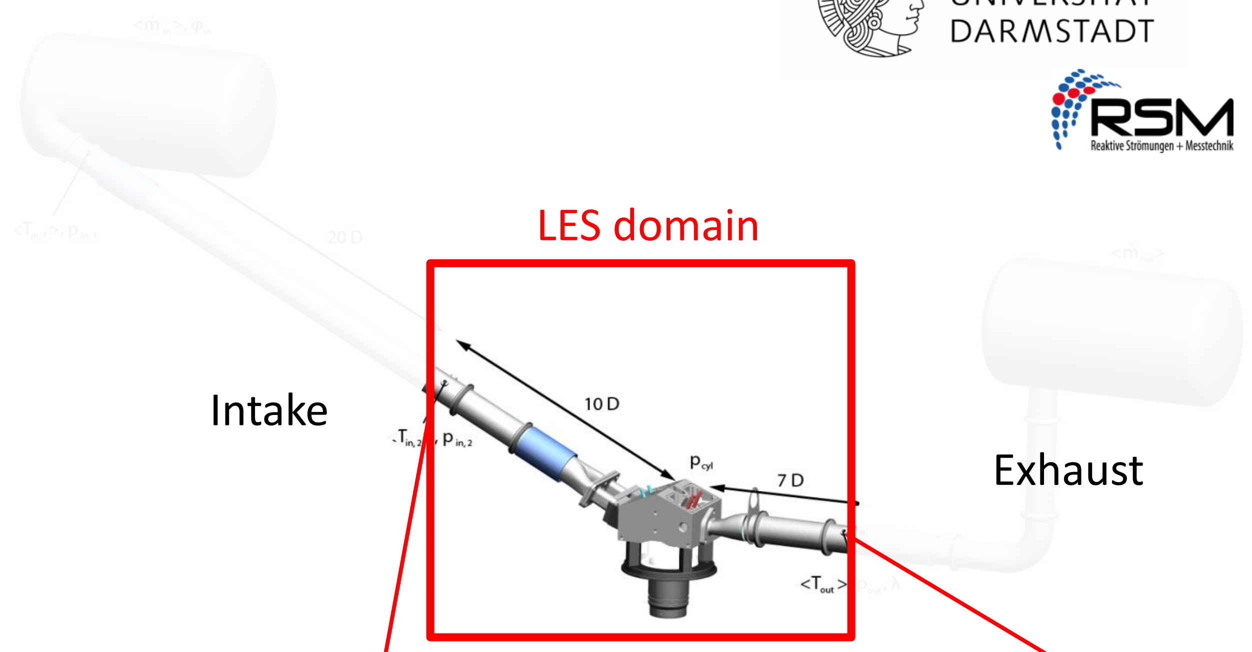
INSTITUT CARNOT IFPEN Transports Energie

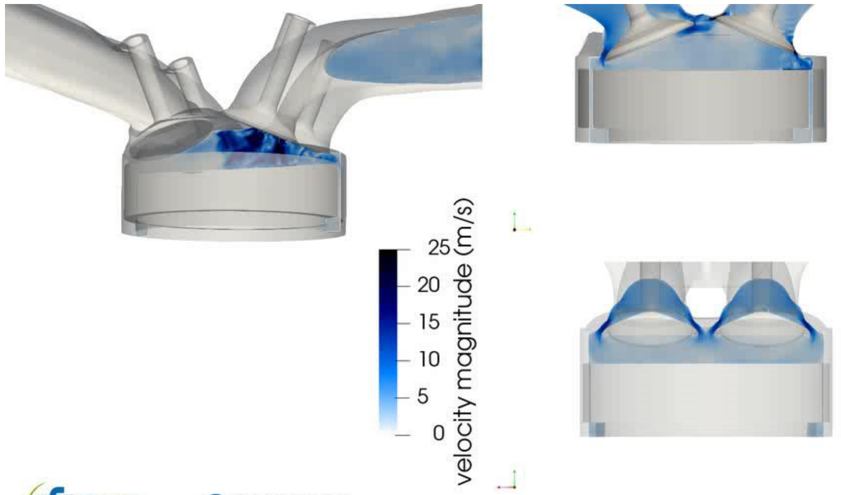
IFP Energies nouvelles

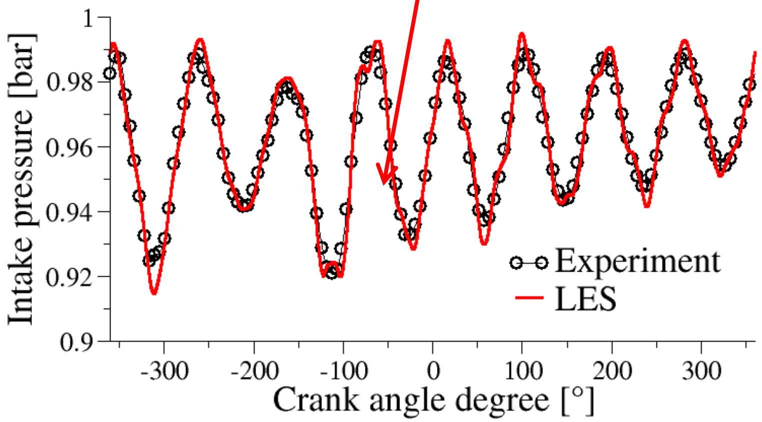
ENGINE CONFIGURATION[1] & OPERATING CONDITIONS

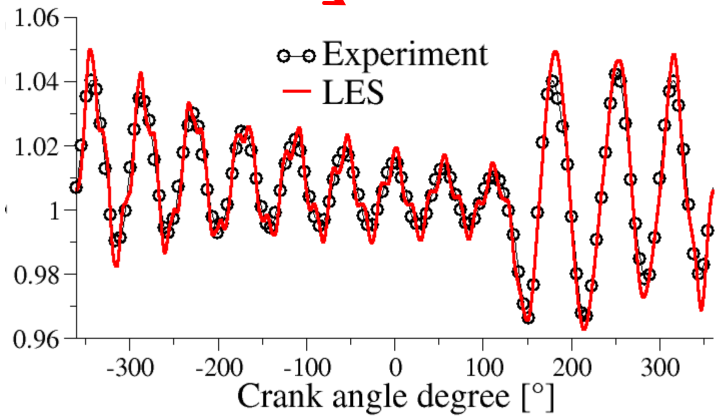
Operating conditions

RPM	800 ± 7 min^{-1}
Press. Intake	0.95 ± 0.002 bar
Intake temp. 1	22.9 ± 0.1 °C
Intake temp. 2	23.2 ± 0.1 °C
Mass air in	11.5 kg/h ± 2%
Mass air out	11.5 kg/h ± 2%
Exhaust temp.	43.7 ± 0.5 °C





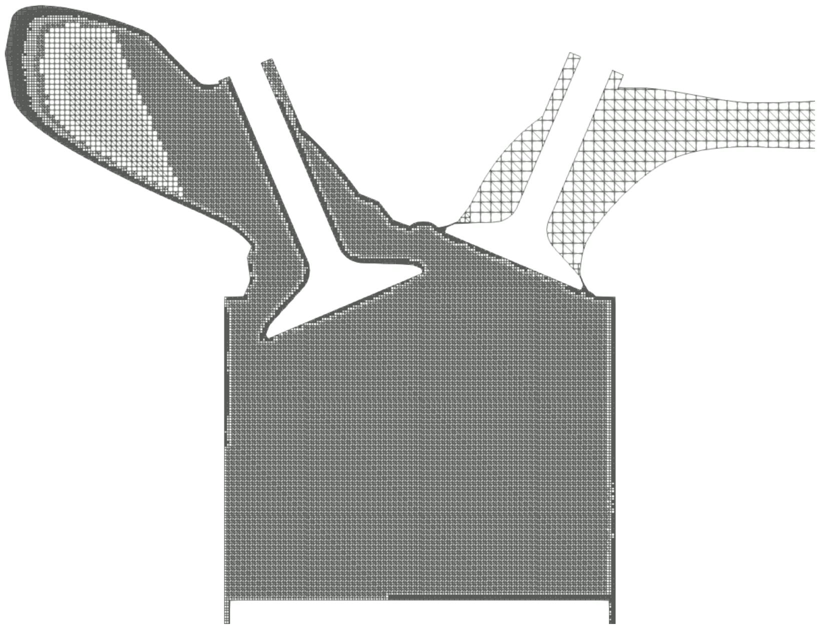


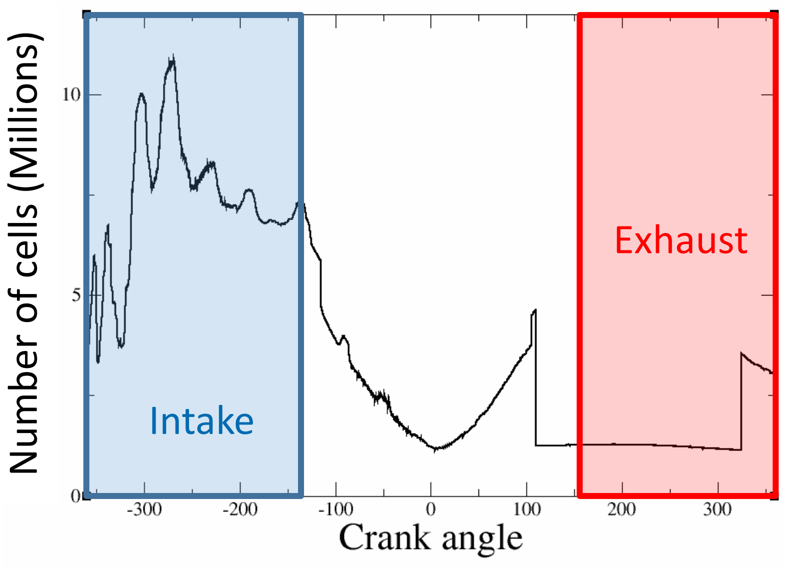


[1] Baum, E., Peterson, B., Böhm, B., & Dreizler, A. (2014). On the validation of LES applied to internal combustion engine flows: part 1: comprehensive experimental database. *Flow, turbulence and combustion*, *92*(1-2), 269-297.

NUMERICAL SET-UP

- Varying cell sizes are used for the different phases of the engine cycle
- Base_mesh = 2mm
- Embedding during Intake, compression and beginning of expansion
  - Regions (Chamber : 0.5mm and intake : 1mm)
- AMR during Intake and compression
  - 3 levels based on velocity
- Resulting mesh between 1.4 to 11.2 Millions cells
- Numerical scheme:
  - Second order spatial discretization for momentum and energy
  - First order implicit time integration
- Wall modeling : wall law of Werner & Wengle





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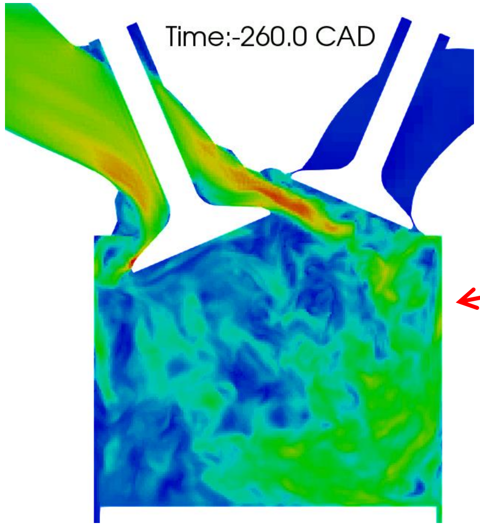
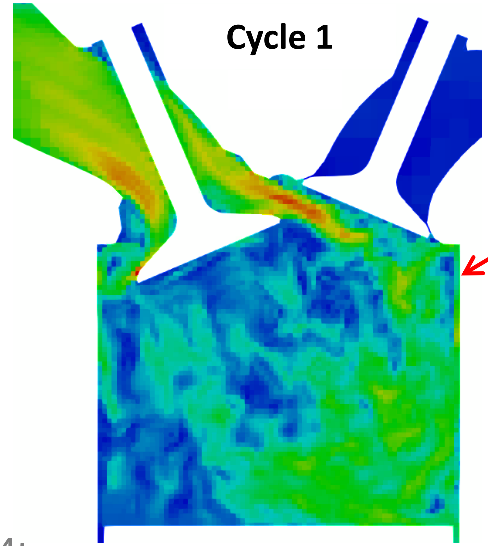
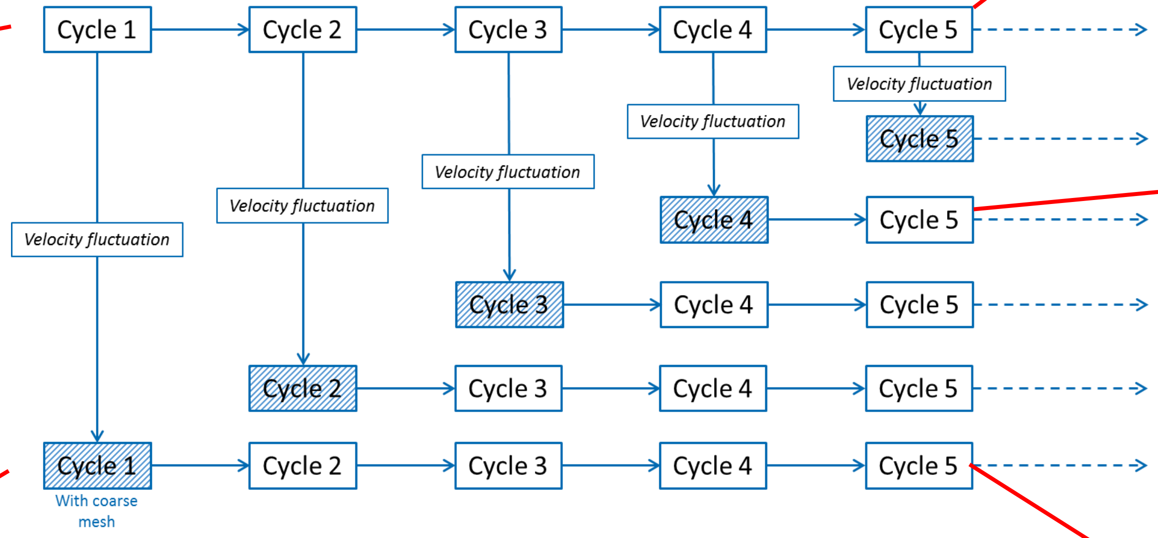
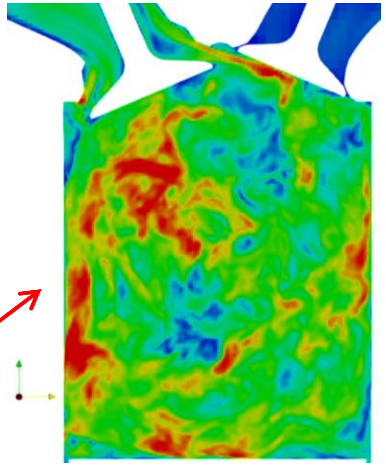
PARALLEL PERTURBATION METHOD

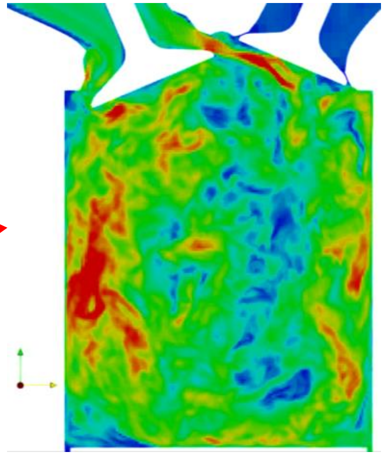
- Validation of this approach in our aerodynamic simulation

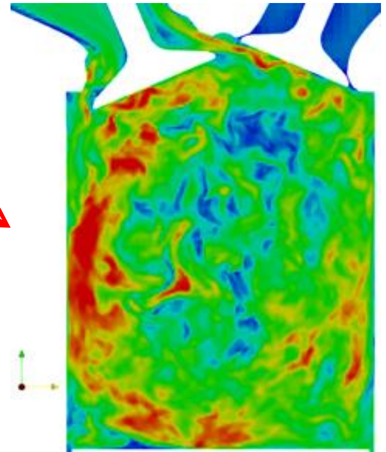


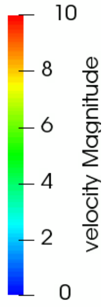












Three instantaneous cycles n°5 at TDC

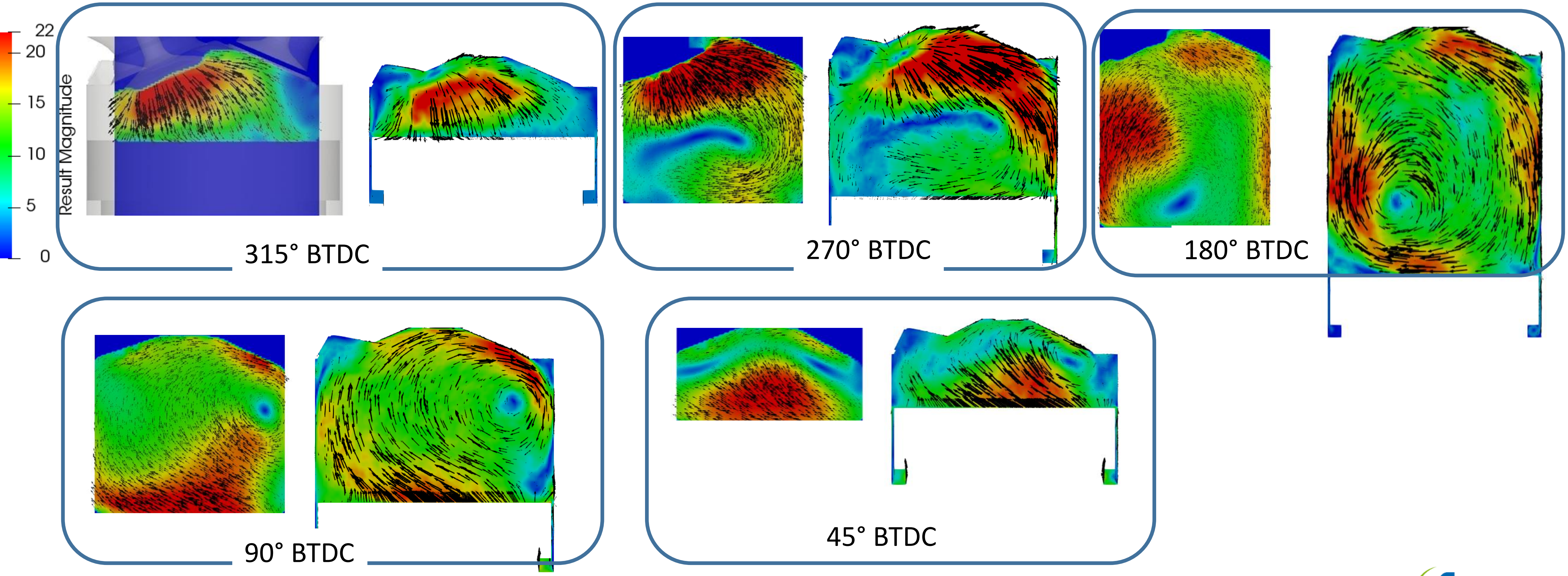
- The three cycles n°5 are uncorrelated individual cycles

COMPARISON OF AVERAGED VELOCITY FIELDS

- Velocity fields are compared on the central plane
- Instant : 315°- before TDC

Experimental average (600 cycles) – Left side

LES average (20 cycles) – Right side



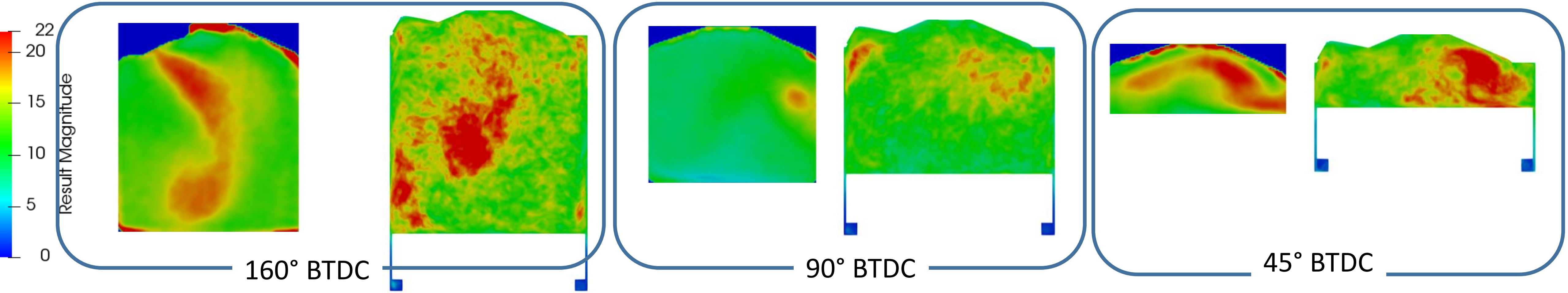
COMPARISON OF RMS VELOCITY FIELDS

- Velocity fields are compared on the central plane

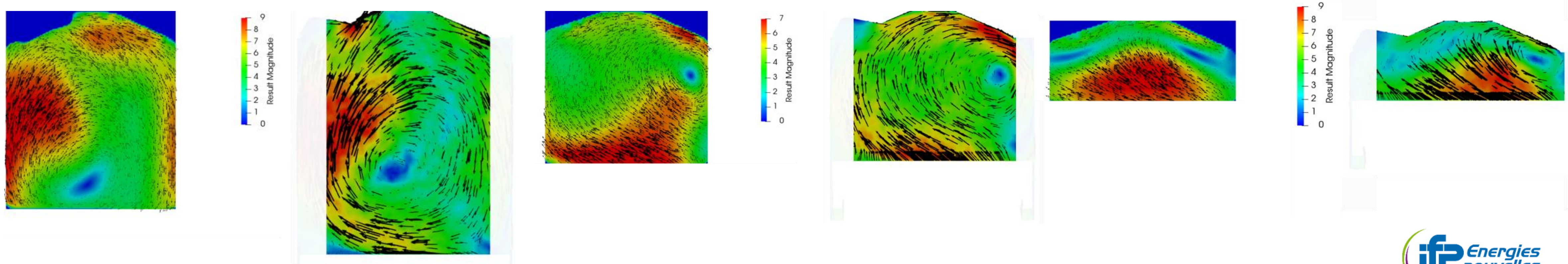
Experimental average (600 cycles) – Left side

LES average (20 cycles) – Right side

RMS

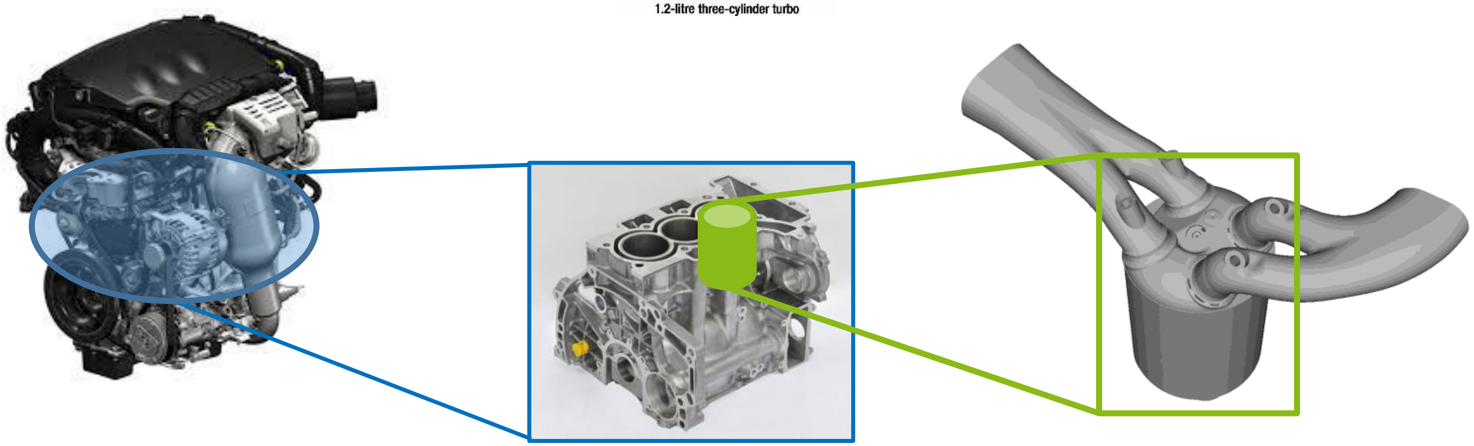


Average



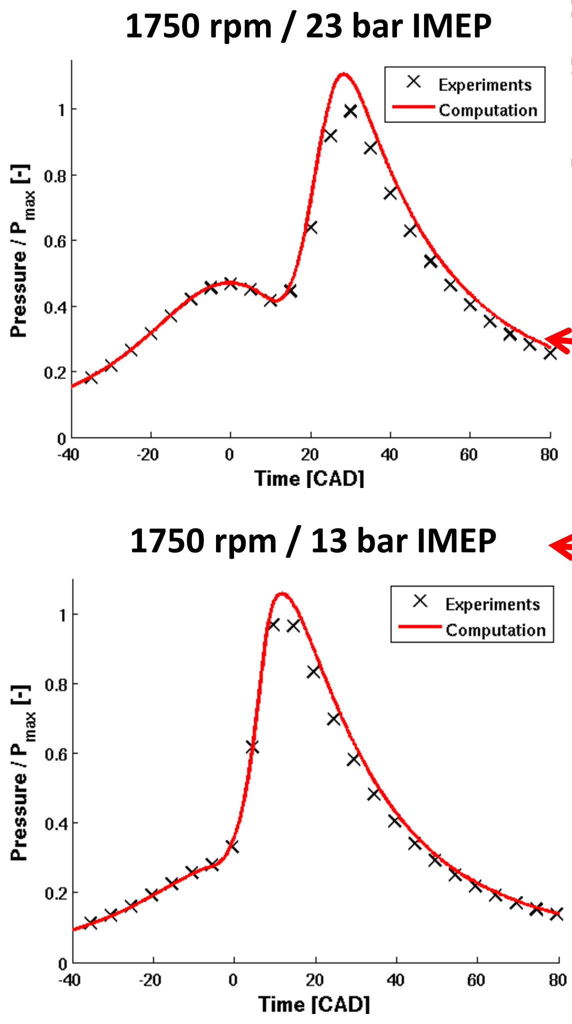
PSA GROUPE ENGINE : 1.2L PURE TECH EB2DT

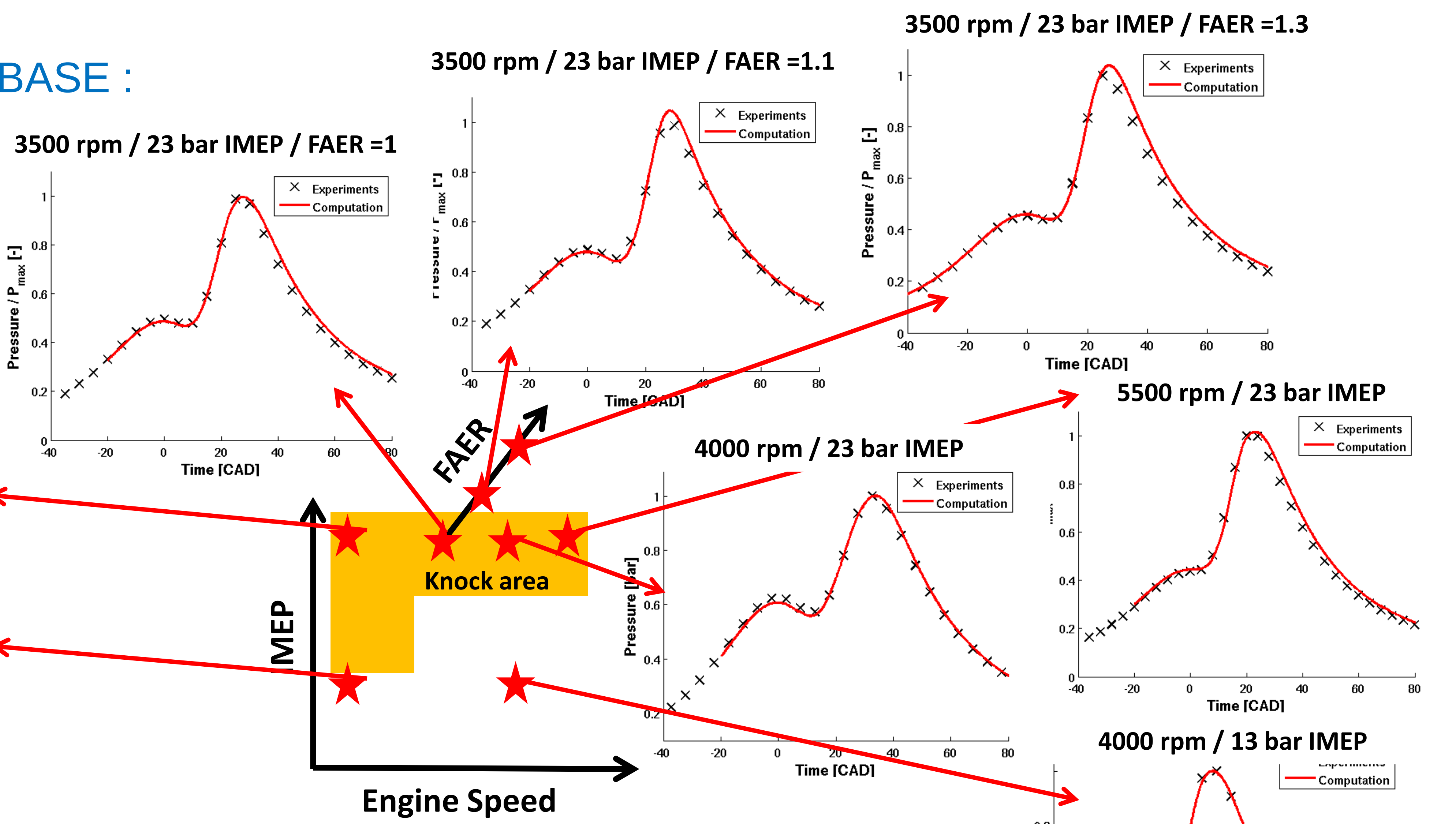
- A real industrial engine configuration
- All following results are normalized
- Only one of the three cylinders is simulated with CONVERGE

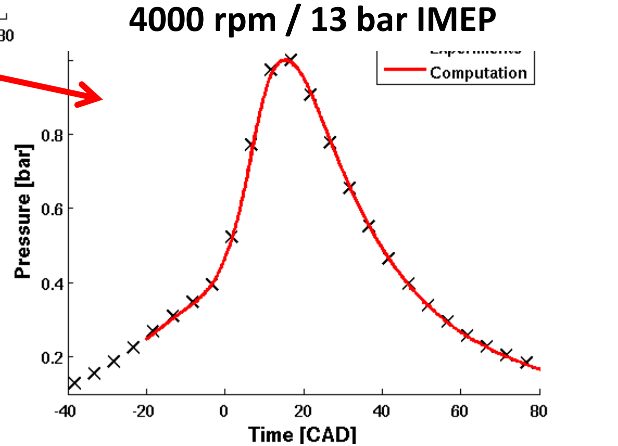


Engine capacity	400 cm^3
Compression rate	10,3
Fuel	SP95-E10
DATA base	
High load / RPM	5500rpm / 23 bar
Load variation @ 1750rpm	12 bar and 23 bar IMEP
FAER variation @ 3500rpm/23bar	ϕ_m=1 , ϕ_m=1.1 and ϕ_m=1.3
Load variation @ 4000rpm	13 and 23 bar IMEP

EB2DT DATA BASE :







- ➔ Good agreement with experimental data over the whole database
- ➔ Slight overestimation of energy released (pressure overestimation during the expansion stroke) maybe linked to the choice of thermodynamic properties
- ➔ To obtain these results, Ξ_{init} and α_{CFM} have been optimised to fit experimental pressure traces

MODEL CALIBRATION

SUSTAINABLE MOBILITY

- Approach : adjust modelling parameters to fit experimental combustion process
  - Goals :
    - Provide deeper understanding on combustion process (heat release, flame development)
    - Perform knock study through spark timing sweep (correct CA50 needed)
    - Perform geometry variation from calibrated case (relative comparison)
  - Drawback :
    - Can not be used for prospective study (experimental data needed)
- Modelling parameters over EB2DT data base

	1750rpm 13bar	1750rpm 23 bar	3500rpm 22bar FAER = 1	3500rpm 25bar FAER = 1.1	3500rpm 25bar FAER = 1.3	4000rpm 12bar	4000rpm 20bar	5500rpm 20bar
Ξ_{init}	15	7	8	6	7	15	6	6
α_{cfm}	1.03	0.8	0.8	0.7	0.5	1.0	0.6	0.8

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Ξ_{init}	15	7	8	6	7	15	6	6
α_{cfm}	1.03	0.8	0.8	0.7	0.5	1.0	0.6	0.8

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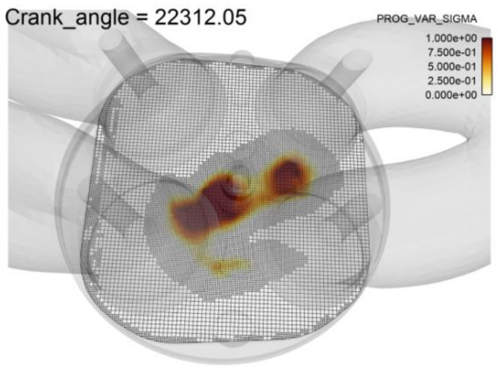
Ξ_{init}	15	7	8	6	7	15	6	6
α_{cfm}	1.03	0.8	0.8	0.7	0.5	1.0	0.6	0.8

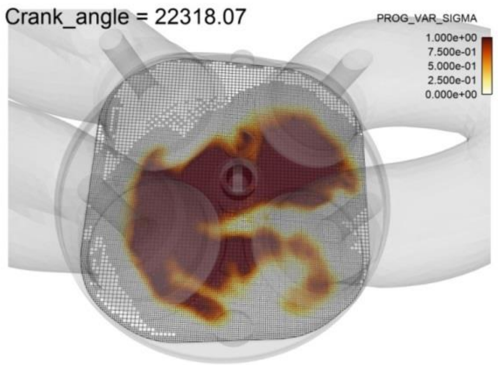
LES SIMULATION :
ARGONNE ENGINE – FIRED OPERATING CONDITIONS (1/3)



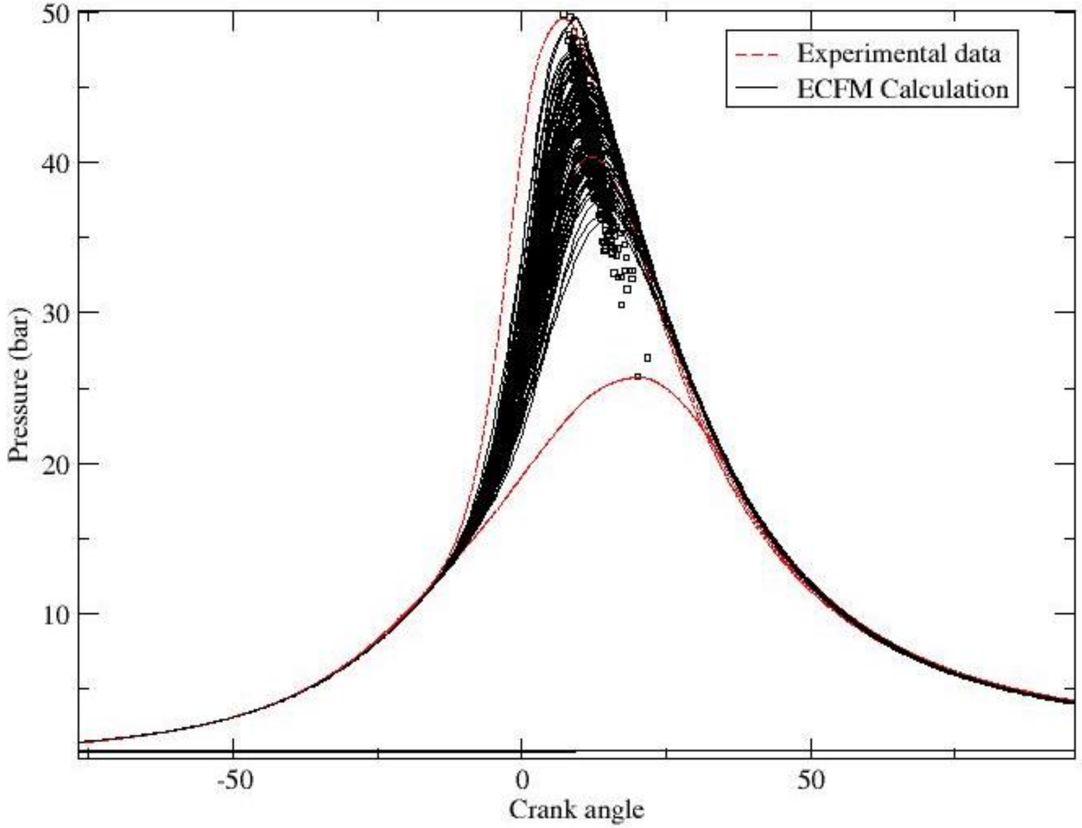
Displacement	0.626 L
Bore	89.04 mm
Stroke	100.6 mm
Compression Ratio	12.1:1
Intake Valve Opening	334° dATDC
Exhaust Valve Opening	135° dATDC
GDI injector	6 hole, solenoid
Injection Pressure	150 bar
Spark System	Coil-based, 0.7 mm gap
Fuel	EPA Tier II EEE

Engine Speed (RPM)	2000
IMEP (bar)	6
EGR (%)	0
Relative AFR (λ)	1
Start of Injection (SOI, °aTDC)	-300
Fuel mass injected (mg)	23
Spark Advance (SA, °aTDC)	-24

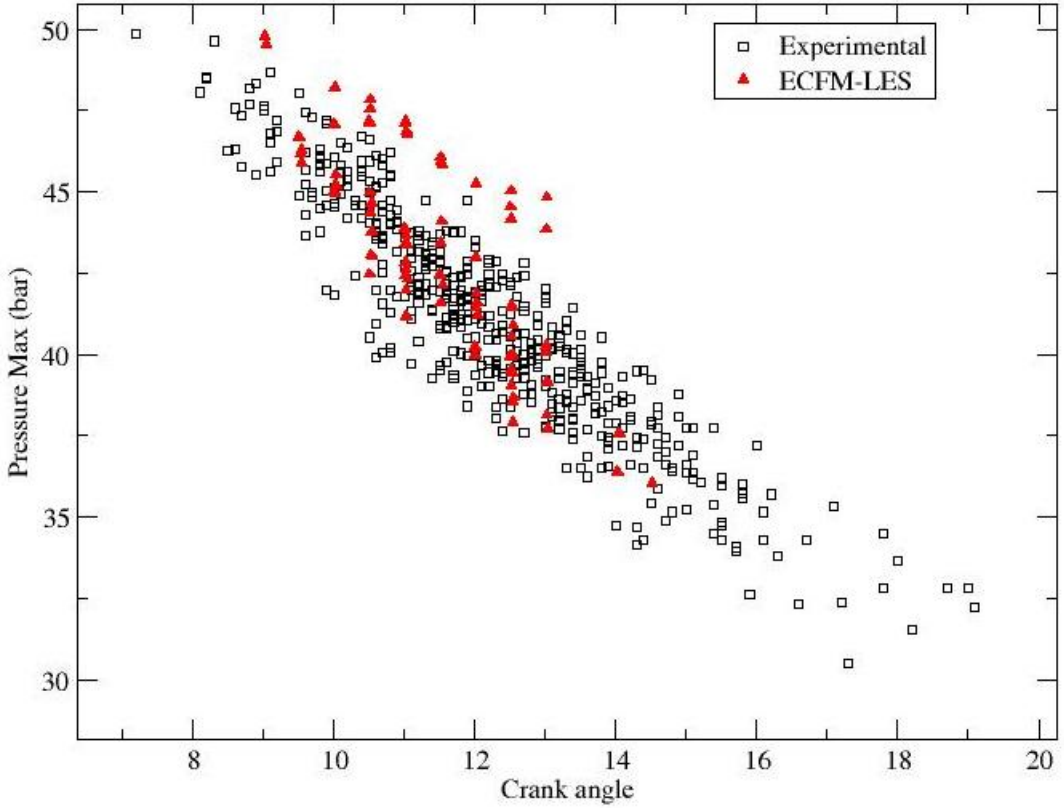
- ECFM-LES calculation with ISSIM-LES
- Grid / AMR – dx_{base}=4mm | dx_{min}=0.5mm (coarse LES)
  - Maximum number of cells = 2.5 Millions
- AMR on ECFM progress variable
- Number of cores = 56 - (Intel Skylake 2.7 Ghz – 14 cores per proc)
  - 1 cycle per 24 hours in sequential mode
- Perturbation method - **5 runs simultaneously = 80 cycles computed in 16 days (with V2.4)**



ARGONNE ENGINE – FIRED OPERATING CONDITIONS (2/3)



COV(Pmax) Experiment = 0.086
COV(Pmax) LES = 0.073

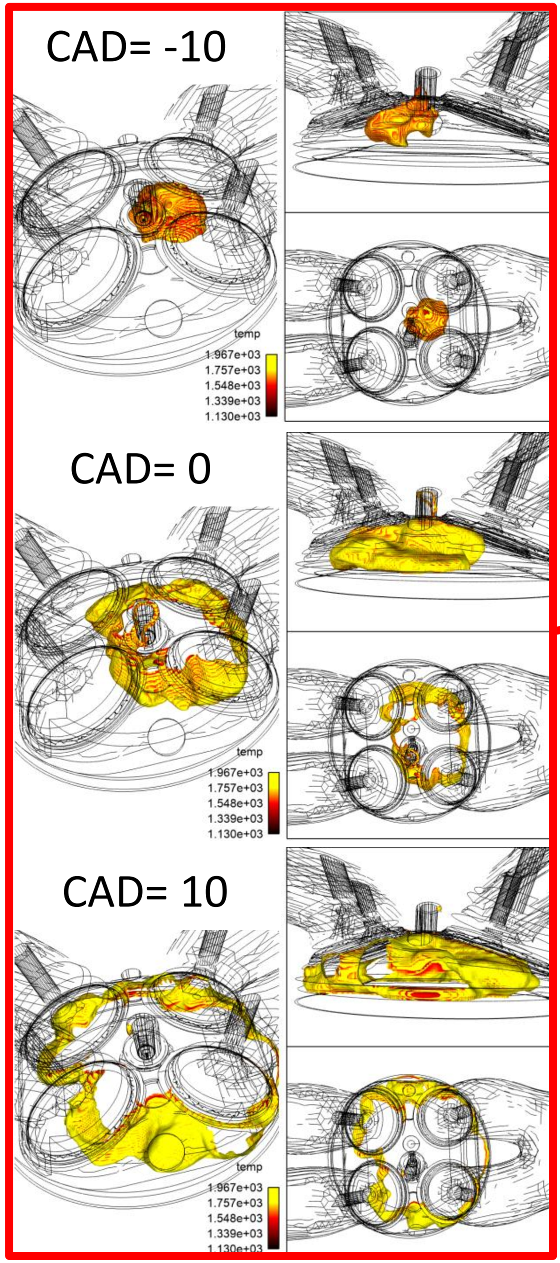


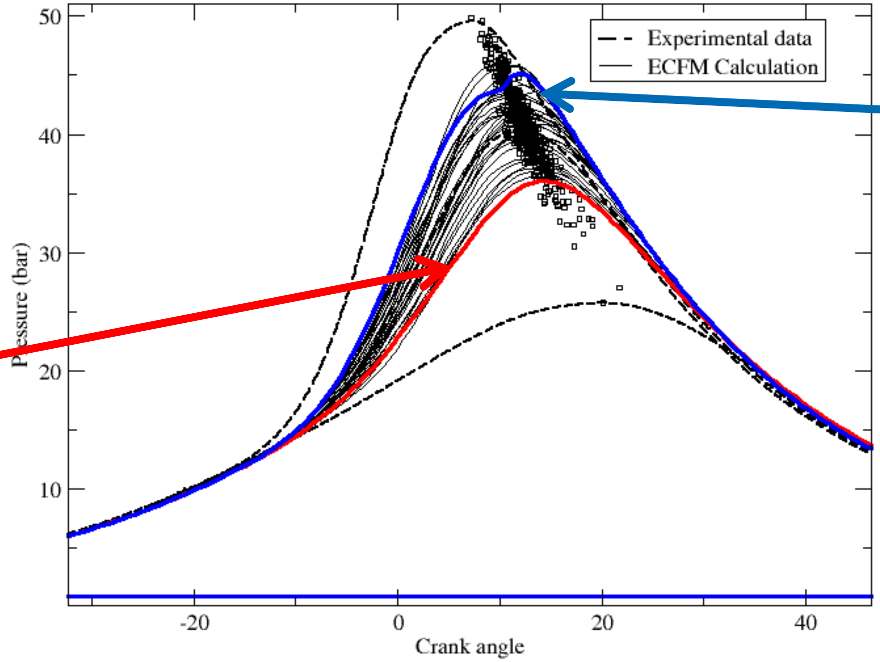
Pmax_moy Experiment= 40.9 bar
Pmax_moy LES = 43.1 bar

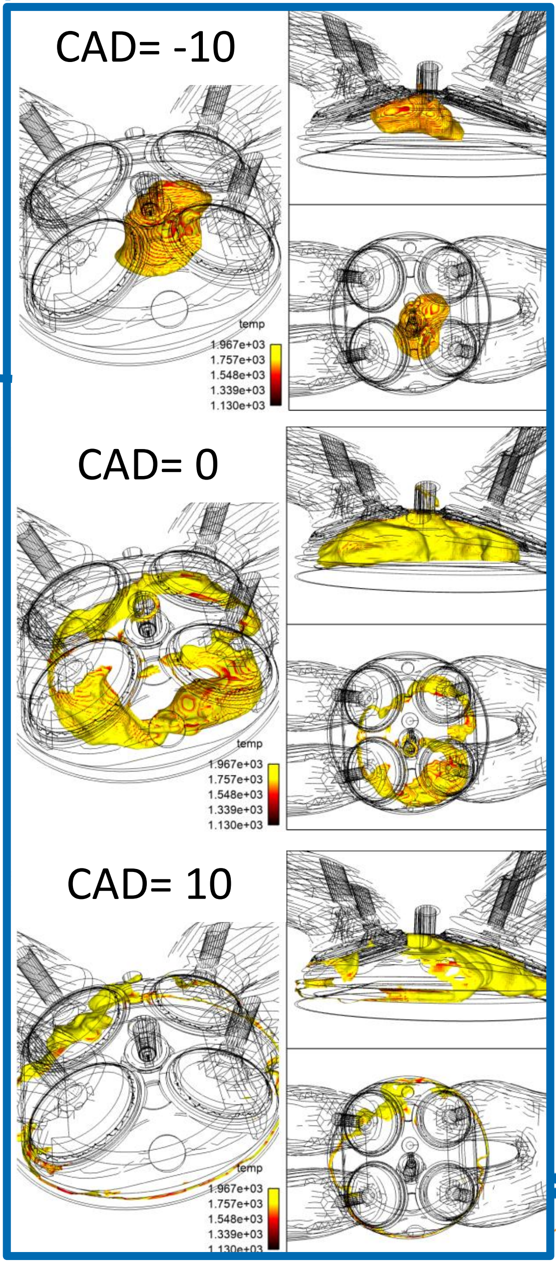
- LES is able to reproduce the CCVs amplitude even if the full envelope is not fully described with these 80 cycles

ARGONNE ENGINE – FIRED OPERATING CONDITIONS (3/3)

Slow cycle





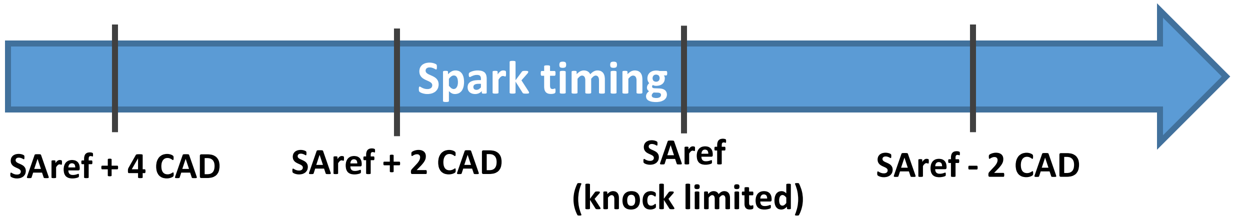


Fast cycle

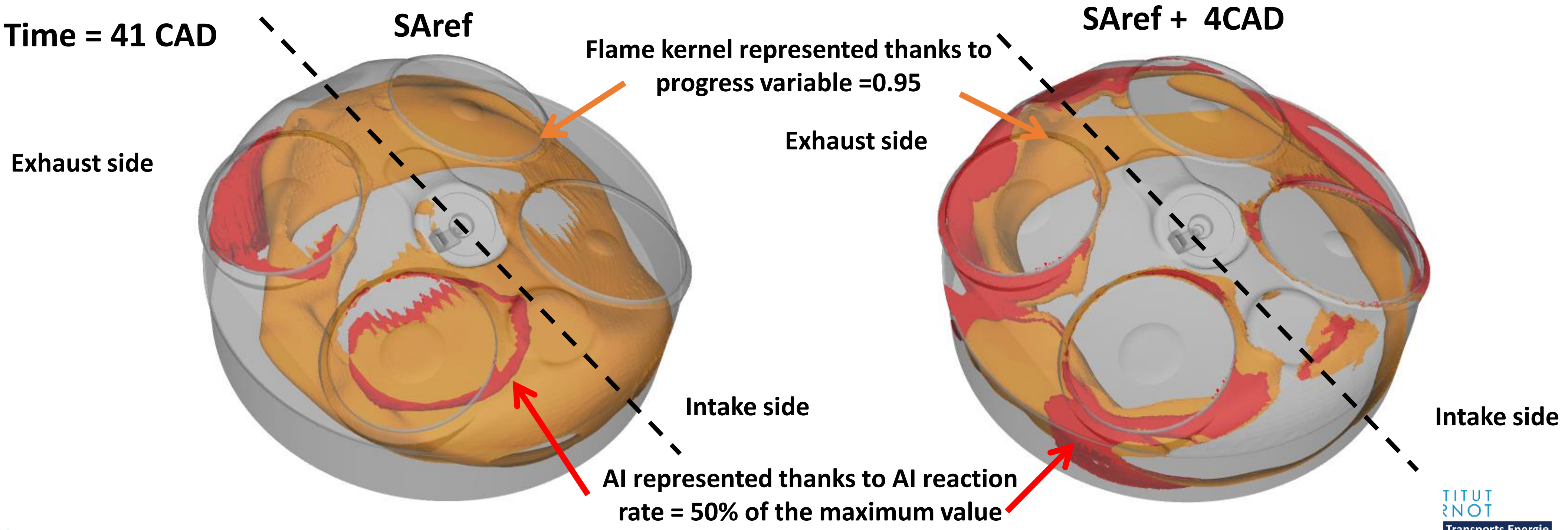
- The aerodynamic field at the spark plug is mainly responsible for the combustion velocity of each cycle

KNOCK INVESTIGATION : SPARK TIMING SWEEP

Methodology



Field analysis : Visualization of flame kernel and AI spots



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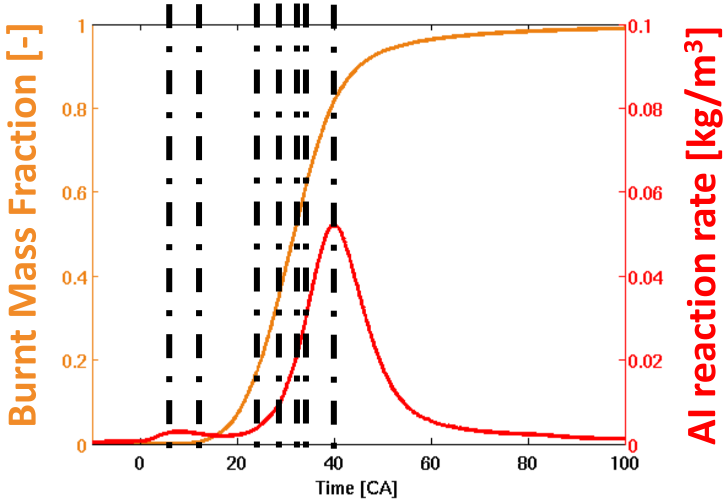
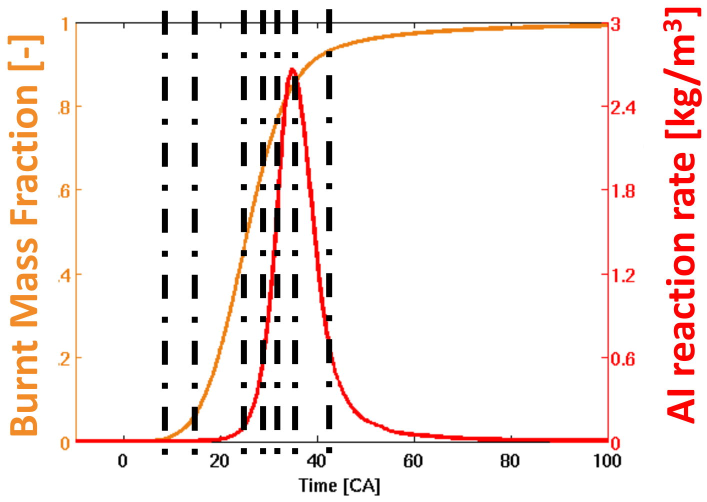
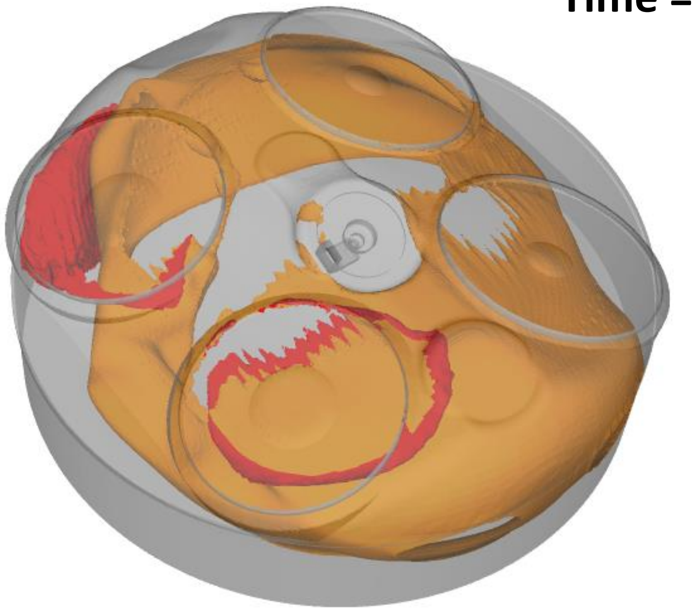
KNOCK INVESTIGATION : SPARK TIMING SWEEP

@ 7CAD :
Case SAref + 4 ➔ first kernel development
Case SAref ➔ Combustion initiation

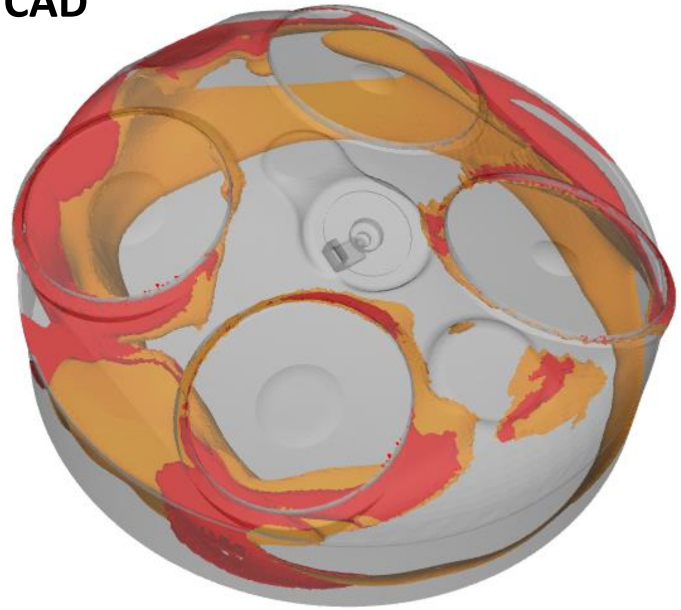




Time = 41 CAD



SAref



SAref + 4

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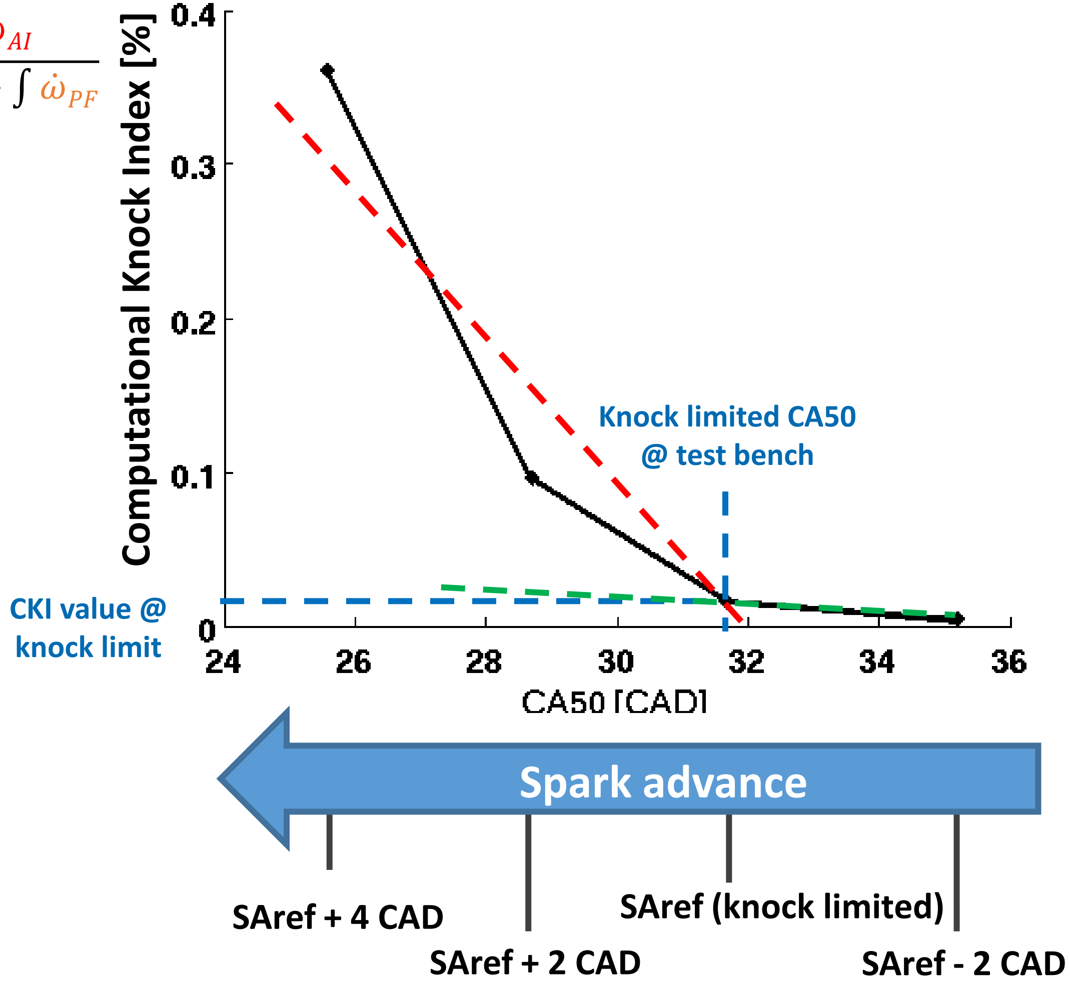
KNOCK INVESTIGATION : SPARK TIMING SWEEP

- Computational knock criterion

$$CKI = \frac{\int \dot{\omega}_{AI}}{\int \dot{\omega}_{AI} + \int \dot{\omega}_{PF}}$$



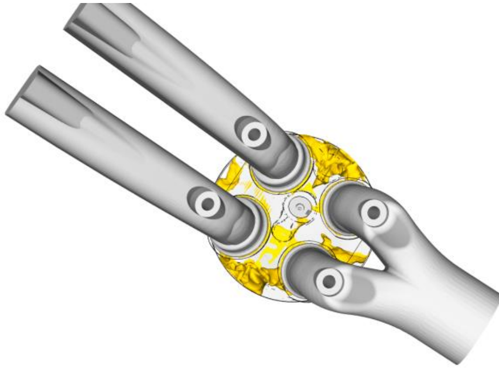
- Clear slope break @ knock limited CA 50
- Possibility to define a computational knock limit
  - depends on experimental knock limit definition
- The absolute value of the computational knock limit is engine dependent

INSTITUT CARNOT IFPEN Transports Energie

IFP Energies nouvelles

CSI IFPEN - CONVERGE

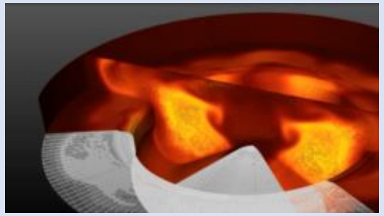
SUSTAINABLE MOBILITY

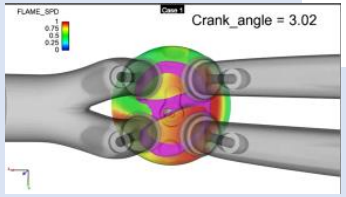


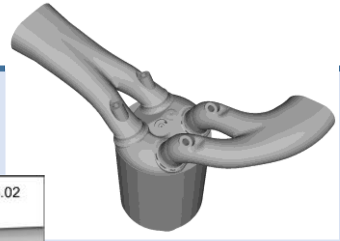
Since V2.3.16 version (2016), IFPEN RANS model are implemented into CONVERGE and are extensively used (switch in 2016 from IFP-C3D to CONVERGE).

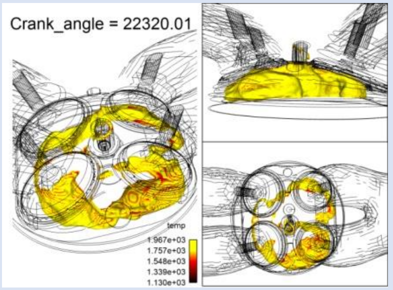
Since V2.4.24 version (2019), IFPEN LES model are available into CONVERGE and are used in IFPEN collaborative research project.

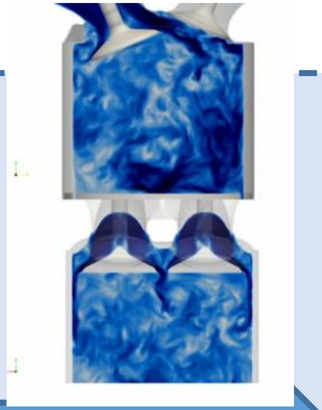
In 2019, IFPEN is currently working in RANS and LES modeling











2015

2019

ECFM3Z-TKI Soot / Nox modeling

ECFM-ISSIM TKI

ECFM-ISSIM- TKI LES modeling
Soot Modeling / Liquid film evaporation

CONVERGE

CI Engine

SI Engine

CI & SI Engine

IFPEN MODEL PORFOLIO
TABULATED KINETIC IGNITION MODEL - **TKI**

TKI Database can be generated with ConvergeStudio

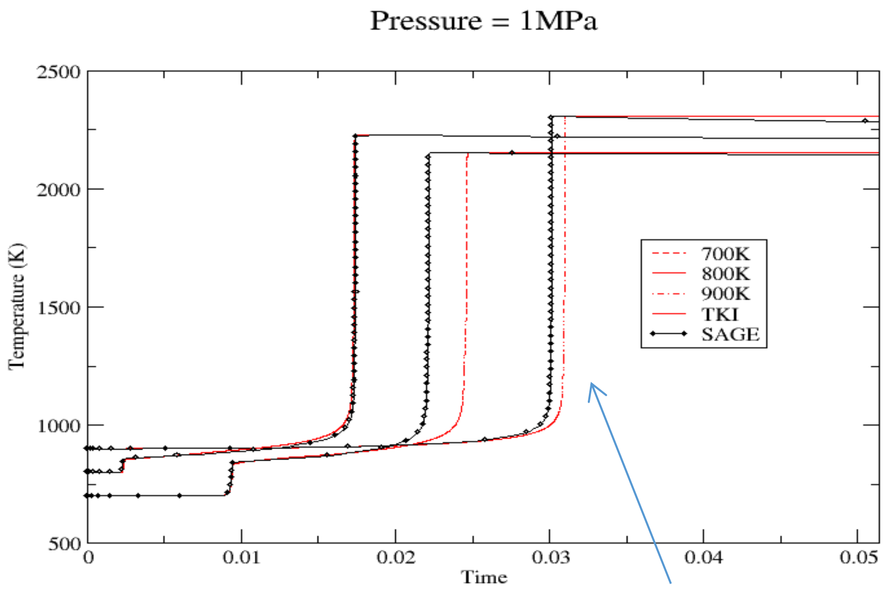
Each data base for each fuel contains more than **2.000.000 values**, done *a priori*:

Delay and fuel consumption for **cool flame**

7 reaction rates

Function of :

- Fresh gas temp. (600 - 1500 K)
- Pressure (1- 8 Mpa)
- Fuel/air equivalence ratio (0,3 - 3)
- Dilution (0 - 90 %)



Interpolation error

Calculations using **detailed kinetic mechanisms** (more than **500 species** and **2000 reactions**)

