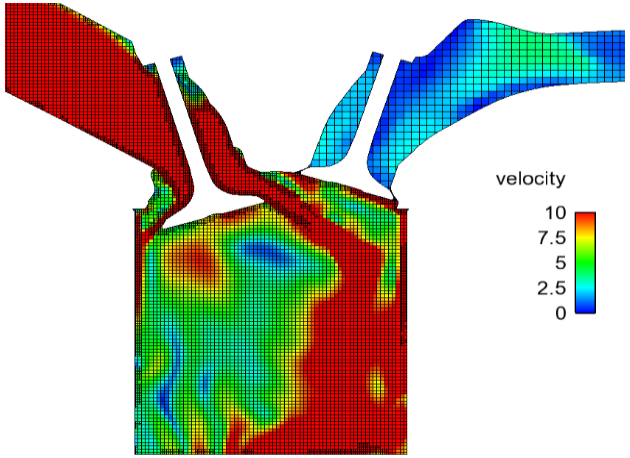
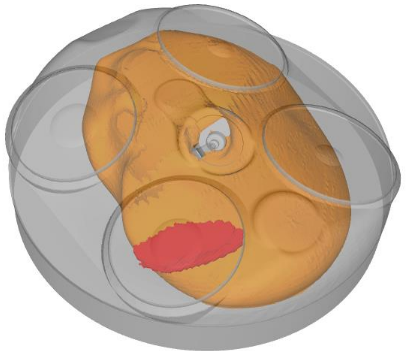
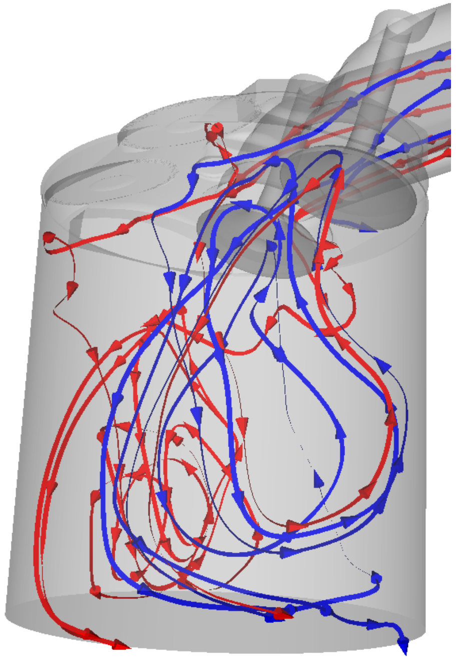






PISTON ENGINE COMBUSTION WITH ECFM3Z:

KEY ELEMENTS OF IFPEN COMBUSTION MODELING APPROACH

Olivier Colin (IFPEN), Stéphane Chevillard (IFPEN), Julien Bohbot (IFPEN),
Anthony Velghe (IFPEN), Mingjie Wang (CSI)

Your True Partner for
CAE×CFD
ICSC2016
IDAJ CAE Solution Conference

CONVERGENT SCIENCE

ifp Energies nouvelles

IDENTITY CARD OF IFPEN

A French public-sector R&I body (RTO)

A training center

An industrial group

An international scope in the fields of energy, transport and the environment

IDENTITY CARD OF IFPEN

1,660
people
of whom

155
doctoral and post-doctoral researchers

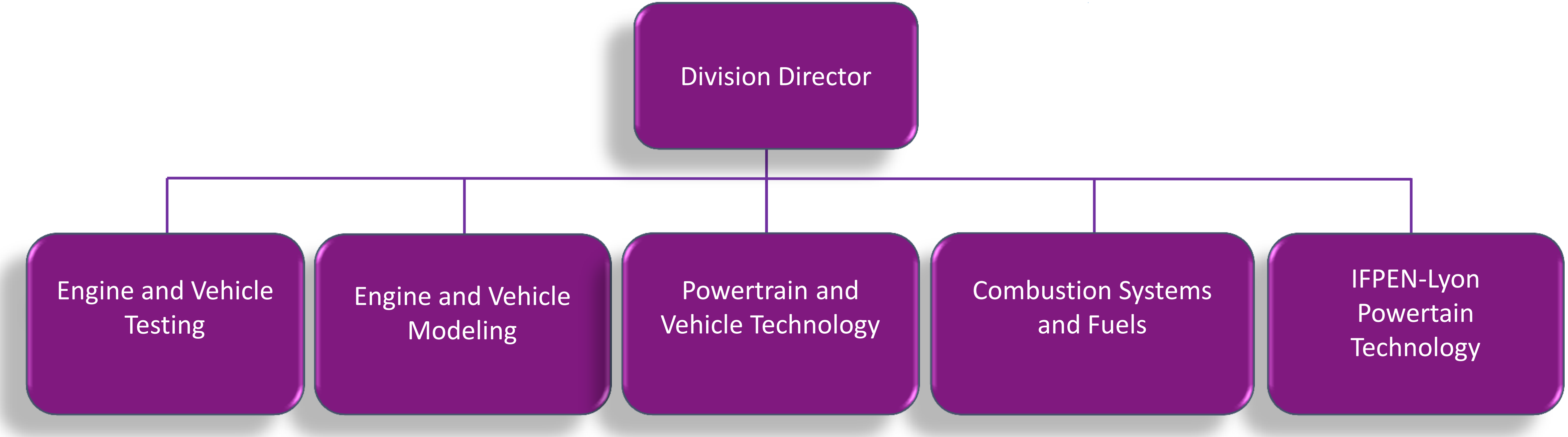
2 sites:
Rueil (near Paris)
and Solaize (near Lyon)

1,130
researchers

A very high-quality technical environment: testing resources, equipment, **110** teraflop supercomputer

More than **50** professions, from geological engineers to powertrain engineers

POWERTRAIN AND VEHICLE DIVISION



96 Engineers
63 Technicians
18 PhD students
2 Post-docs
2 Apprentices

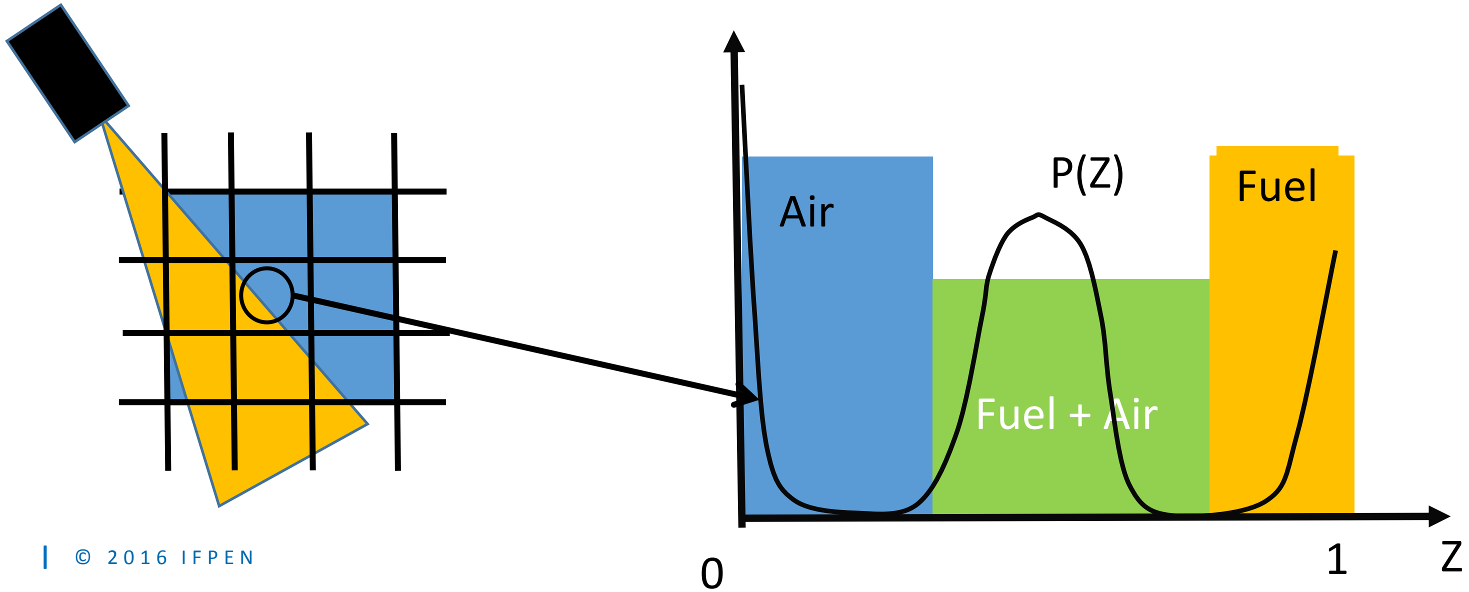
11 Engine test benchs
5 Optical test benchs

OUTLOOK OF THE PRESENTATION

- The ECFM3Z combustion model
- Diesel application
- SI application
- Future developments in Converge
- Conclusions

THE ECFM3Z COMBUSTION MODEL [1]

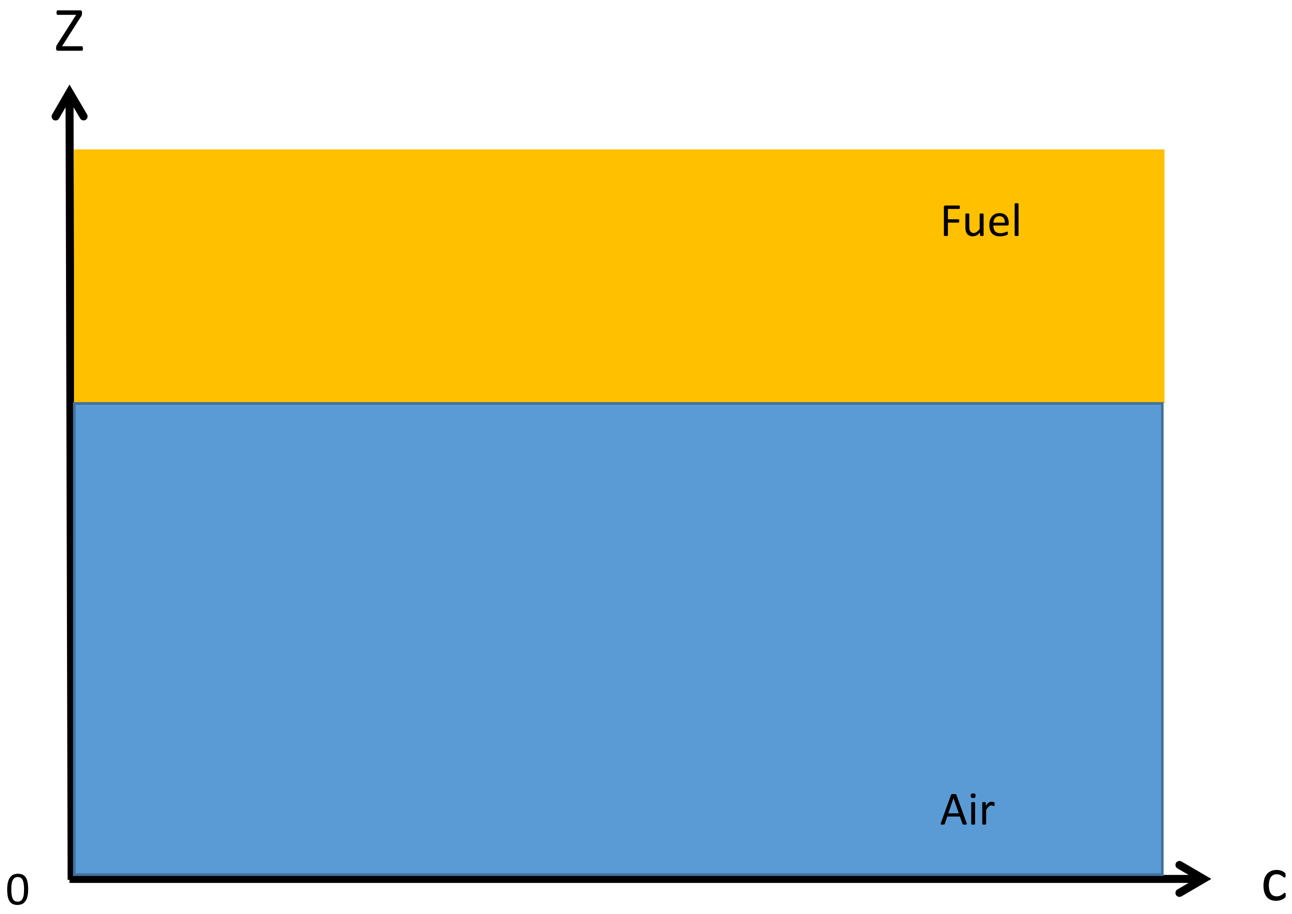
- General purpose model developed at IFPEN the last 20 years
  - Based on premixed flame propagation model (ECFM) [2,3] for gasoline engines
  - Spark plug ignition description: AKTIM [4] then ISSIM [5]
  - Knock/auto-ignition model: TKI [6]
  - Local fuel/air ratio fluctuations for Diesel combustion: three mixture fraction description
    - Pure air + EGR
    - Pure gaseous fuel (from evaporating liquid spray)
    - Mixed zone air+EGR+fuel



[1] Colin et al, OGST, 2003
[2] Duclos et al, SAE, 1996
[3] Colin et al, OGST, 2004
[4] Duclos et al., COMODIA, 2000
[5] Colin and Truffin, PCI, 2010
[6] Colin et al, PCI, 2004

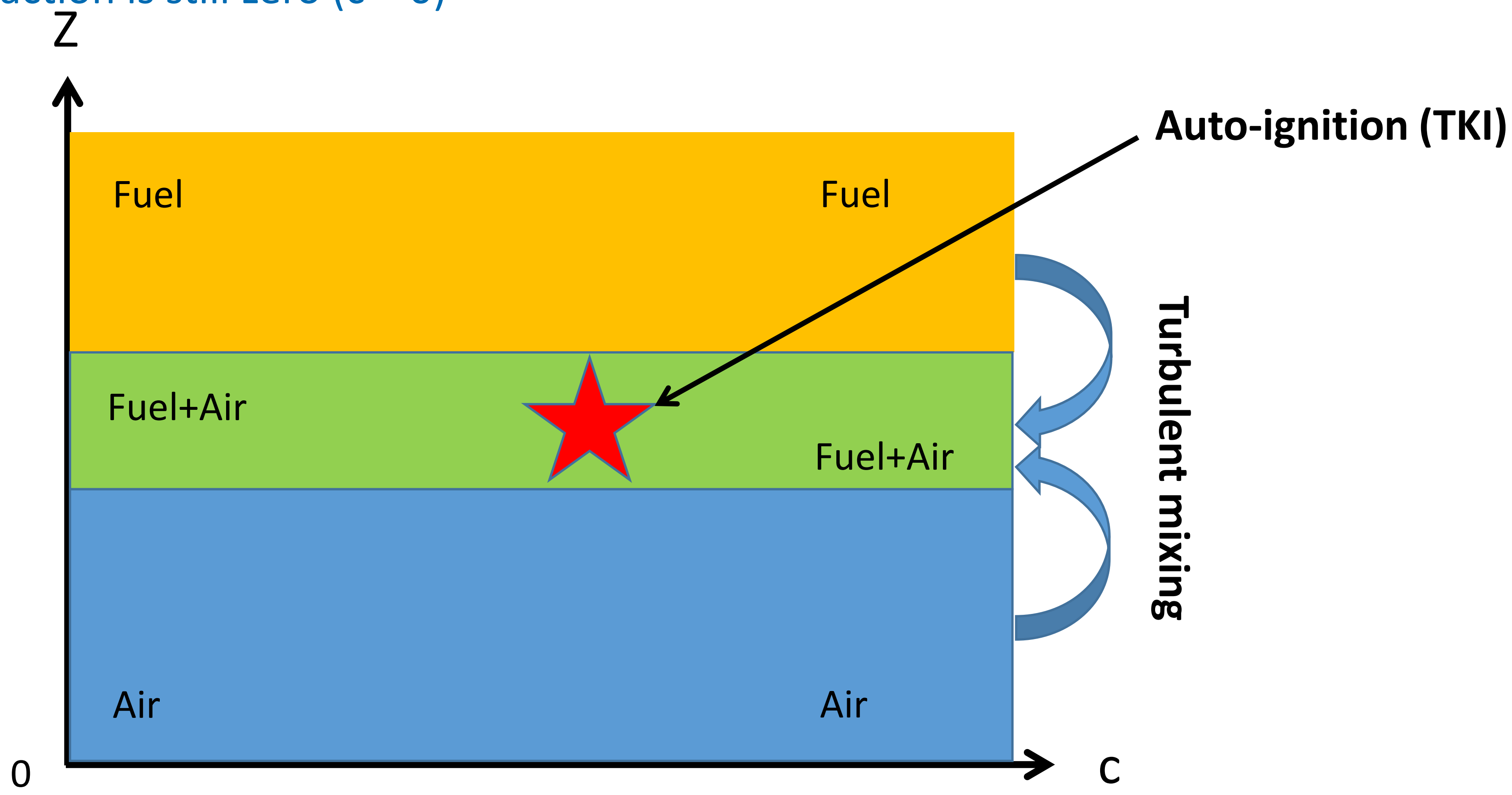
SEQUENCE OF COMBUSTION WITH ECFM3Z

- Fuel and Air initially not premixed
- Progress of reaction c = 0



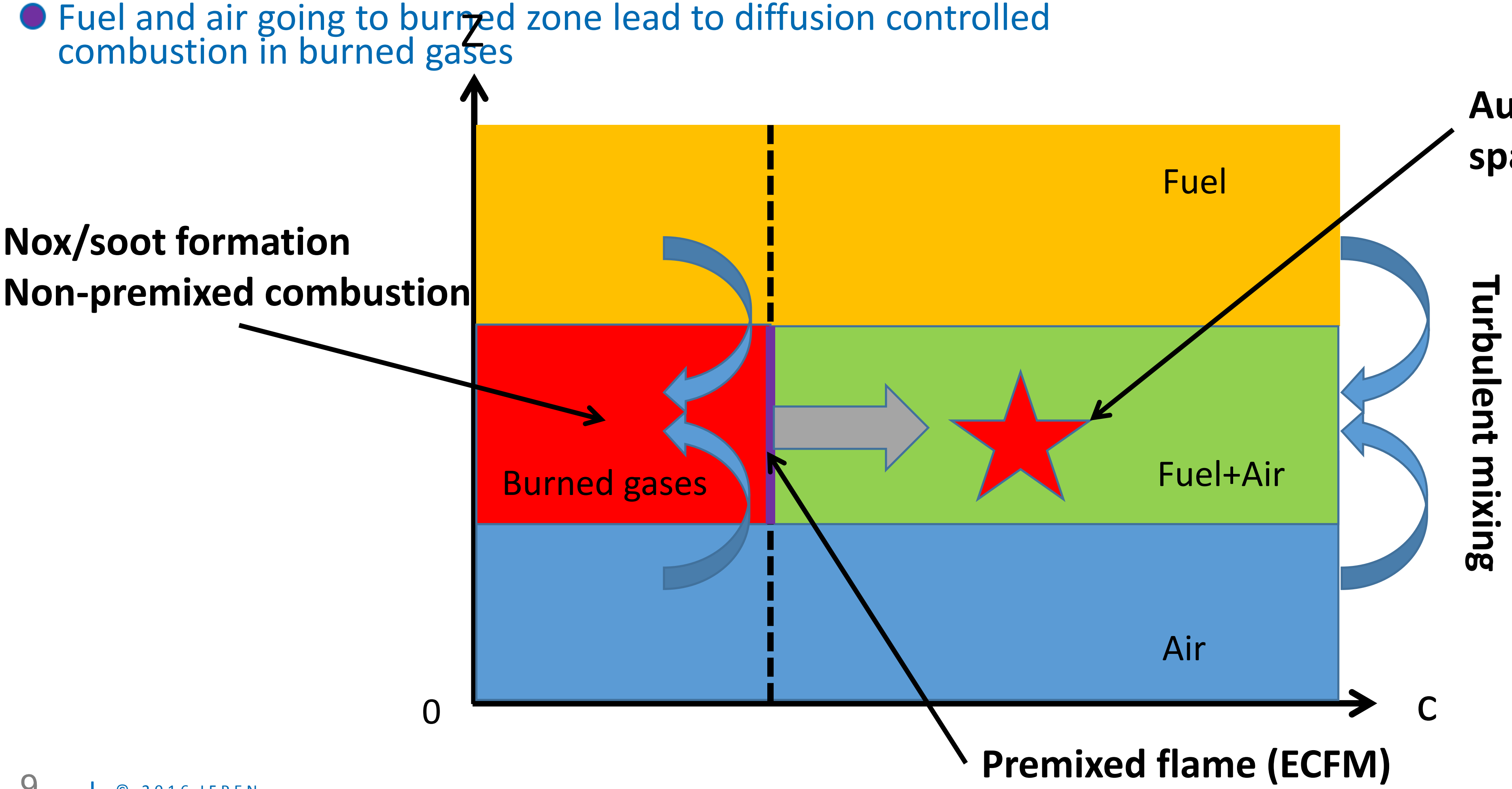
SEQUENCE OF COMBUSTION WITH ECFM3Z

- Mixed zone is formed
- Auto-ignition description starts in mixed zone
- Progress of reaction is still zero (c = 0)



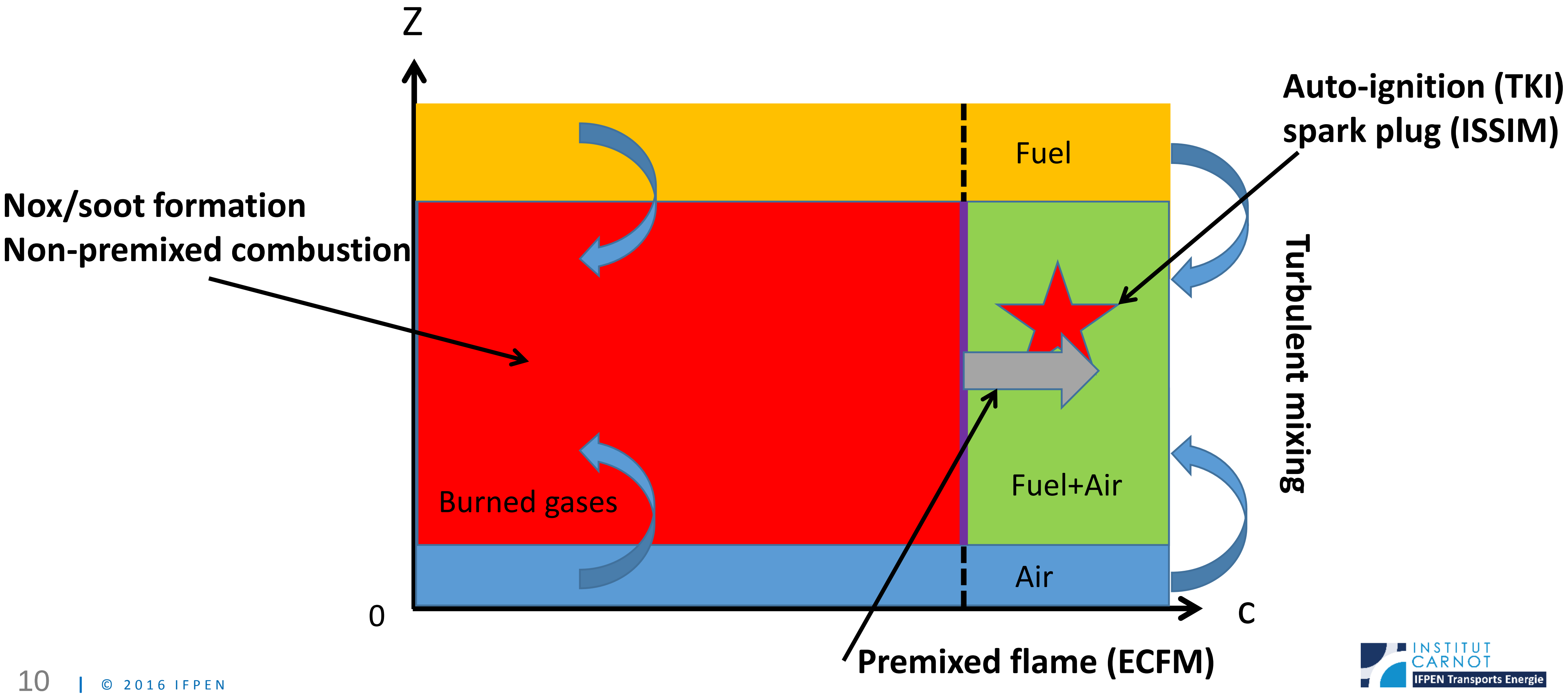
SEQUENCE OF COMBUSTION WITH ECFM3Z

- 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



SEQUENCE OF COMBUSTION WITH ECFM3Z

- Combustion proceeds till c=1 and unmixed zones are void



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ECFM3Z UNBURNED/BURNED GASES STATES

- Standard transport equations for species mass fractions Yi and sensible energy

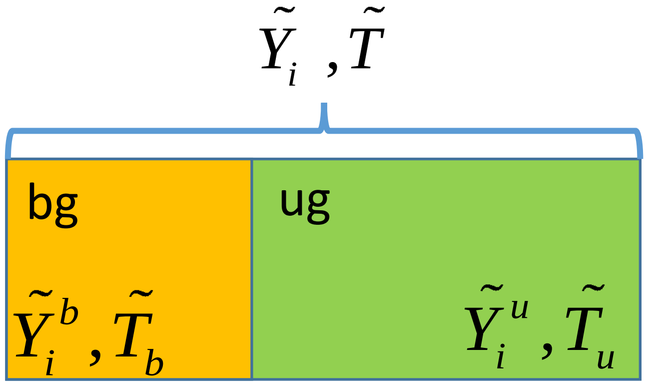
$$\frac{\partial \bar{\rho}\tilde{Y}_i}{\partial t} + \nabla.(\bar{\rho}\tilde{u}\tilde{Y}_i) = \nabla.(\mu_t \nabla \tilde{Y}_i) + \bar{\rho}\tilde{\dot{\omega}}_i$$

Chemical source term contributions (ECFM+TKI+ISSIM+post-oxidation)

- Same equations for species and energy passives

- Local fresh gases composition (i=O_2, Fuel, CO, CO_2, H_2, H_2O, N_2) and temperature (Tu) can be deduced

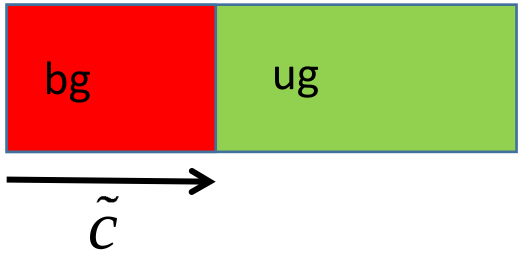
- Local burned gases composition and temperature (Tb) can be deduced



ECFM3Z AUTO-IGNITION PROGRESS VARIABLE

- Global progress variable = burned gases fraction in mixed zone=> defined as the ratio of unburned fuel and fuel tracer

$$\tilde{c} = \frac{m_b}{m_u + m_b} = 1 - \frac{\tilde{Y}_F}{\tilde{Y}_{TF}}$$



- Specific progress of reaction for auto-ignition model (TKI model)

$$\tilde{c}_{ai} = 1 - \frac{\tilde{Y}_F^{ai}}{\tilde{Y}_{TF}}$$

- Fuel burned by auto-ignition $\tilde{Y}_F^{ai}$ is given by its transport equation

$$\frac{\partial \bar{\rho} \tilde{Y}_F^{ai}}{\partial t} + \nabla.(\bar{\rho}\tilde{u}\tilde{Y}_F^{ai}) = \nabla.(\mu_t \nabla \tilde{Y}_F^{ai}) + \bar{\rho}\tilde{\dot{\omega}}_{\tilde{Y}_F^{ai}}$$

Chemical source term contribution (TKI)

LINK BETWEEN ALL PROGRESS VARIABLES

- Premixed flame separates fresh auto-igniting gases and burned gases

$$\tilde{\Phi} = (1-\tilde{c}_\Sigma)\,\Phi\big|^{ai} + \tilde{c}_\Sigma\,\Phi\big|^{b}$$

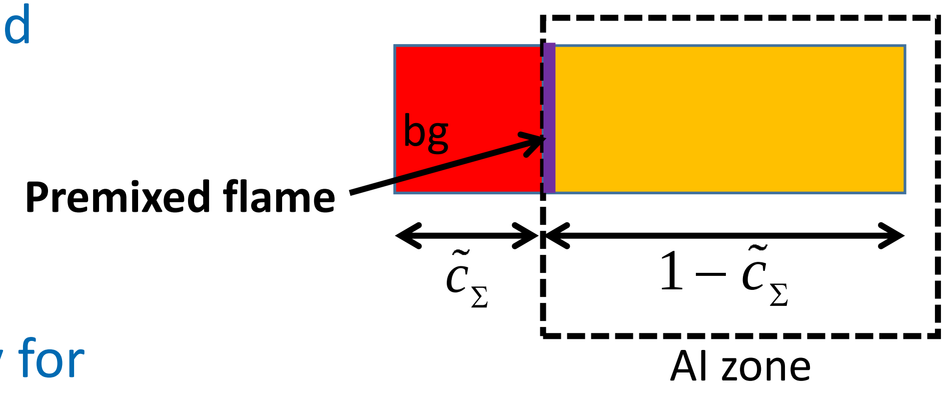
- Fresh auto-igniting gases are treated in a bimodal way for simplicity (homogeneous zone in reality)

$$\Phi\big|^{ai} = (1-\tilde{c}_{ai})\,\Phi\big|^{u} + \tilde{c}_{ai}\,\Phi\big|^{b}$$

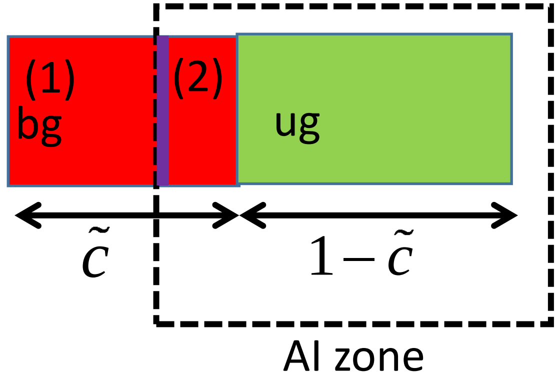
- Total burned gases fraction $\tilde{c}$ is then given by:

$$\underbrace{\tilde{c} = \tilde{c}_\Sigma}_{(1)} + \underbrace{(1-\tilde{c}_\Sigma)\tilde{c}_{ai}}_{(2)} \;\Rightarrow\; \tilde{c}_\Sigma = \frac{\tilde{c}-\tilde{c}_{ai}}{1-\tilde{c}_{ai}}$$

Real bimodal decomposition

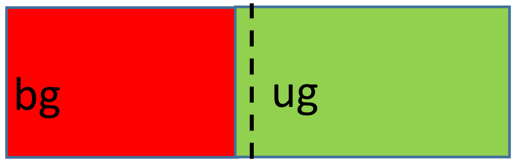


Model bimodal decomposition



SPECIES SOURCE TERMS

- Based on previous relations, species source term can be deduced



$$\dot{\tilde{\omega}}_i = (\tilde{Y}_i^b - \tilde{Y}_i^u)\dot{\tilde{\omega}}_c + \tilde{c}\,\dot{\tilde{\omega}}_i^b$$

$$\dot{\tilde{\omega}}_c = (1-\tilde{c}_{ai})(\dot{\omega}_c^{\Sigma} + \dot{\omega}_c^{ign}) + (1-\tilde{c}_{\Sigma})\dot{\omega}_c^{ai}$$

Post-oxidation model

ISSIM model

TKI model

ECFM model

- Same for passive species $\tilde{Y}_F^{ai}$

$$\dot{\tilde{\omega}}_{Y_F^{ai}} = \tilde{Y}_{TF}\,\dot{\omega}_c^{ai}$$

INSTITUT CARNOT IFPEN Transports Energie

IFP Energies nouvelles

TKI TABLE GENERATION WITH KICGEN AND USAGE

- 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

KicGen
- Kinetic mechanism
- Range of parameters
- Generate input files for SAGE

SAGE
- Full parallel 0-dimensional SAGE homogeneous calculations

KicGen
- 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

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

TKI REACTION RATE CALCULATION [1,2]

[1] Colin et al., PCI, 2004
[2] Robert et al., PCI, 2015

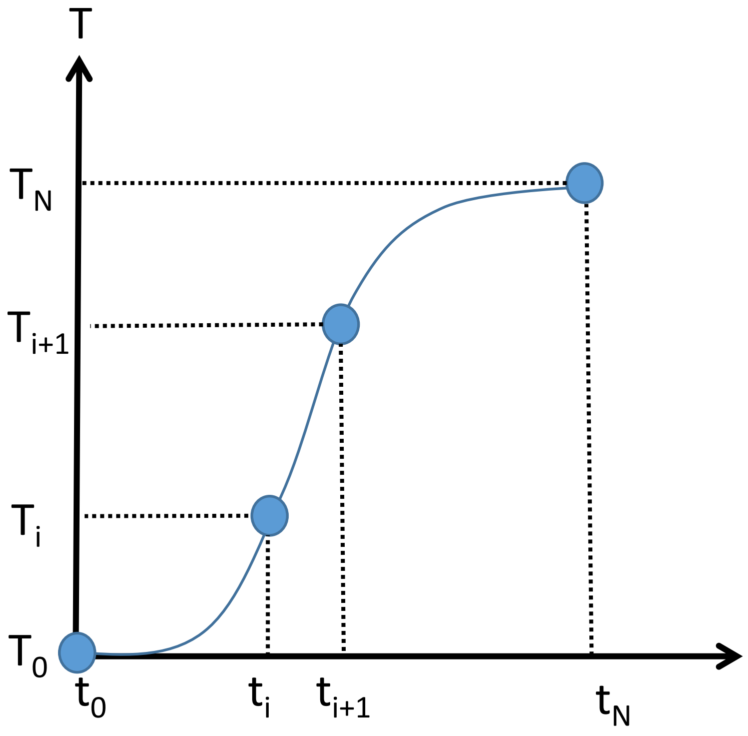
SUSTAINABLE MOBILITY

- Algorithm for one thermodynamic condition
  - Calculation of a constant pressure homogeneous reactor using any complex mechanism with a kinetic solver (Sage, etc…)
  - Progress variable defined as the normalized reactor temperature

$$c_i = \frac{T_i - T_0}{T_N - T_0}$$

  - TKI reaction rate defined as the progress variable derivative

$$\dot{\omega}_c^{TKI}(c_i) = \frac{c_{i+1} - c_i}{t_{i+1} - t_i}$$



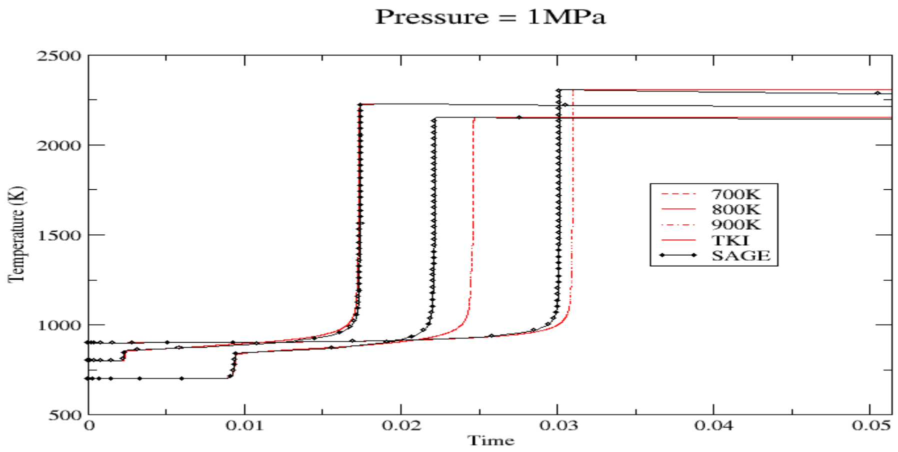
- Repeat for all thermodynamic conditions

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

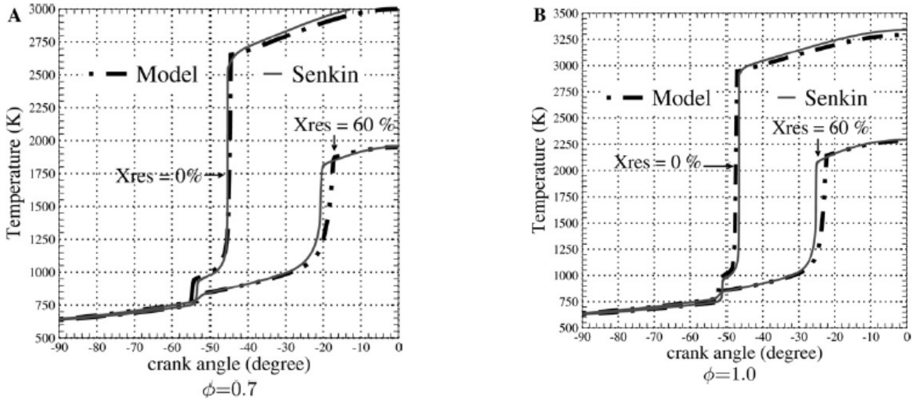
TKI MODEL VALIDATION

SUSTAINABLE MOBILITY

- Constant pressure homogeneous reactor case
  - Comparison with kinetic solver simulations



- Variable volume homogeneous reactor case
  - Comparison with kinetic solver simulation [1]



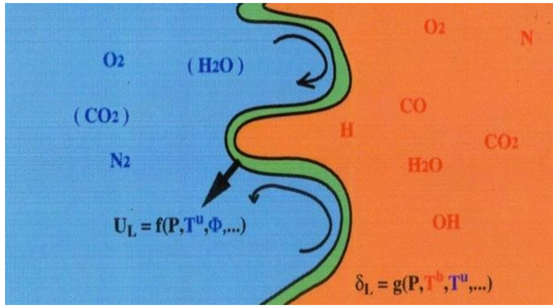
[1] Colin et al. (2004)

ECFM MODEL

- Based on the flamelet assumption
  - flame thickness smaller than all turbulent scales
  - => locally, the flame is identical to a laminar flame propagating at the laminar flame speed S_l
  - Reaction rate is thus the product of the flame surface density Σ (=S/V) by the laminar flame speed:

$$\bar{\rho}\dot{\omega}_c^{\Sigma} = \rho_u S_l \bar{\Sigma}$$

Effect of chemistry **Effect of turbulence**



- Exact unclosed equation of Σ proposed by [1]
- Closed equation for RANS proposed by IFPEN [2,3]:

$$\frac{\partial \bar{\Sigma}}{\partial t} + \nabla.(\tilde{u}\bar{\Sigma}) = \nabla.(\mu_t \nabla \bar{\Sigma}) + \alpha a_t \bar{\Sigma} + \frac{2}{3}\nabla.\tilde{u} + \frac{2}{3}\frac{S_l}{\tilde{c}}\bar{\Sigma}^2 - \frac{S_l}{1-\bar{c}}\bar{\Sigma}^2 + \dot{\omega}_{\Sigma}^{ign}$$

Time evolution **Averaged transport** **Turbulent transport** **Turbulent strain rate** **Mean strain rate** **Curvature** **Destruction** **Spark source**

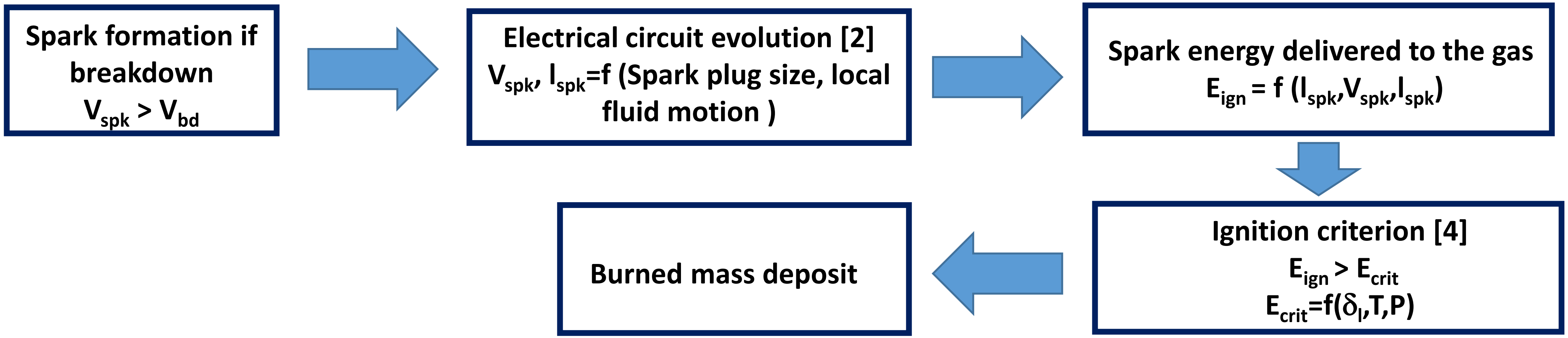
modelling constant

[1] Candel and Poinsot, CST, 1990
[2] Duclos et al, SAE, 1996
[3] Colin et al, OGST, 2004

ISSIM MODEL[1]

[1] Colin and Truffin, PCI, 2011
[2] Duclos and Colin, Comodia, 2000
[3] Adelman, PCI, 1981

- Provides spark plug ignition source terms in Σ and species equations
- It accounts for various phenomena :
  - Electrical circuit model
  - Local mixture properties (fuel/air ratio, temperature etc…) at the spark plug
  - Effect of convection on the initial kernel
  - Effect of turbulence of kernel wrinkling
- Electrical circuit description[2]



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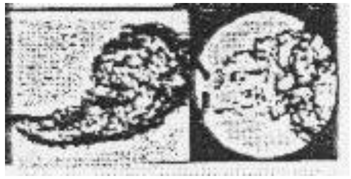
ISSIM MODEL SOURCE TERMS[1]

[1] Colin and Truffin, PCI, 2011
[2] Duclos and Colin, Comodia, 2000
[3] Erweg and Maly, SAE, 1992
[4] Mulla et al, CF, 2016

- Initial burned gases mass deposition proportional to electrical energy in gas

$$m_b^{ign}(t) = \frac{E_{ign}(t)}{C_p \Delta T_{ign}}$$

Eign increases with time as long as arc exists =>mbign also increases (flame holder effect[3])



- Distribution of the initial burned gases mass on a Gaussian profile centered on eletrodes gap

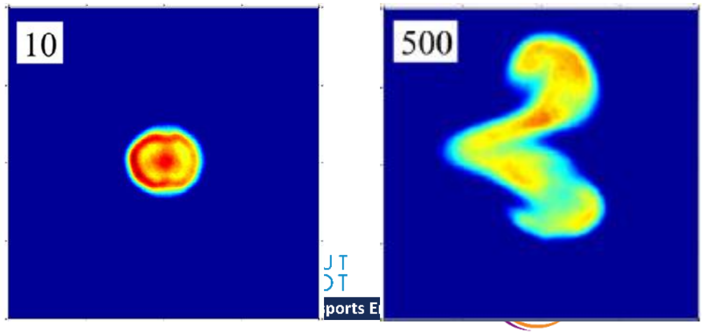
$$\bar{c}_{ign}(x,t) = \frac{m_b^{ign}(t)\exp(-r^2/\delta_{spk}^2)}{\int \exp(-r^2/\delta_{spk}^2)dV}$$

- Species and Σ source terms

$$\dot{\omega}_c^{ign} = \max(\bar{c}_{ign} - \bar{c}, 0)/dt$$

$$\dot{\omega}_\Sigma^{ign} = \max(\Xi_{ign}\frac{3}{r_{ign}}\bar{c}_{ign} - \bar{\Sigma}, 0)/dt$$

modelling constant= initial flame wrinkling
Sources of initial wrinkling:
- **Toroidal shape of the kernel due to chock wave [4]**
- **Flow around spark plug**
- **Plasma dynamics**



BURNED GASES REACTIONS

- Major species reaction rate (Fuel, CO, CO_2, H_2, H_2O, H, O, OH)
  - Given by simplified two-step reaction mechanism + radicals equilibrium computation

$$C_xH_y + (\frac{x}{2} + \frac{y}{4})O_2 \rightarrow xCO + \frac{y}{2}H_2O$$

$$CO + \frac{1}{2}O2 \rightleftarrows CO2$$

  - Allows:
    - Generic fuel oxidation for non-premixed combustion (Diesel or very rich zones in SI engines)
    - Correct estimation of burned gases composition => correct Tb and CO/CO2 ratio
  - Does not allow:
    - Fuel formulation impact on reaction rate
    - Minor species prediction (HC)
- Pollutants reaction rate (passive species formulation)
  - Zel'Dovitch NO mechanism [1] (thermal NO model)
  - Hiroyasu soot model from Converge [1] (semi-empirical soot model)

[1] Heywood, 1988
[2] Hiroyasu and Kadota, SAE, 1976

ECFM3Z CALCULATION PROCEDURE

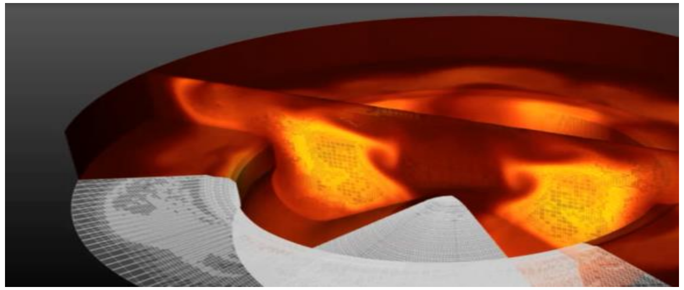
- fuel surrogate definition
  - Mean fuel formulation: CxHyOz
  - Thermodynamic data (liquid and gas)
- TKI table
  - Use existing table (available from CSI)
  - Or generate table with KicGen (need mechanism)
- Laminar flame speed
  - Set Sl correlation parameters in combust.in
  - Or use UDF table
- Set ISSIM parameters in issim.in (spark timing, ignition energy etc…)
- Set ECFM3Z parameters in combust.in (factor α etc…)
- Set correct species and passives for ECFM3Z
- Run Converge
- Specific ECFM3Z outputs in passive.out, ecfm3z.out and issim_ignition_0.out

OUTLOOK OF THE PRESENTATION

- The ECFM3Z combustion model
- Diesel application
- SI application
- Future developments in Converge
- Conclusions

PASSENGER CAR DIESEL ENGINE DATABASE

SUSTAINABLE MOBILITY



Experimental database (provided by Renault SA) :

- 40 operating points, 10 calculated
- Load and high load
- Engine speed (rpm) variation (1500rpm, 4000rpm)
- EGR rate variation at low load (0%,15%,30%)
- Start of Injection (SOI) variation (full and partial load)

Renault Diesel Engine

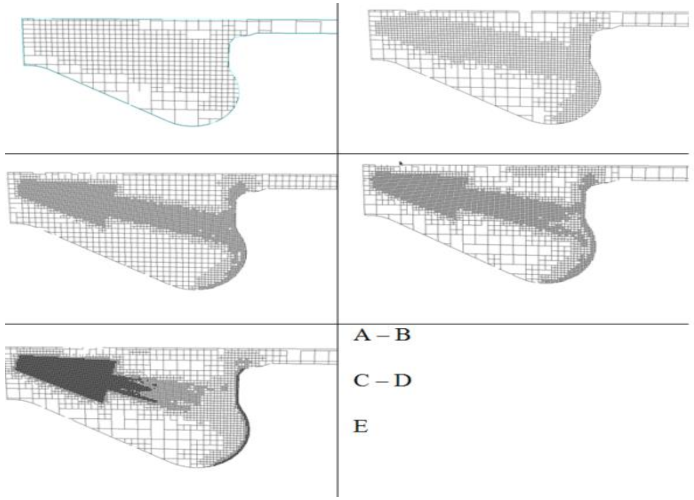
Number of cylinder	1
Compression ratio	14.8:1
Engine bore	0.084m
Stroke	0.09m
Connective rod length	0.1435m
Number of holes	6
Nozzle diameter	155μm

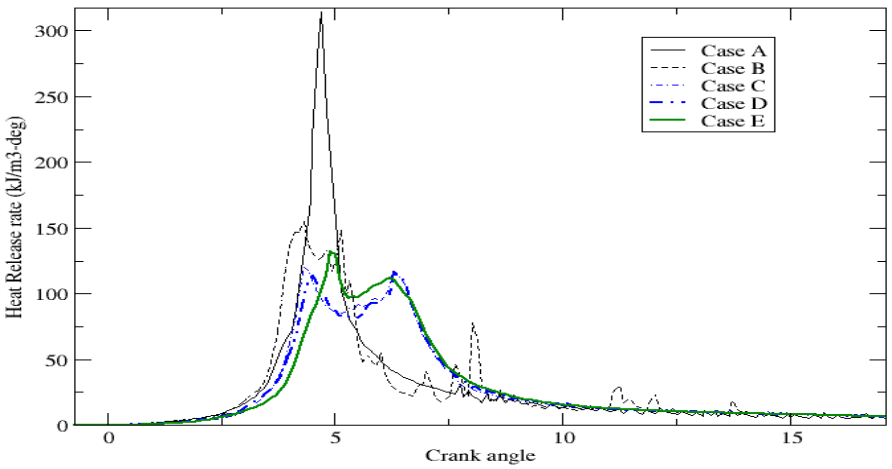
MESH RESOLUTION STUDY

- Aim: find the correct settings of AMR, embedding and dx_base to ensure mesh convergence
  - Wedge mesh (1/6th)
  - Compression and expansion only

	A	B	C	D	E
Dx_base	2.8	1.4	0.7	1.4	1.4
Embed scale	2	2	2	3	4
Dx_min	0.7	0.35	0.175	0.175	0.0875

Cells min	5k	7k	38k	18k	34k
Cells max	46k	180k	420k	960k	3600k
Number of Parcels	70k	100k	500k	500k	800k
Simulation return time (16 cores)	1680	6600	52452	38598	260140



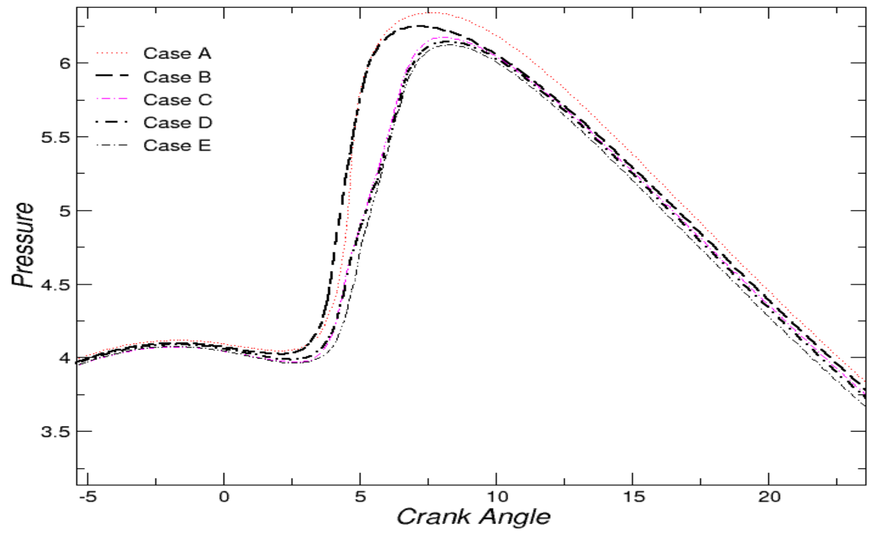


- A mesh is too coarse
- C,D,E meshes are converged
- B is a good compromise between CPU and accuracy

MESH RESOLUTION STUDY

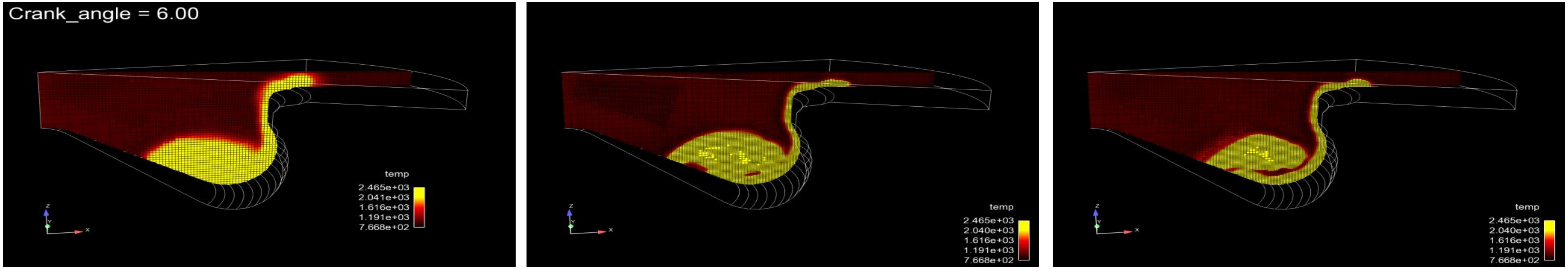
- Comparison of temperature and pressure for different meshes

	A	B	C	D	E
Dx_base	2.8	1.4	0.7	1.4	1.4
Embed scale	2	2	2	3	4
Dx_min	0.7	0.35	0.175	0.175	0.0875



Cylinder pressure

Temperature in cut plane

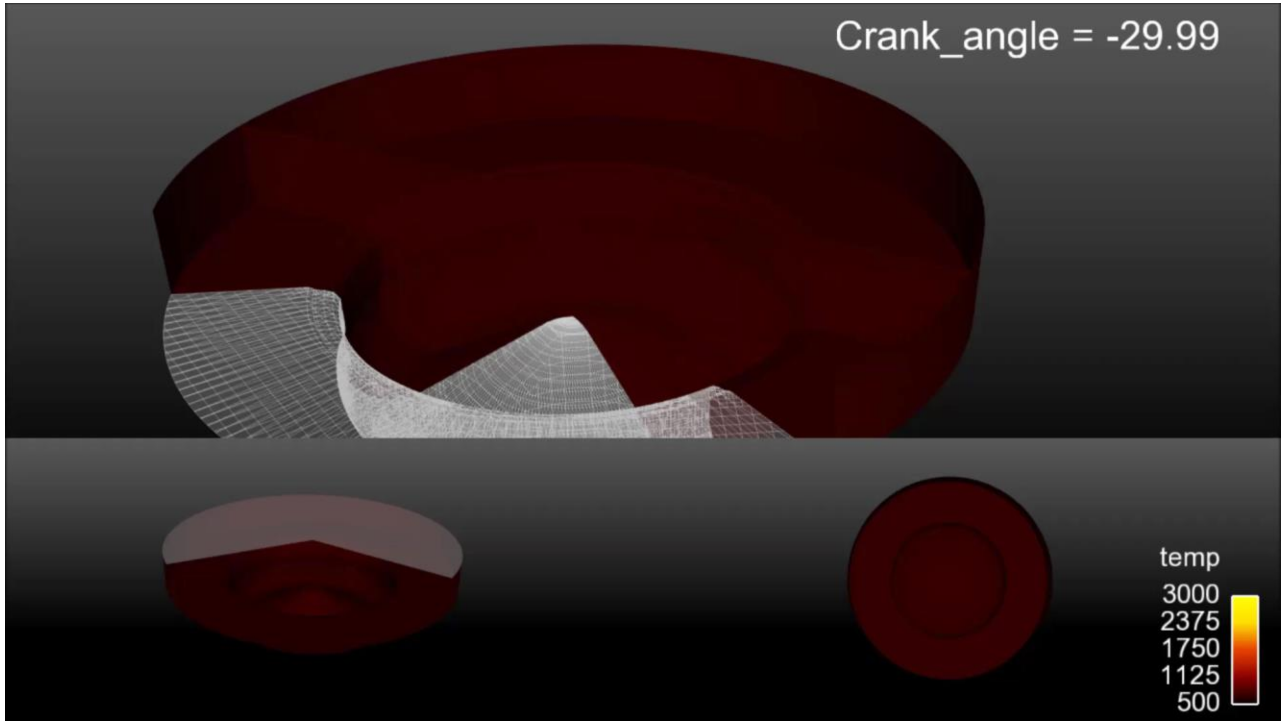


B → C → D

MESH RESOLUTION STUDY

	A	B	C	D	E
Dx_base	2.8	1.4	0.7	1.4	1.4
Embed scale	2	2	2	3	4
Dx_min	0.7	0.35	0.175	0.175	0.0875

- Embedded zone around the spray
- AMR on temperature / velocity
- Set AMR to C case
- ECFM3Z with the Anderlhor kinetic mechanism



Temperature field

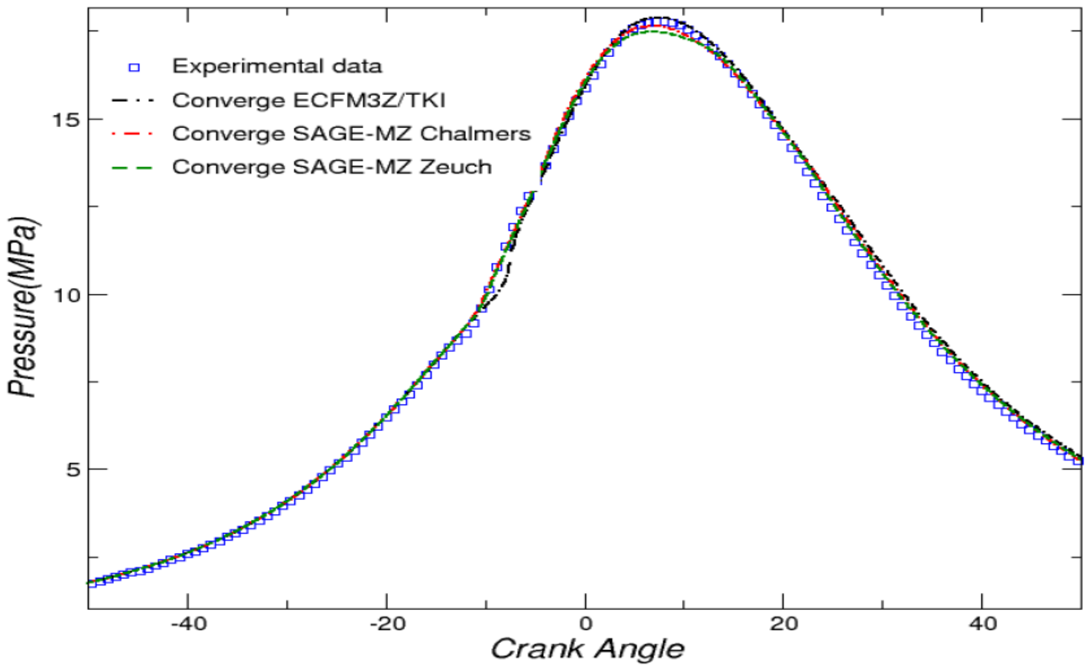
CPU TIME OF ECFM3Z COMPARED TO SAGE

SUSTAINABLE MOBILITY

- Mesh B is used
- Very similar results between ECFM3Z and Sage
- CPU cost reduction by 3.5 to 11 with ECFM3Z compared to Sage with multi-zone enabled

	A	B	C	D	E
Dx_base	2.8	1.4	0.7	1.4	1.4
Embed scale	2	2	2	3	4
Dx_min	0.7	0.35	0.175	0.175	0.0875

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

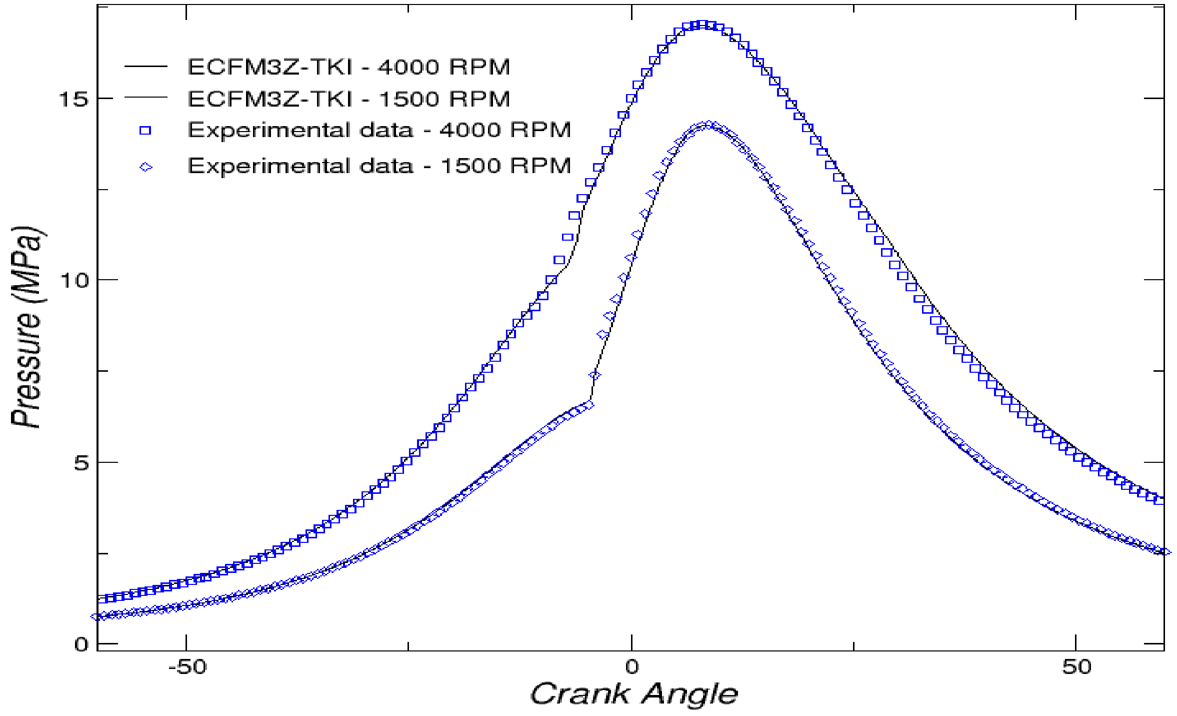


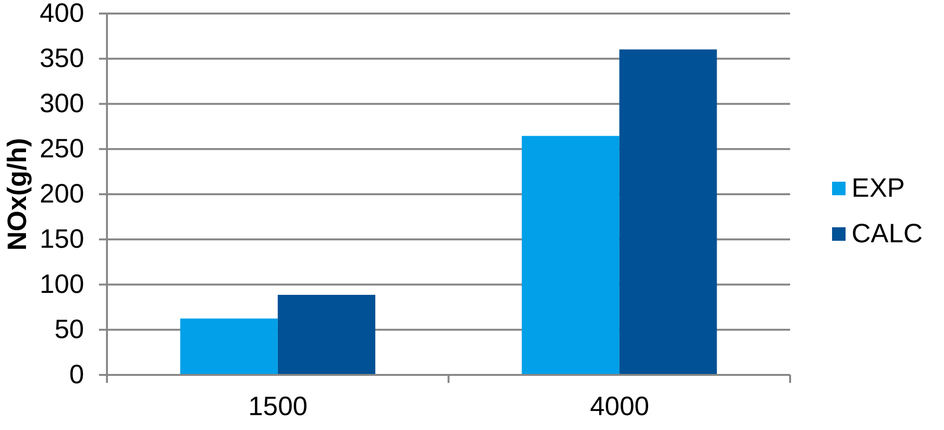
	Normalized Simulation return time
ECFM3Z/TKI Anderlohr	1
SAGE MZ Chalmers	3.43
SAGE MZ Zeuch	10.84

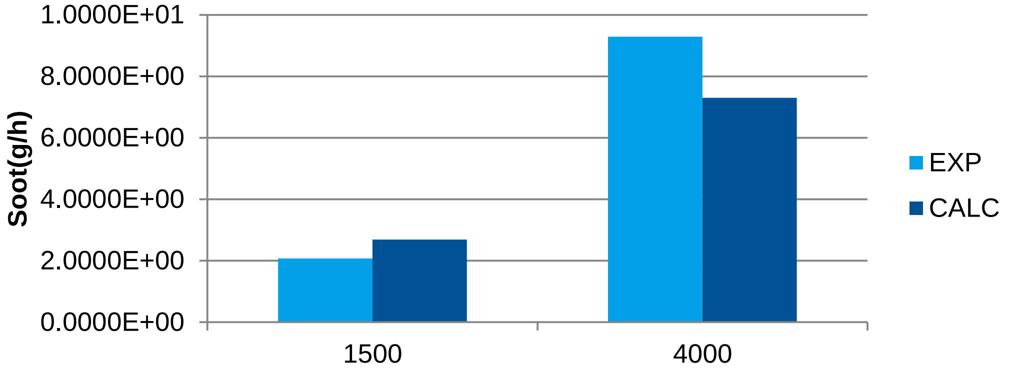
ECFM3Z RESULTS ON DIESEL DATABASE

1500 and 4000 rpm at full load

- Good prediction of pressure
- Good NOx and soot prediction





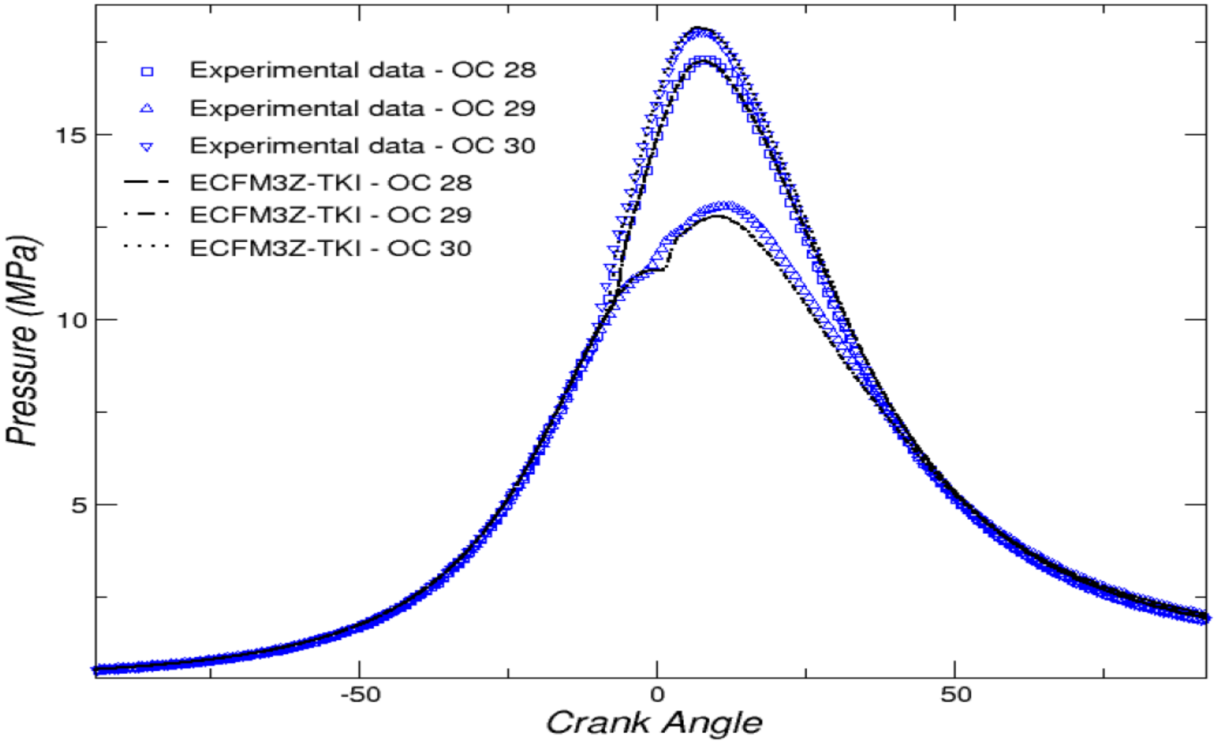


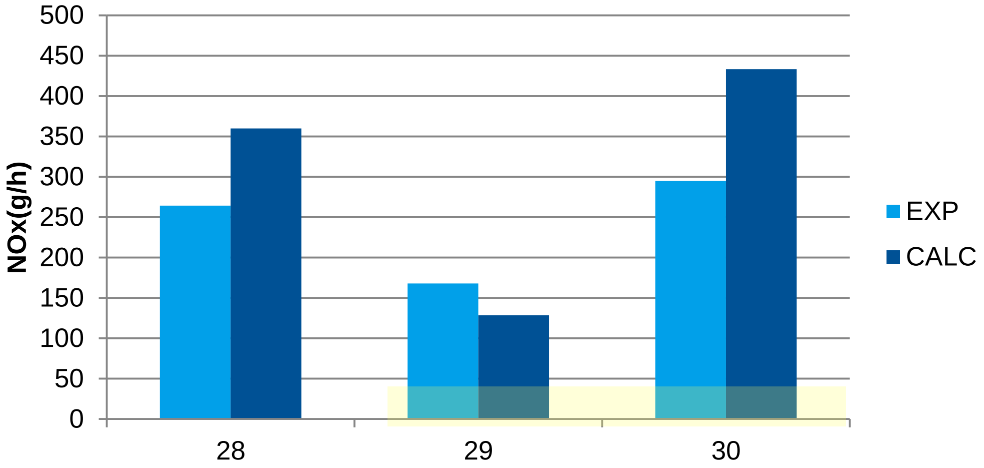
ECFM3Z RESULTS ON DIESEL DATABASE

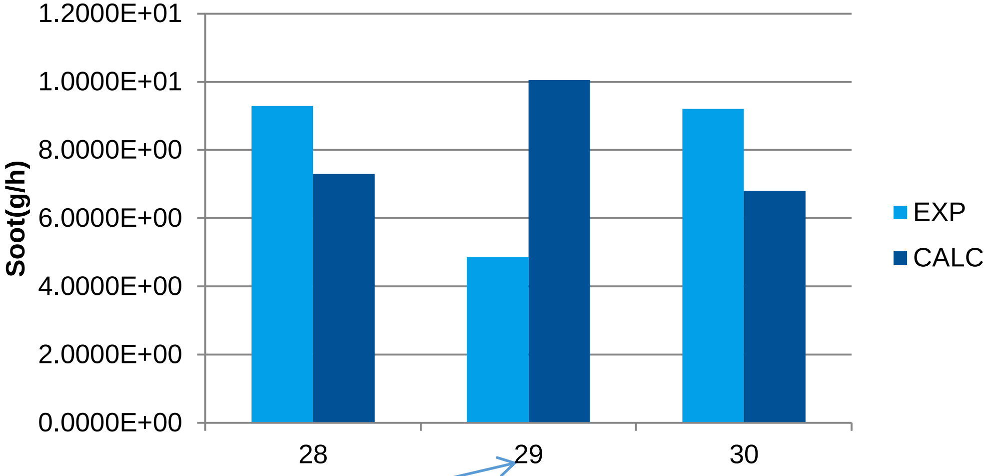
OC	28	29	30
SOI1 SOI2	-14.2	-5.2	-16.2

4000 rpm at full load – SOI variation

- Good pressure prediction
- Reasonable NOx and soot prediction
- Difficulty for late injection case







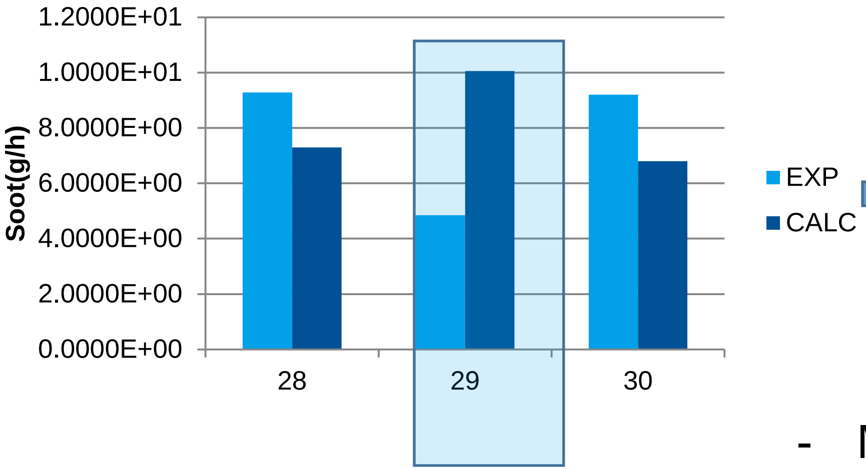
Late injection

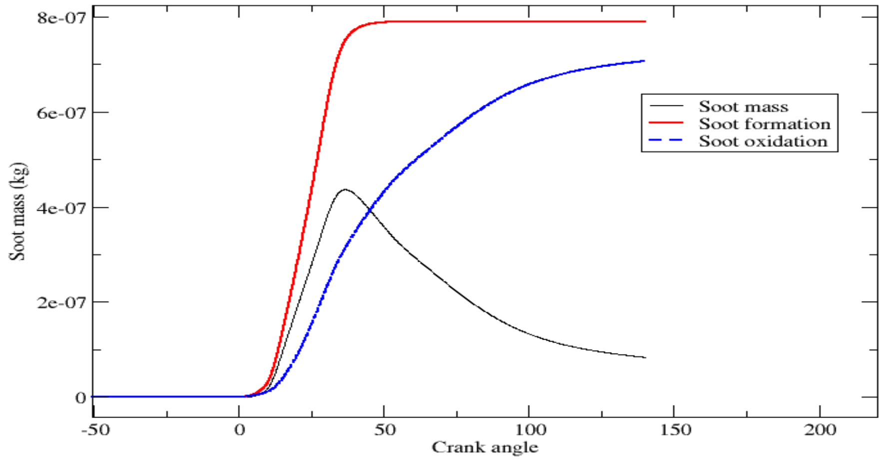
INSTITUT CARNOT IFPEN Transports Energie

IFP Energies nouvelles

ECFM3Z RESULTS ON DIESEL DATABASE

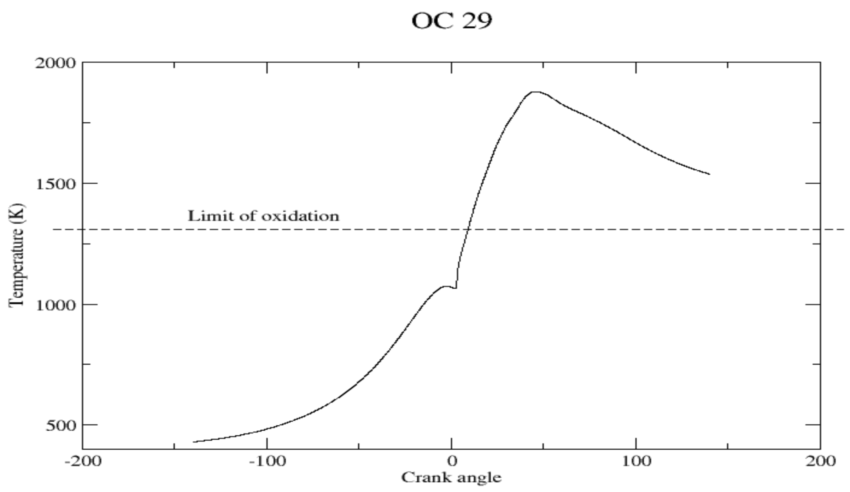
Operating point 29

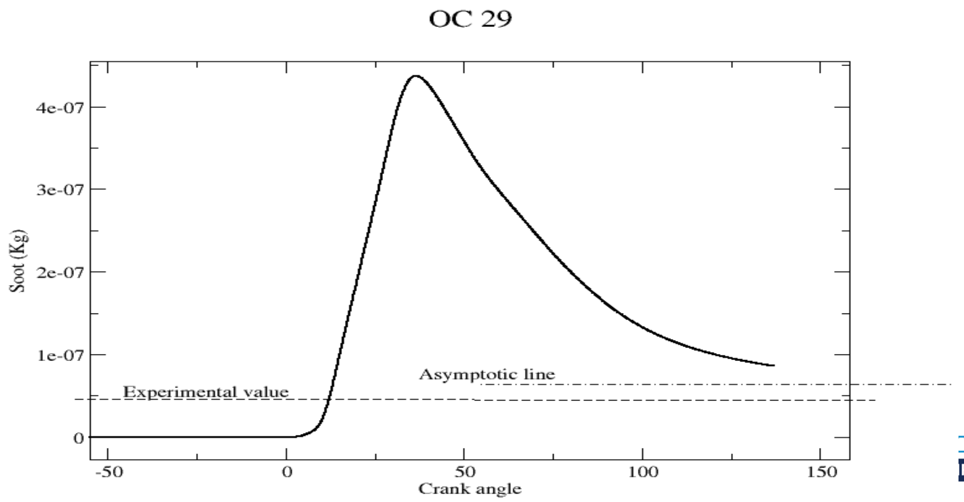




- Maximum mass soot produced at +25 CAD
- Oxidation of soot are not finalised at +140CAD

→ Oxidation during the start of the exhaust phase

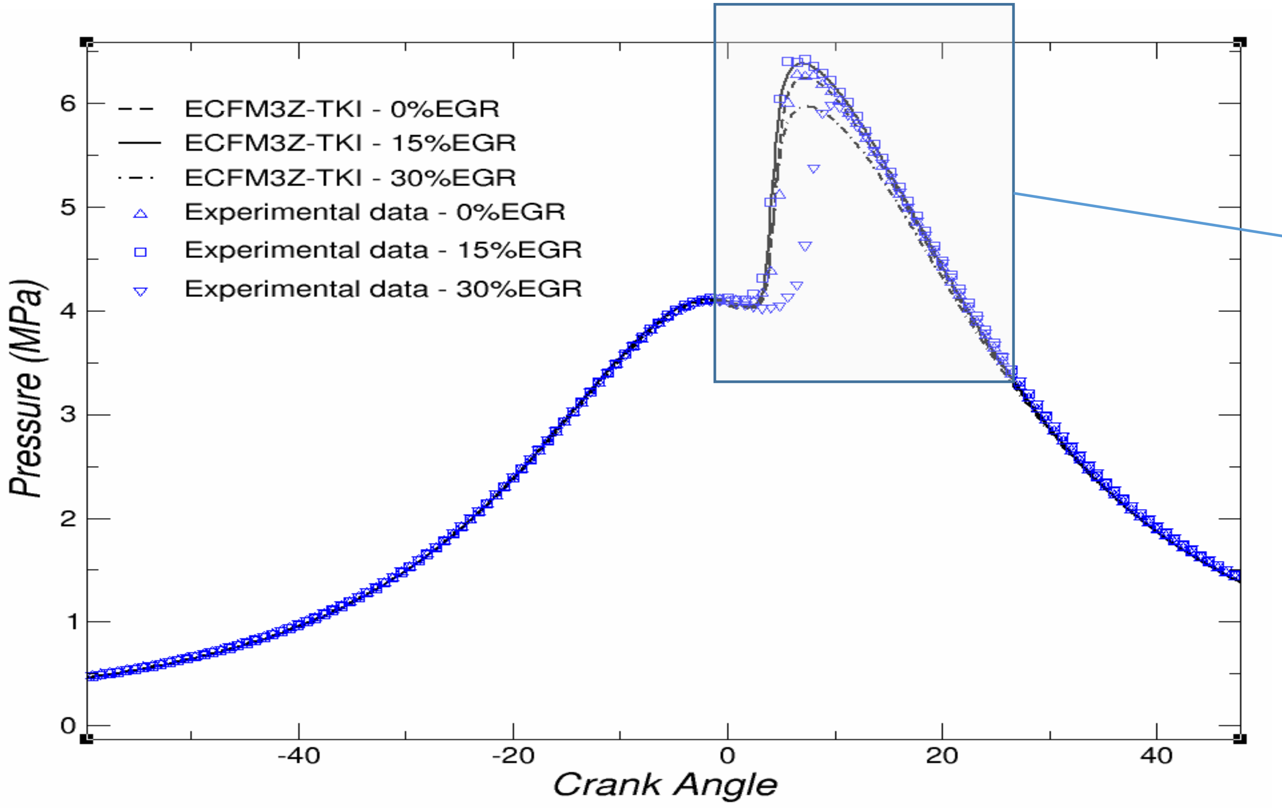


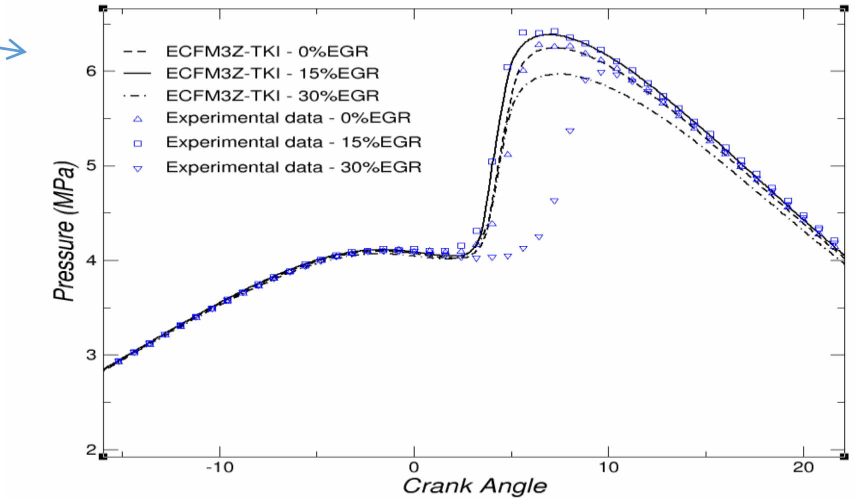


ECFM3Z RESULTS ON DIESEL DATABASE

1500 partial load – EGR variation

- Good prediction of pressure for 0 and 15% cases
- Under-prediction of auto-ignition delay for 30% case (possible causes: mechanism, strain effect)

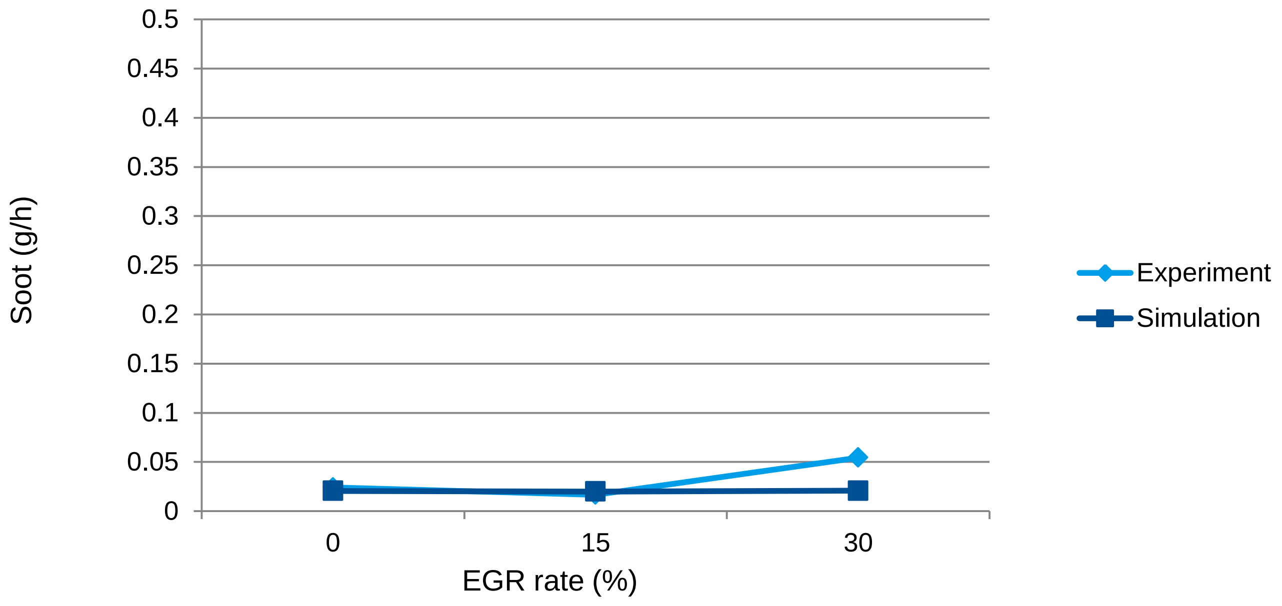


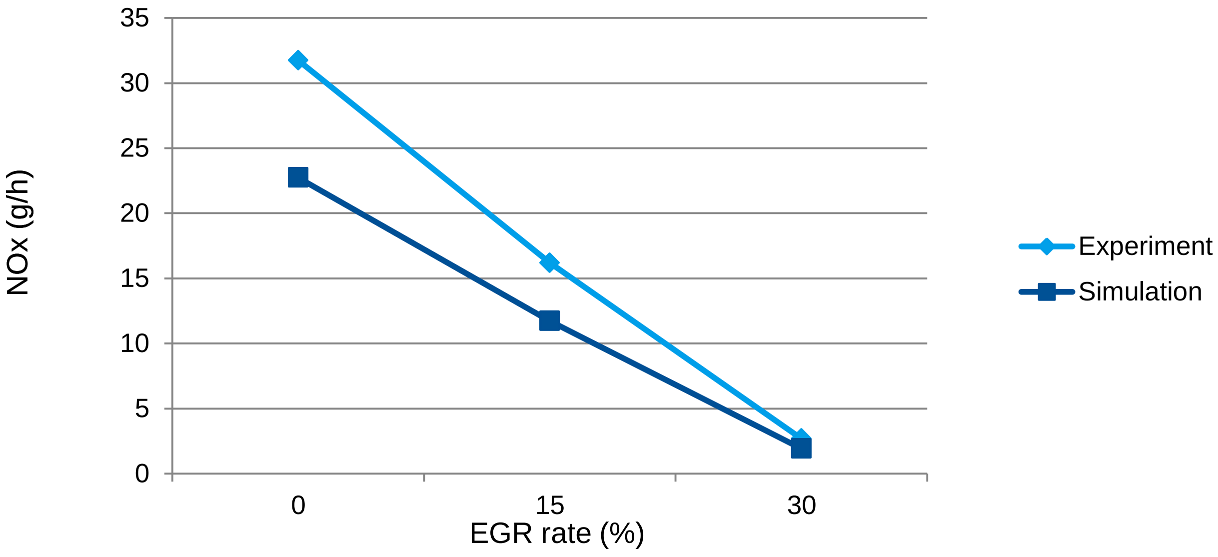


ECFM3Z RESULTS ON DIESEL DATABASE

1500 partial load – EGR variation

- Good prediction for NOx
- Soot increase at 30% not reproduced





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OUTLOOK OF THE PRESENTATION

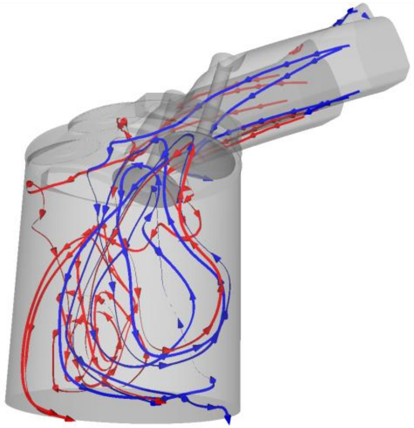
- The ECFM3Z combustion model
- Diesel application
- SI application
- Future developments in Converge
- Conclusions

EXPERIMENTAL SET UP AND METHODOLOGY

SUSTAINABLE MOBILITY

- ICAMDAC single cylinder engine
  - Description
    - Experimental set up dedicated to abnormal combustion study
    - Representative of an up to date SI engine (turbocharged, direct injection)
    - Two experimental devices : optical engine and full metal engine
  - Optical engine

    - High frequency sensors
    - PIV visualization
  - Full metal engine
    - High frequency sensors
    - Combustion analysis



- Numerical set-up definition
- Fluid motion comparisons

➔One operating point :

- **engine speed 1800rpm IMEP 19 bar**

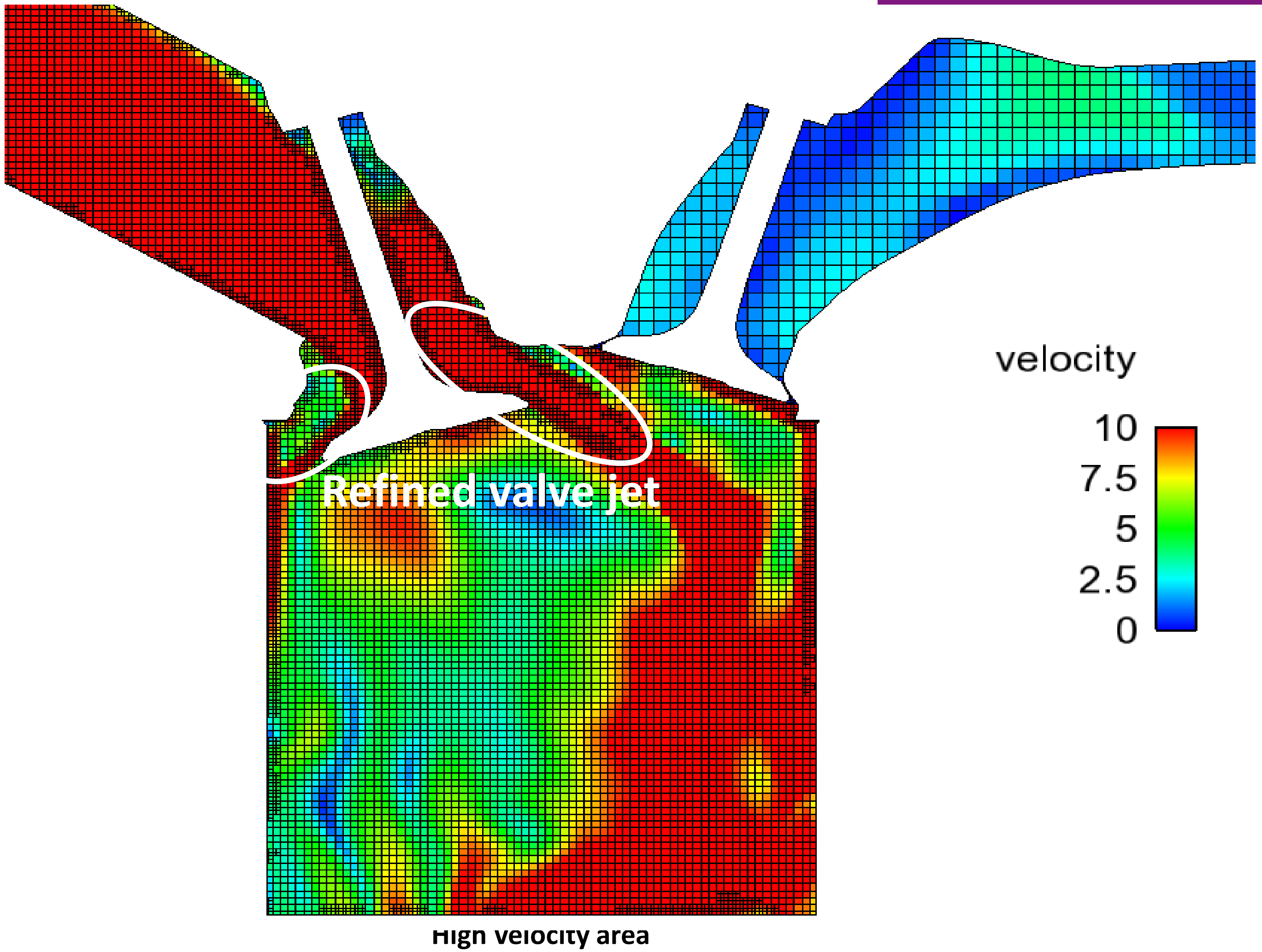
- Model calibration
- Combustion comparisons

➔Five operating points :

- **engine speed 1800rpm IMEP 19 bar**
- **engine speed 1200rpm IMEP 20 bar**
- **engine speed 4000rpm IMEP 19 bar**
- **engine speed 1200rpm IMEP 6 bar**
- **engine speed 3000rpm IMEP 6 bar**

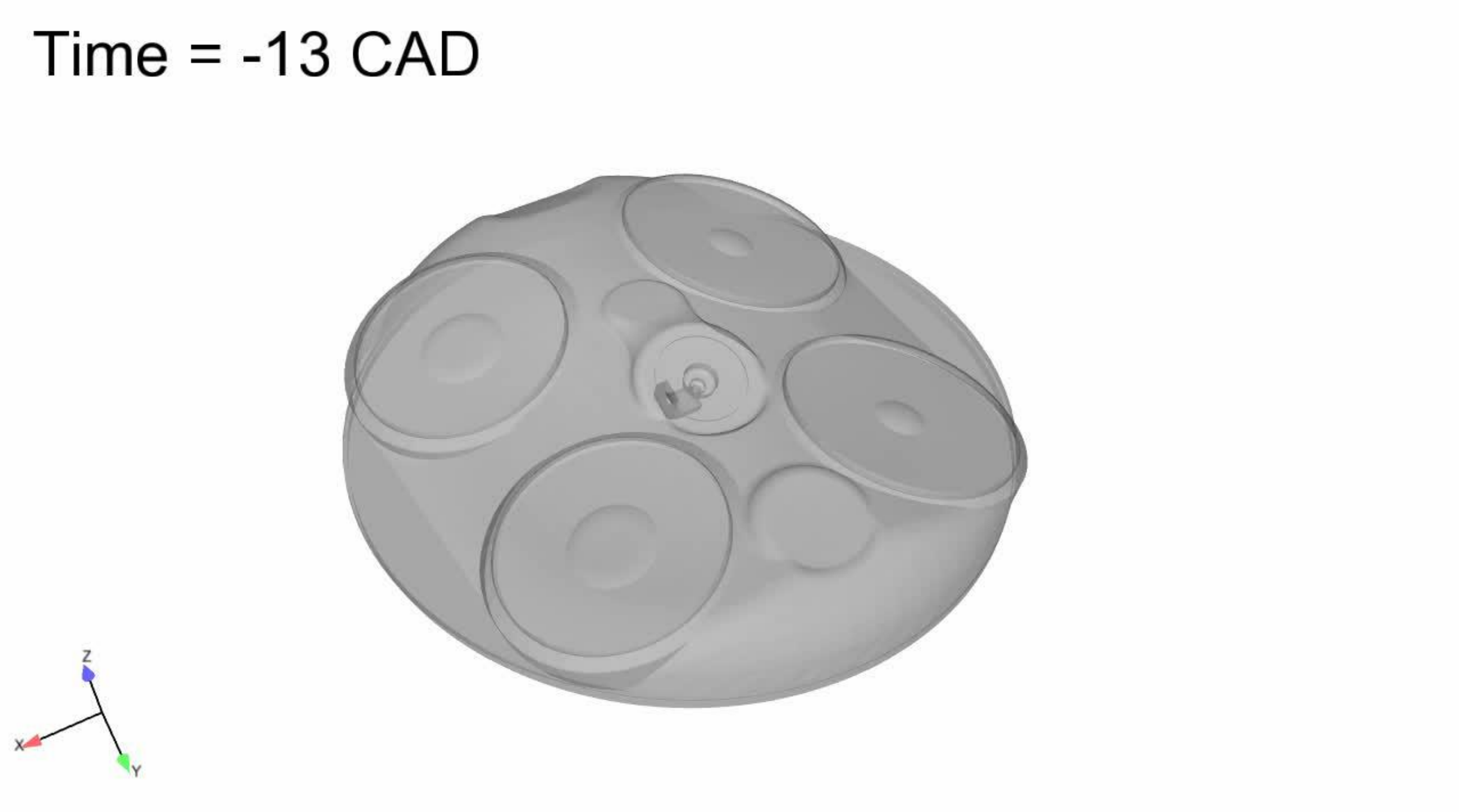
OPTICAL ENGINE

- Numerical setup validation
  - Embedding area
  - AMR levels
  - Turbulent model



FULL METAL ENGINE

- ECFM3Z simulation
  - 1800rpm 19 bar operating point with spark timing set at the knock limit

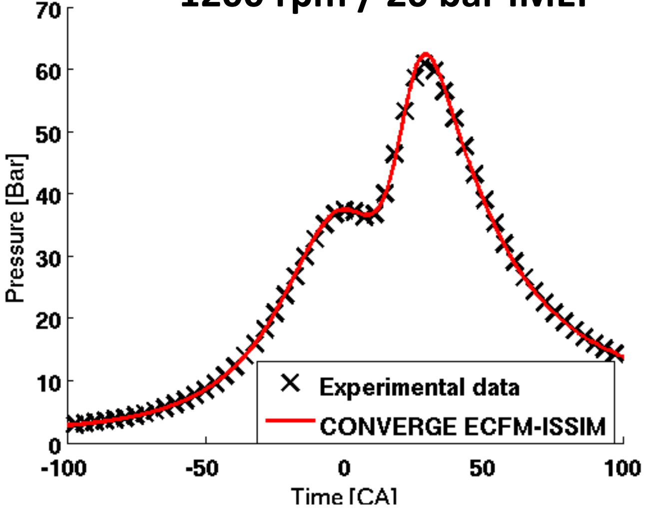


  - ECFM approach allows to record the flame front displacement

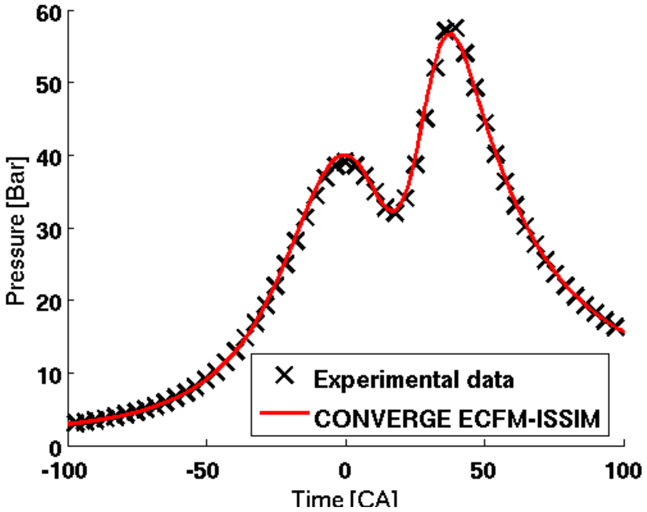
ECFM VALIDATION

- **Perfect agreement with experiment**
- **Only two parameters have been adjusted**
  - α : turbulent strain in Σ equation of ECFM
  - Ξ_{ign}: initial flame kernel wrinkling in ISSIM
- **For the whole data base**
  - Experimental spark timing is used
  - α is close to unity (between 1.1 and 1.5)
  - Ξ_{ign} between 7 for low load OP and 13 for high load OP

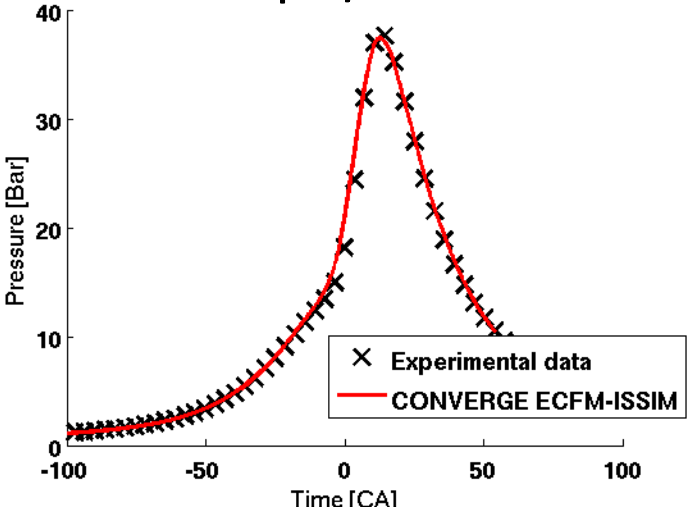
1200 rpm / 20 bar IMEP



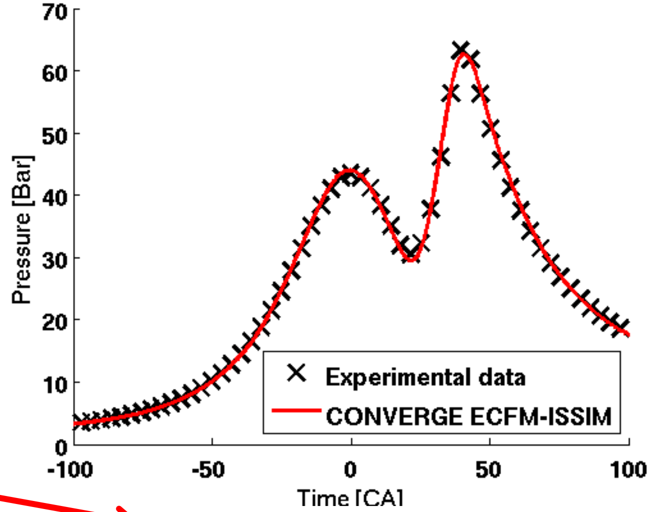
1800 rpm / 19 bar IMEP



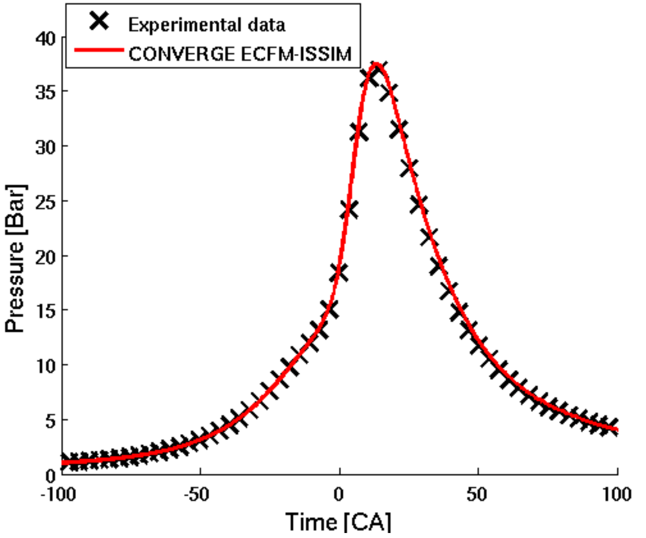
1200 rpm / 6 bar IMEP



4000 rpm / 19 bar IMEP



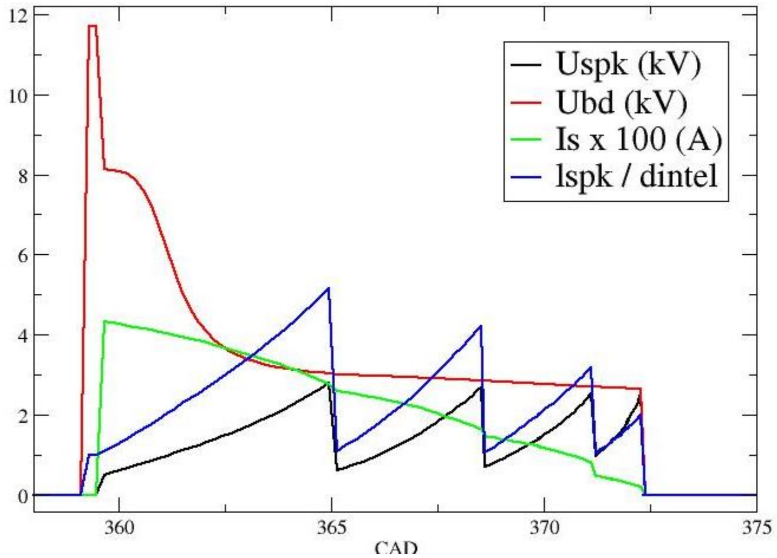
3000 rpm / 6 bar IMEP



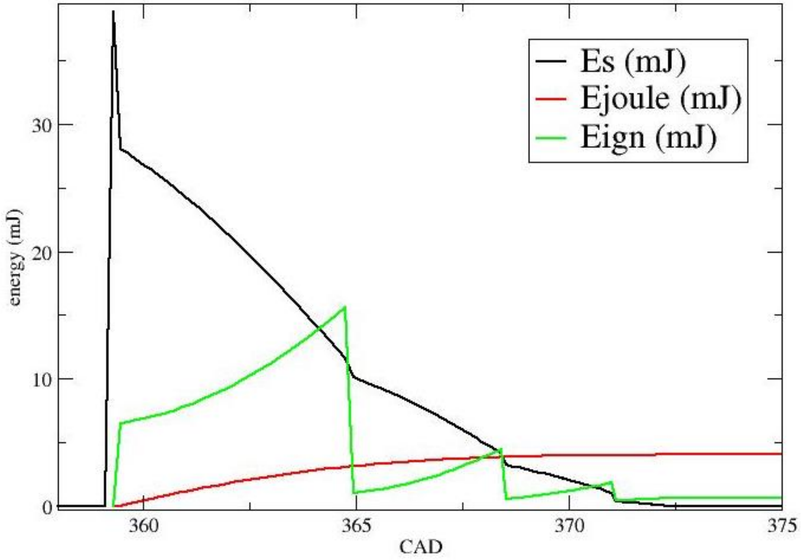
ISSIM IGNITION SEQUENCE (4000RPM/19 BAR)

SUSTAINABLE MOBILITY

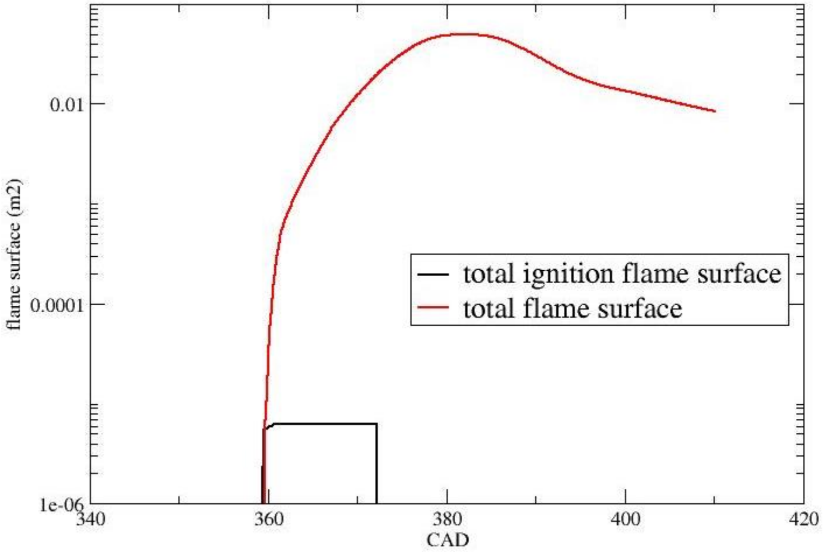
- Current and voltage



- Electrical energy



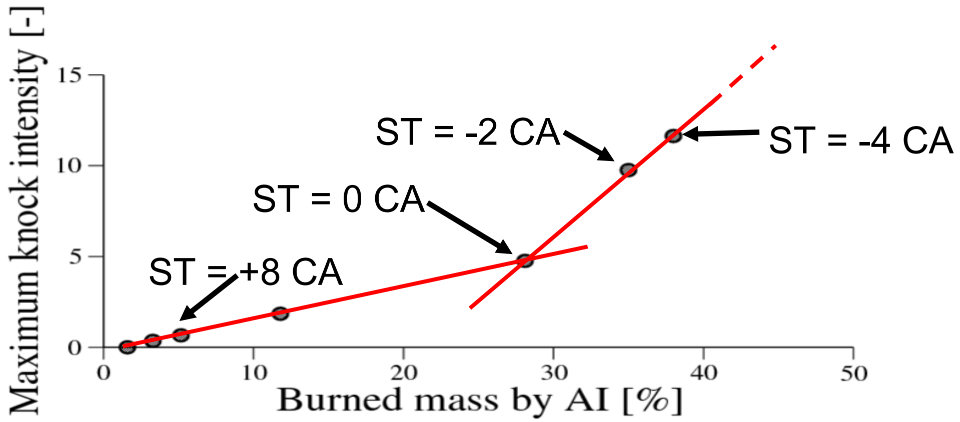
- Flame surface



KNOCK VALIDATION METHODOLOGY

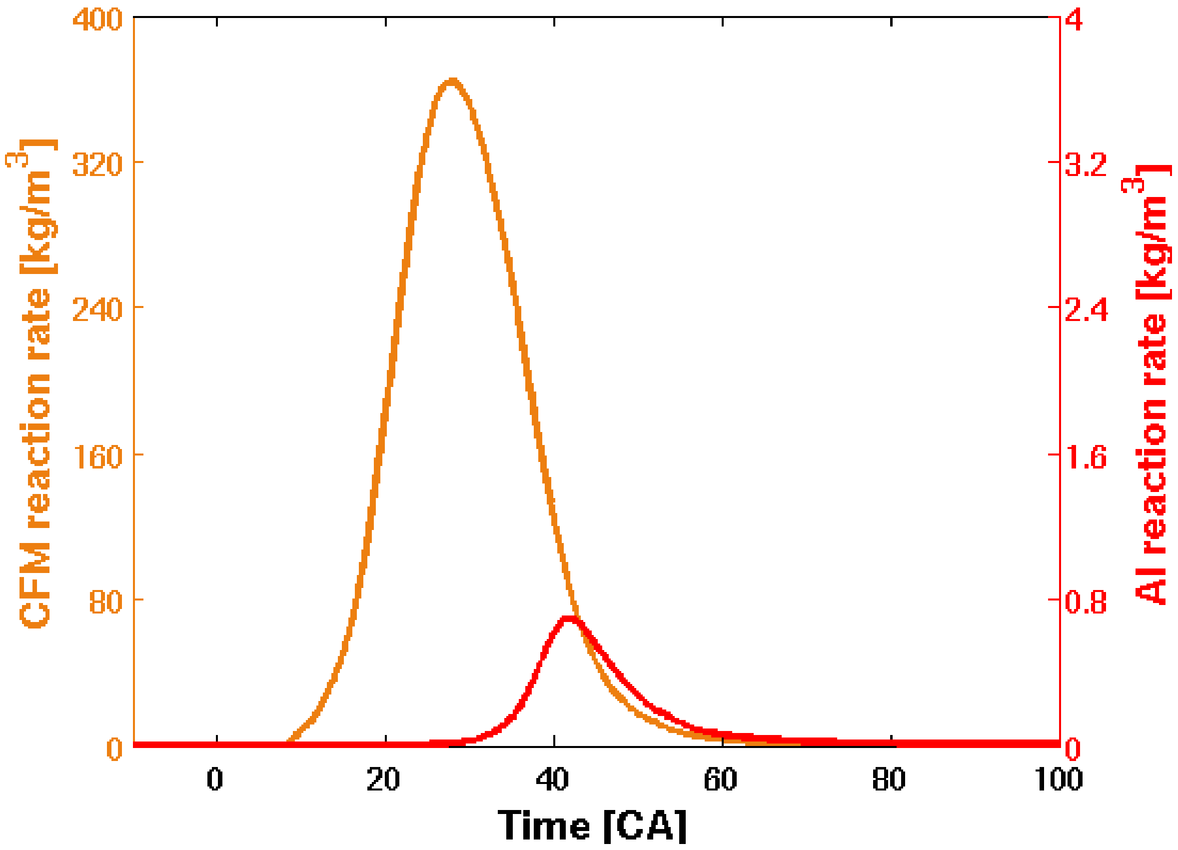
SUSTAINABLE MOBILITY

- Direct comparison of pressure with experiments is difficult
  - At test bench knock detection is performed recording pressure and applying high pass filter to get pressure fluctuations
  - In LES, these pressure fluctuations could be reproduced [1]
  - In RANS, pressure fluctuations are damped because:
    - the mean fresh gases mass given by RANS is much smaller than the instantaneous fresh gases mass of a knocking cycle=> the pressure fluctuation will be under-predicted
    - large time-step (to save CPU time) tend to damp pressure fluctuations
- It was shown in LES that the fresh gases mass burned by auto-ignition is proportional to the experimental knock index [1]
  - This fact is used here to define a Computational Knock Index that can help determining the knock limit



[1] Robert et al. , PCI, 2015

- Premixed and AI HRR for the 1800rpm/19bar OP



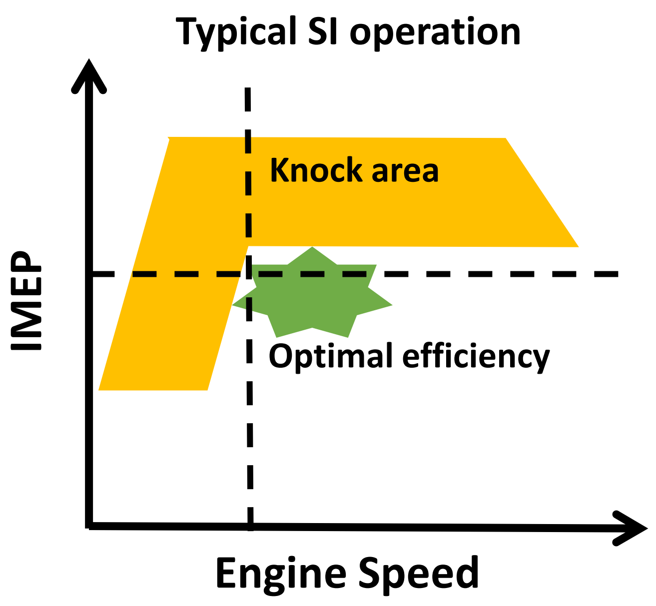
- Computational Spark Advance (SA) is set to the knock limited SA defined @ test bench
- Reaction rate linked to flame propagation is more than 1000 times larger than AI reaction rate
- Auto-ignition (knock) occurs late in the combustion process (maximum @ BMF ~0.8)
- Integrating AI reaction rate and comparing with global reaction rate allows to define a “Computational Knock Index” CKI:

$$CKI = \frac{\int \dot{\omega}_F^{ai} dV}{\int \dot{\omega}_F^{\Sigma} dV + \int \dot{\omega}_F^{ai} dV}$$

KNOCK VALIDATION METHODOLOGY

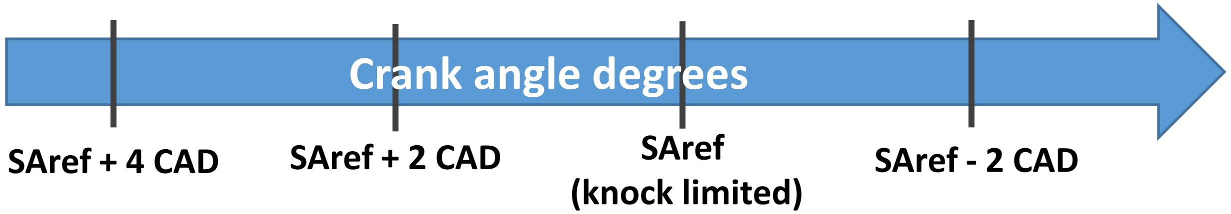
- The goal is to check if ECFM and TKI models are able to reproduce main trends concerning knock with the CKI

@ iso –Engine speed :
- Knock intensity increases with the load
- Higher loads lead to tougher thermodynamic conditions which reduces AI delays

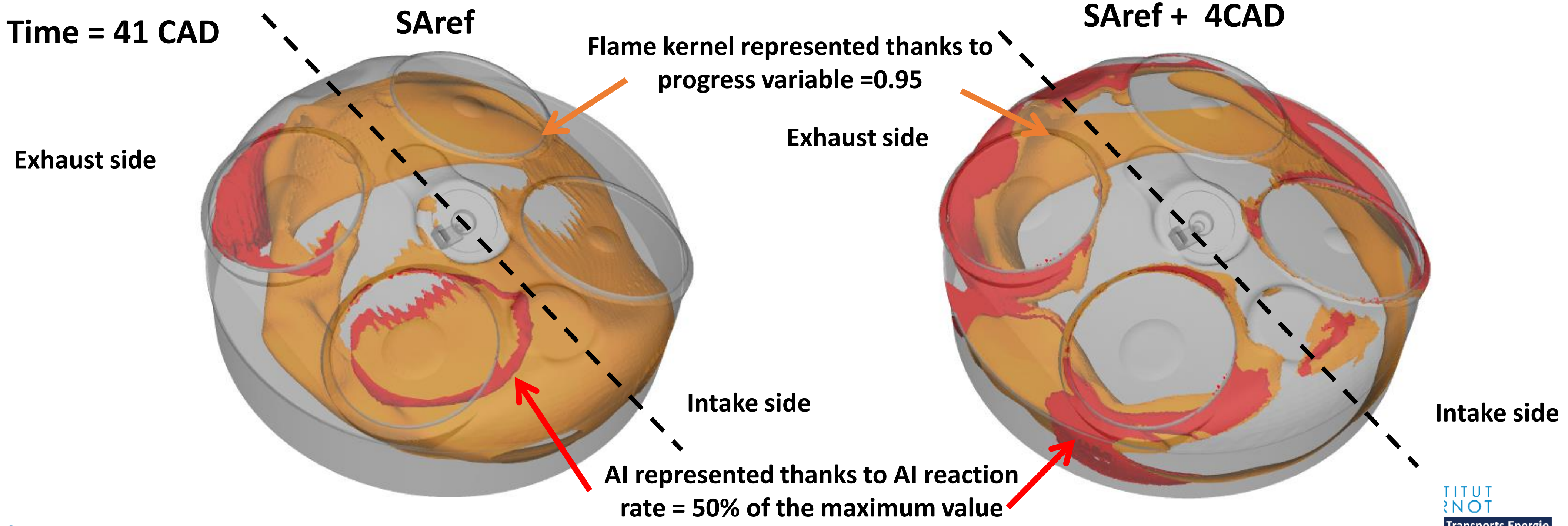


@ iso -IMEP :
- Knock intensity decreases with engine speed
- Larger engine speed leads to lower residence time and therefore lower AI

- Methodology

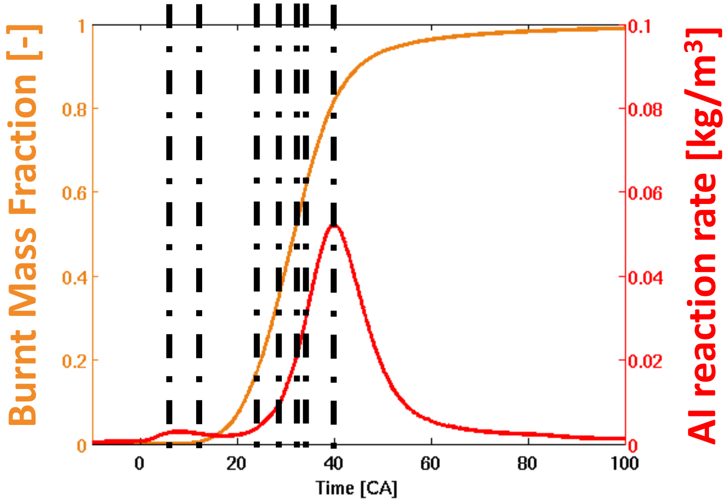


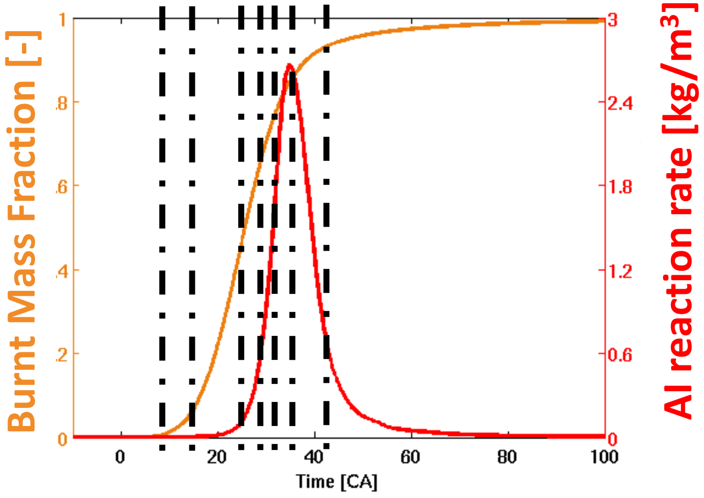
- Field analysis : Visualization of flame kernel and AI spots



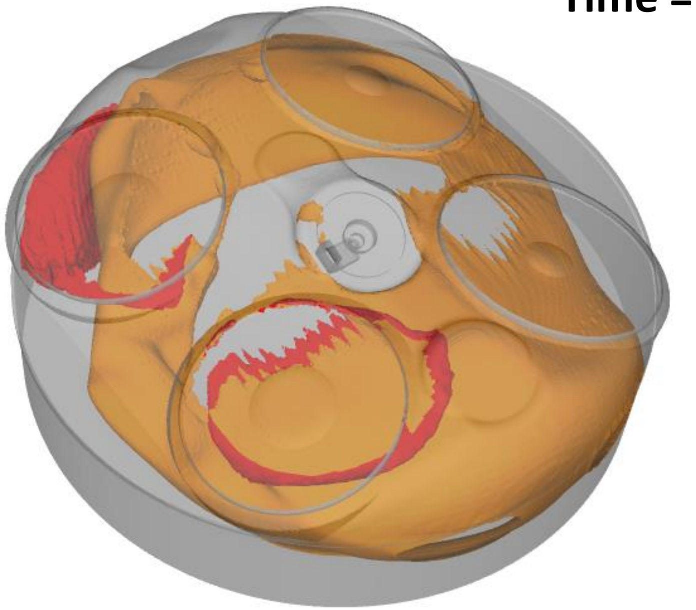
KNOCK INVESTIGATION : SPARK TIMING SWEEP ON 1800RPM/19BAR

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

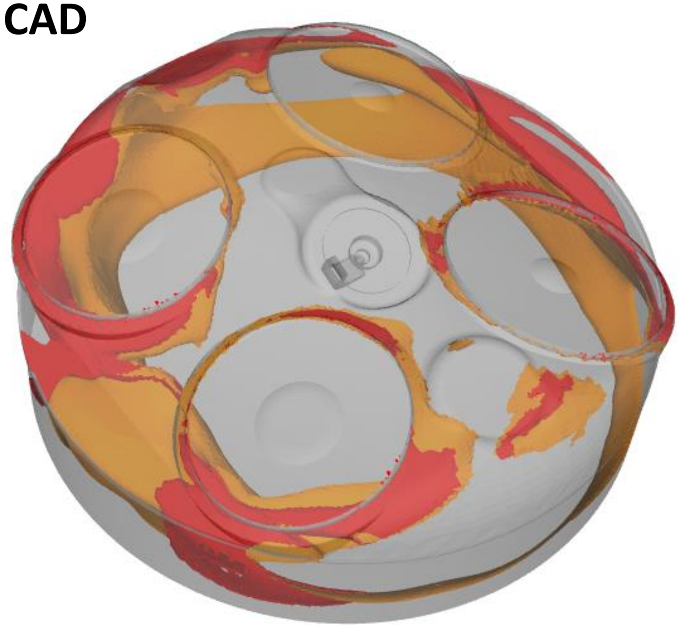




Time = 41 CAD



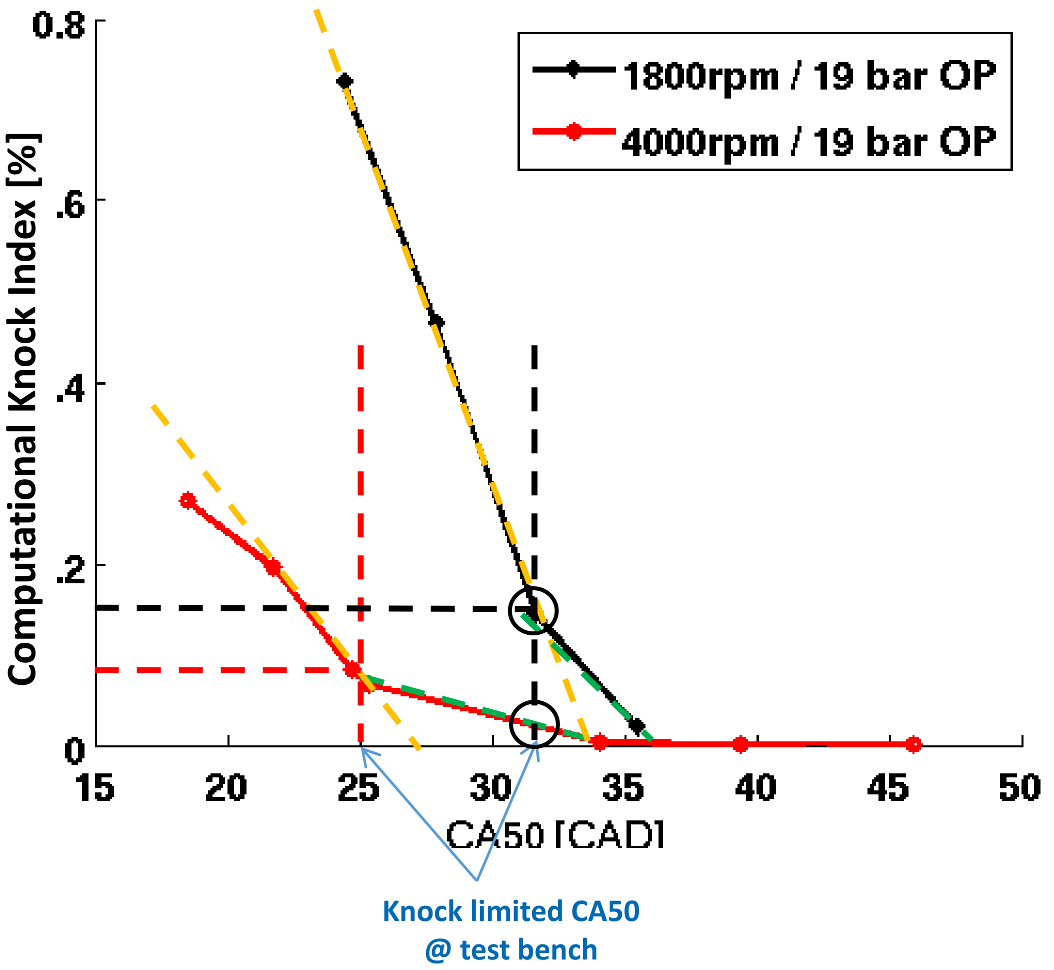
SAref



SAref + 4

ANALYSIS OF CKI : DEPENDENCY TO ENGINE SPEED

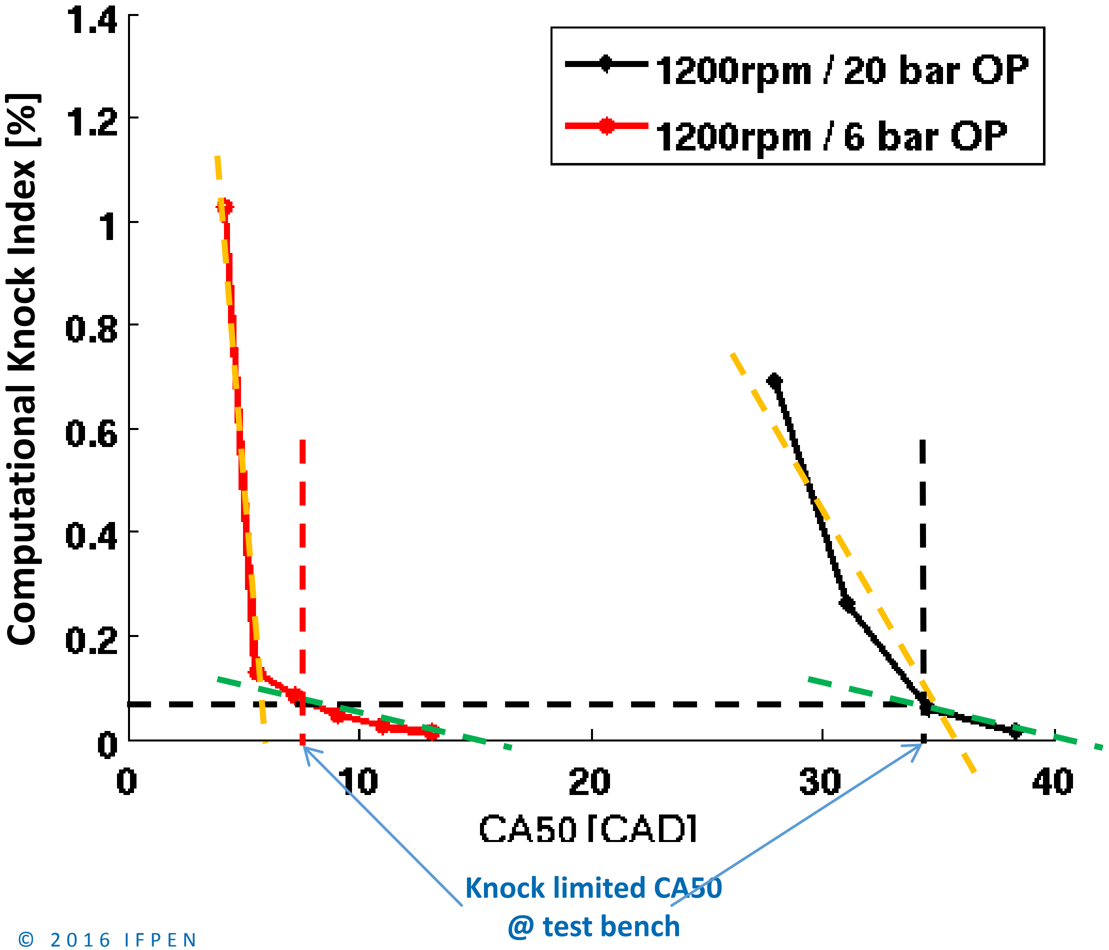
Comparison between 1800rpm/19bar OP and 4000rpm/19bar OP



- Low increase of CKI at large CA50 like in experiment
- Steep increase of CKI close to experimental knock limited CA50
  - CKI recovers qualitatively the knock limit
- Larger value of CKI at knock limit for low engine speed
  - Expected result: longer residence time at low engine speed =>more time to auto-ignite
  - A single value of CKI cannot be defined for the whole map
  - A more complex index needs to be defined in the future
- Sensitivity of knock to SA is larger at low engine speed (i.e. slope is steeper for 1800rpm OP)
- Results fully coherent with experimental observations

ANALYSIS OF CKI: DEPENDENCY TO IMEP

Comparison between 1200rpm/6bar and 1200/20bar operating points



- High load OP
  - Low increase of CKI at large CA50 like in experiment
  - steep increase of CKI close to experimental knock limited CA50
  - CKI recovers again the knock limit qualitatively
  - Value of CKI again different from other high load operating points
- Low load OP
  - slope of CKI remains low at experimental optimal CA50
  - means that CKI recovers that this OP is not limited by knock
  - strong knock (i.e. slope steepening) is observed after the optimal CA50

ANALYSIS OF CKI: HIGH LOAD LIMIT

- CKI varies with engine speed at high load

	1200rpm/20bar	1800rpm/19bar	4000rpm/19bar
Optimal exp. CA50	32	32	25
CKI at opt.exp. CA50	0.26	0.15	0.08

- CKI x rpm is nearly constant for three high load points
- Indicates a new definition of a computational knock index based on HRR by auto-ignition could work better

CPU TIME FOR SI ENGINE

- Low CPU time for a complete cycle

case	1200rpm/20bar	4000rpm/19bar
Elapsed CPU time (on 32 procs)	31h	22h

- Low mesh resolution requirement
  - Base grid in the cylinder: dx = 0.5mm
  - Refinement at spark plug and walls: dx=0.25mm

OUTLOOK OF THE PRESENTATION

- The ECFM3Z combustion model
- Diesel application
- SI application
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- Conclusions

OUTLINE OF ECFM3Z DEVELOPMENT ROADMAP IN CONVERGE

- Available in V2.3.16
  - ECFM3Z as described in this presentation
  - ISSIM
  - TKI and KicGen generator (contact CSI for table generation)
  - Simple NOx and soot models

- Short term developments
  - Multi-fuel description in ECFM3Z and TKI
    - Allows better fuel evaporation and auto-ignition description (multi-component)
  - Simple dual-fuel flame surface density source term
    - Allows dual fuel calculation (e.g. Diesel fuel + natural gas)

OUTLINE OF ECFM3Z DEVELOPMENT ROADMAP IN CONVERGE

- Longer term developments
  - ADF-TKI for Diesel: improved TKI model accounting for effect of strain on auto-ignition [1]
    - Improved lift-off length
    - Improved auto-ignition delays at low loads (cases with long ignition delays)
  - Kinetic solver in burned gases (Sage)
    - Effect of fuel formulation on HRR
    - Minor species prediction enabled (HC)
    - PAH description (for soot)
  - Sectional soot model coupled to ECFM3Z
    - Better prediction of soot mass and number (Diesel and gasoline)
    - Access to soot size distribution
  - High Karlovitz ECFM model
    - Better prediction of premixed flame HRR at high turbulence and EGR rates

[1] Michel et al., CF, 2008

CONCLUSIONS

- ECFM3Z fully revised by IFPEN now available in Converge
- Diesel engine simulations
  - Good prediction of pressure and pollutants
  - Low CPU times compared to Sage
- Gasoline engine simulations
  - Very good prediction of pressure with minor parameters adjustment
  - Good ability to predict knock occurrence with proposed computational knock index
  - Low CPU times compared to other models
- Further model improvements to come in a long term collaboration with CSI

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