LES Simulations in a Lean SI Optical Engine Using Thickened Flame Model

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CONVERGENT SCIENCE

UNIVERSITÀ DEGLI STUDI DI PERUGIA

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Lean combustion and stability

Large-Eddy simulations (LES) are becoming an engineering tool for studying internal combustion engines (ICE)

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able to capture cycle-to-cycle variability resolving most of the turbulent flow structures

ICEs can operate under lean combustion conditions to maximize efficiency

↓

instabilities associated with lean combustion may cause problems, (excessive levels of cycle-to-cycle variability or even misfires)

In this context, the interaction between the igniter and the flow field is a fundamental parameter that affect ignition stability and how combustion takes place and develops

Outline

1. Experimental Setup
   - Optical access SI engine
   - Ignition systems tested in Perugia University

2. CFD Model Setup

3. TFM combustion model
   - Why TFM?
   - Flame sensor
   - Thickening option and AMR
   - Efficiency function
   - Effect of the calibration parameters

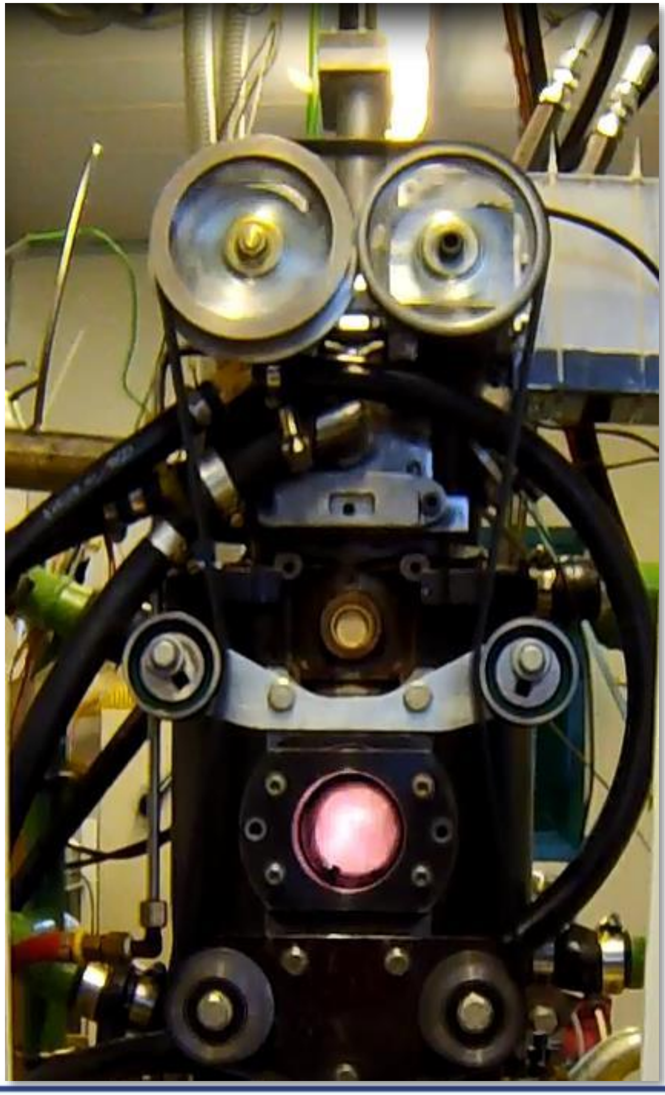
4. Cycle to cycle variability prediction
   - TFM 3D output
   - Mass fraction burned at different λ
   - Flame comparison at different λ

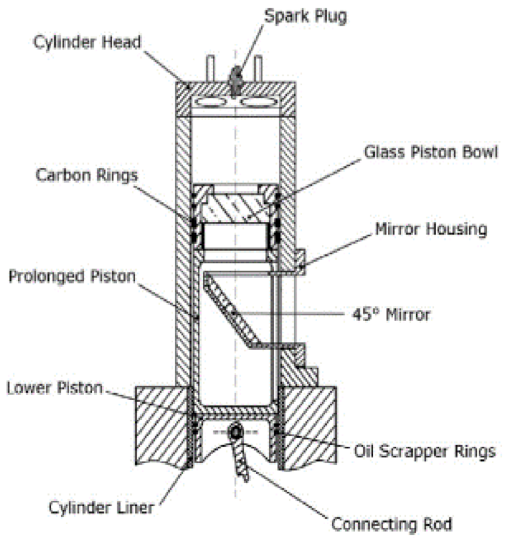
5. Conclusions and next steps

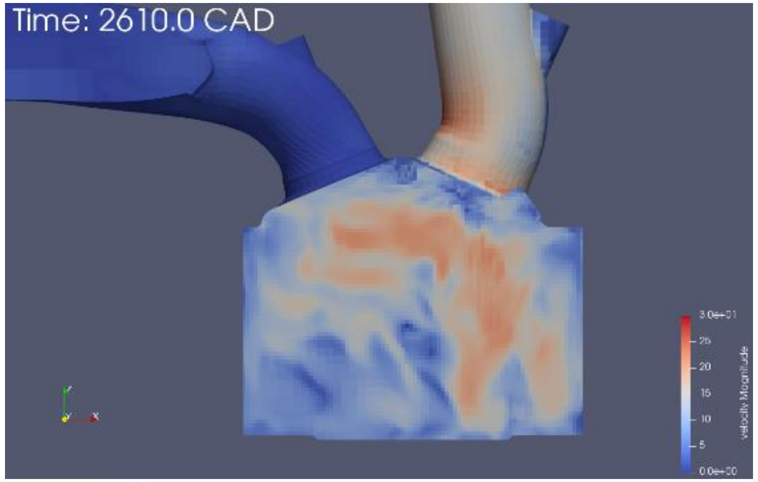
Optical access SI engine

Single cylinder optical engine	
No. of valves	4
Bore	85 mm
Stroke	88 mm
Fueling	PFI (or DI)
CR	9
Chamber type	Pent-roof
Optical access	Bowditch type

Conditions (low load & speed)	
IMEP	~ 5 bar (@ λ=1)
Speed	1000 rpm
λ	1.0 --> lean limit
Spark Advance	Adjusted to MBT
Modes	Fixed throttle, varying injected fuel Fixed fuel, varying air via VVA
Spark Advance	Adjusted to MBT
Fuel	Gasoline, Methane, Hydrogen-Methane blends



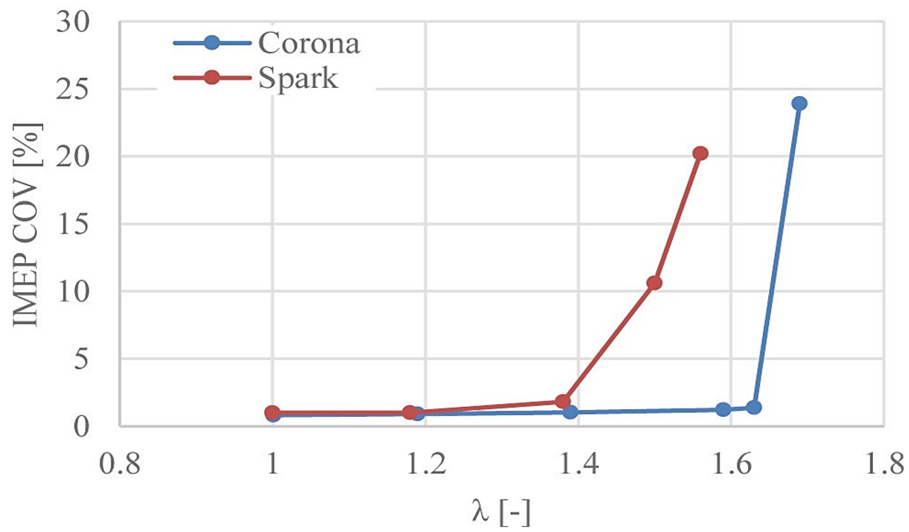




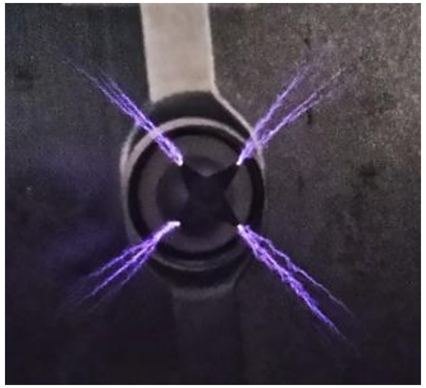
Ignition systems tested in Perugia University

Conventional Spark

High temperature plasma



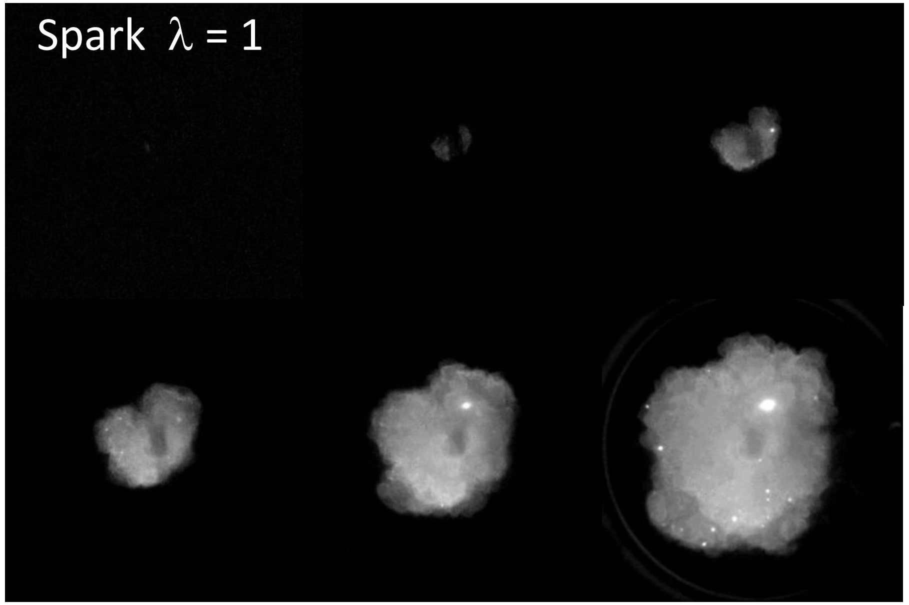
Advanced Corona Ignition System

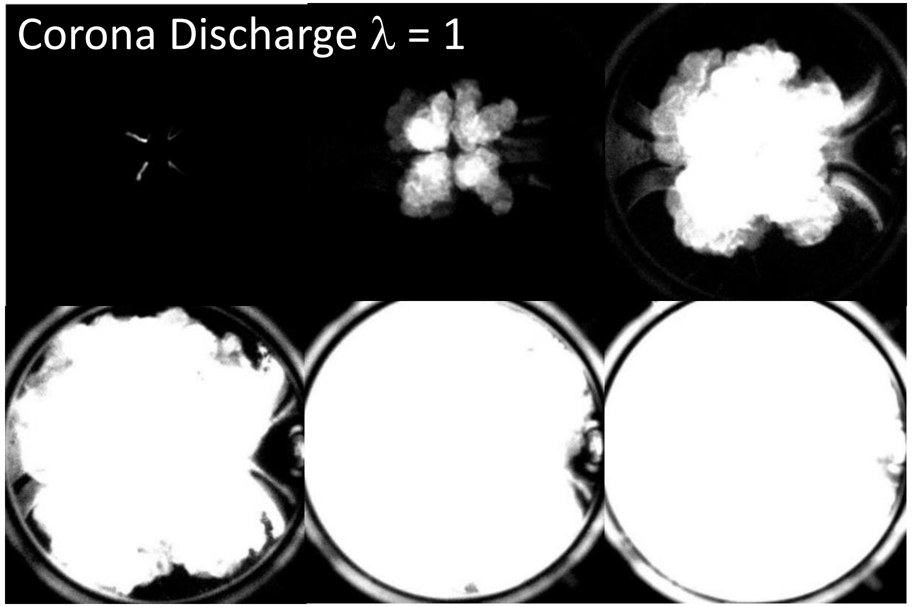


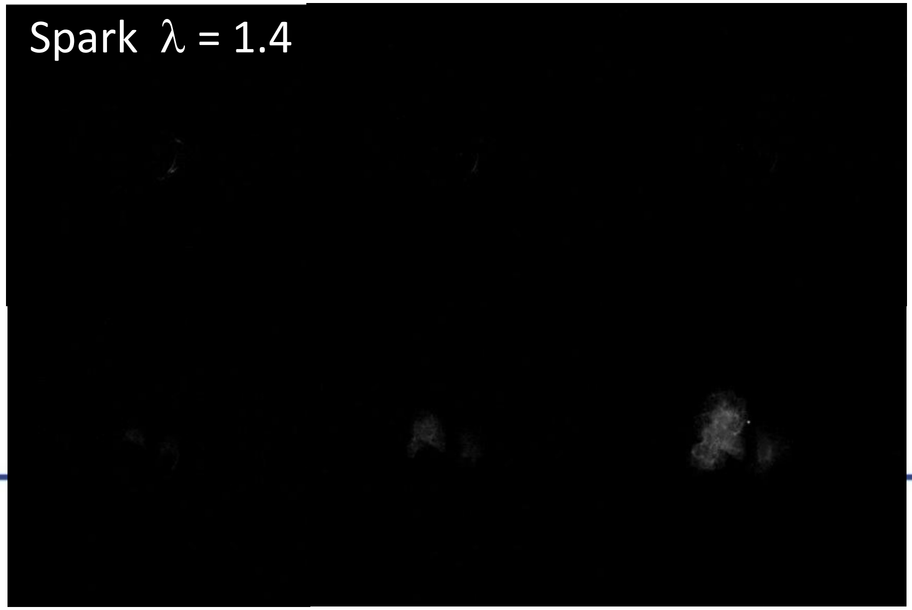
Non-equilibrium plasma

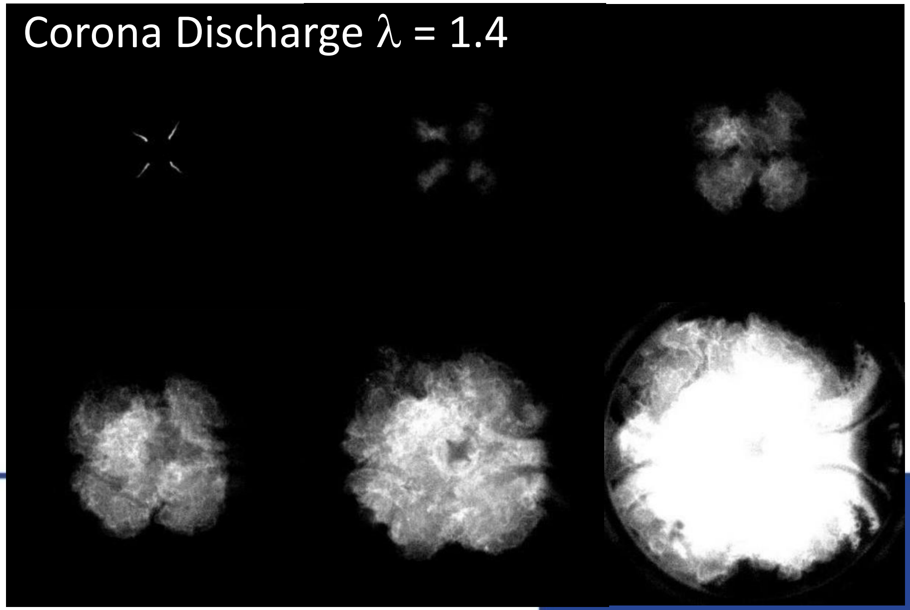
- Extend the lean stable limit
- Improve performance near the knock limit
- Improve EGR tolerance

Spark vs. corona discharge: optical engine flames









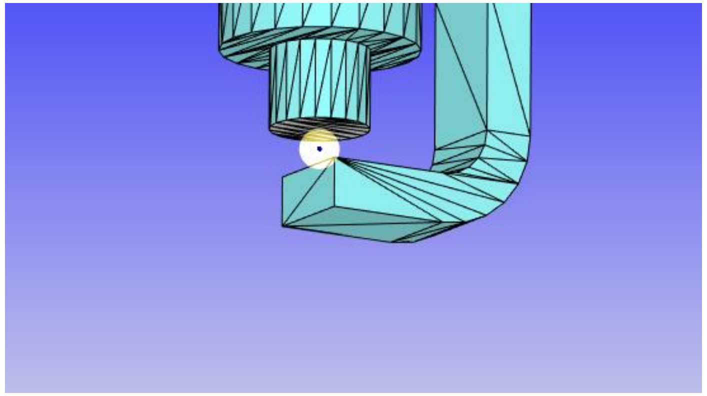
Outline

CFD Model Setup

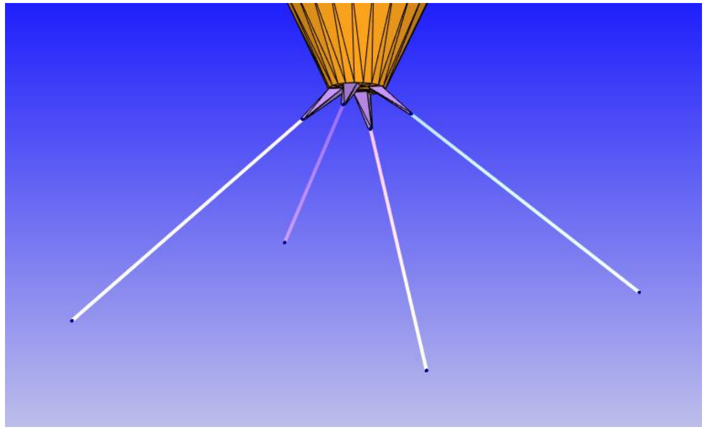
CFD model in **CONVERGE 3.0**

- Turbulence: **LES** dynamic structure
- Discretization: Space: 2nd order, finite volume; Time: 1st Euler
- Combustion model:
  - **TFM** coupled with Perfectly Stirred Reactor (**PSR**), SAGE solver and adaptive zoning
  - Mech: **LLNL** reduced mech for low-pressure
  - Fuel: Gasoline **RON 95**
- Spark ignition source:
  - deposition: 10 mJ of energy (breakdown: 5 mJ over 0.5 CAD; arc-glow: 5 mJ over 10 CAD)
  - shape: sphere with 4 mm radius
- Corona ignition source:
  - deposition: 48 mJ of energy over 1.8 CAD (300 μs @ 1000 rpm)
  - shape: 4 cylinders with 0.0625 mm radius and 10.7 mm height

Spark



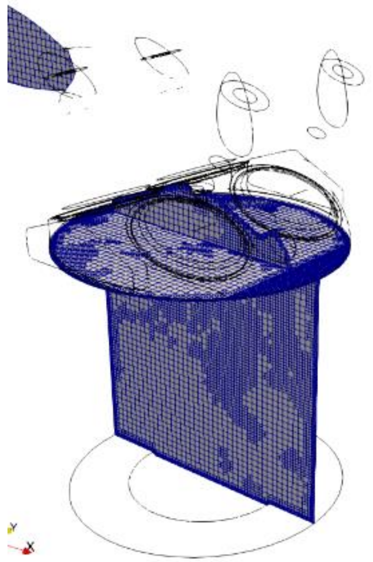
Corona



CFD Model Setup

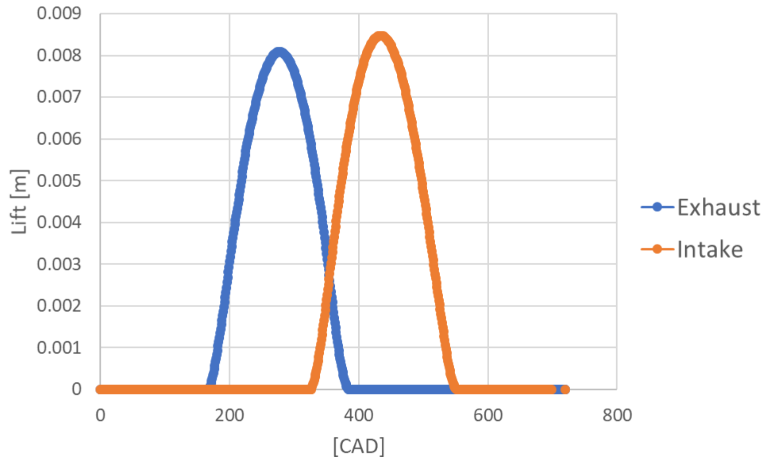
- Grid:

Base grid size outside the cylinder	8 mm
Base grid size in the cylinder	1 mm
Velocity AMR size (and level)	0.5 mm (4)
TFM - AMR size (and level)	0.25 mm (5)
Minimum grid size (around spark)	0.125 mm



- Boundary conditions:

Engine speed	1000 rpm
λ	1.0 --> lean limit
Intake lift	IVO = 329 CAD (aTDCf) IVC = 547 CAD (aTDCf)
Exhaust lift	EVO = 170 CAD (aTDCf) EVC = 380 CAD (aTDCf)
Inlet	T = 293 K P = 101325 Pa Premixed λ
Outlet	T = 800 K P = 101325 Pa



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   - Thickening options and AMR
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Why TFM combustion model?

1) In LES of premixed flames the cells are not fine enough to resolve the laminar flame thickness → TFM increases the flame thickness without changing the laminar flame-speed → The macroscopic combustion dynamics can be simulated without resolving the flame front explicitly

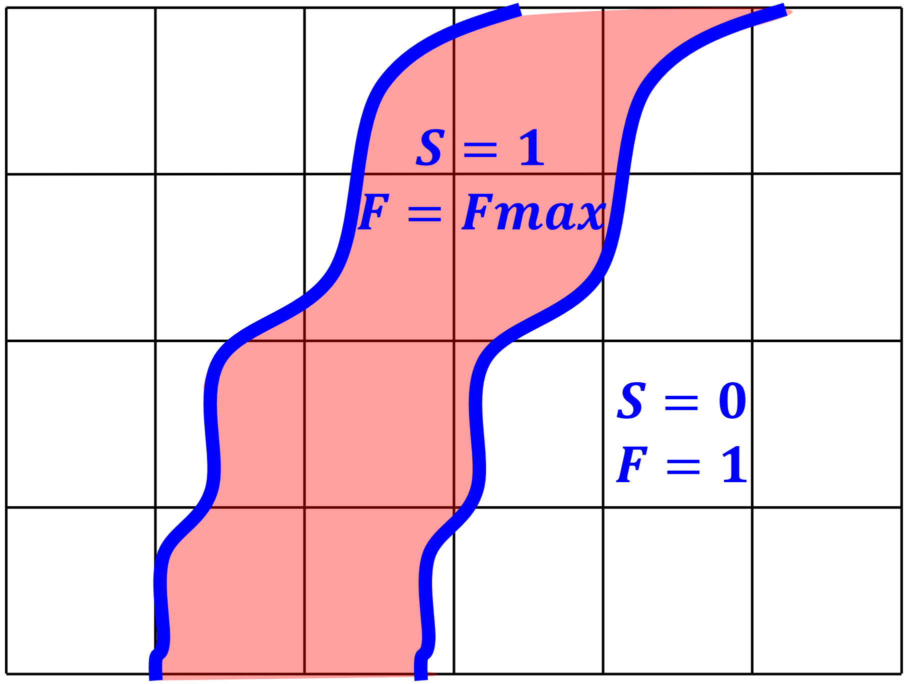
2) TFM is coupled with SAGE detailed chemistry solver → Can take into account Thermal and Kinetic Effect to simulate Corona igniters

3) TFM can compensate the absence of TCI effects

Scaling laws

	Diffusivity	Pre-exponential term	Flamespeed	Flame thickness
Thin flame	D	A	s_l^0	δ_l^0
Thickened flame	$E \cdot F \cdot D$	$E \cdot A / F$	$E \cdot s_l^0$	$F \cdot \delta_l^0$

TFM formulation: flame sensor



Dynamic TFM modeling framework

only thicken in the flame front

$$F = 1 + (F_{max} - 1)S$$

S=0 → F=1 (away from the flame front)

S=1 → F=F_{max} (in the flame front)

This F is the local thickening factor

Definition of a flame sensor *S*

$$S = \max\left[\min\left(\beta \frac{|\dot{\omega}_k|}{|\dot{\omega}_k|_{1D}^{max}} - 1, 1\right), 0\right]$$

Two options in CONVERGE:

1. Standard reaction rate model

2. Jaravel's sensor methodology → *Necessary in a detailed chemistry context*

TFM formulation: flame sensor

$$S = \max\left[\min\left(\beta\frac{|\dot{\omega}_k|}{|\dot{\omega}_k|_{1D}^{max}} - 1, 1\right), 0\right]$$

- In 1D table generation, a **steady solver** is used (newton solver)

↓

the reaction rate is directly evaluated from Arrhenius formula, which is independent of time step

- In 3D case, the reaction rate is the "averaged" reaction rate between t and t+dt and it is **affected by local conditions**

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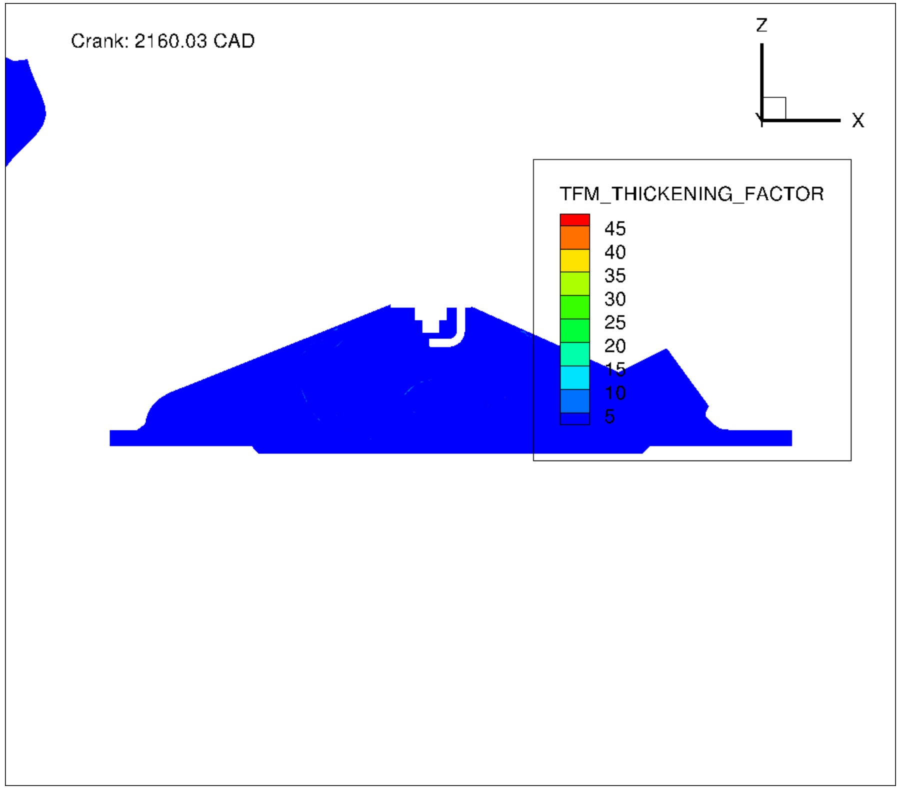
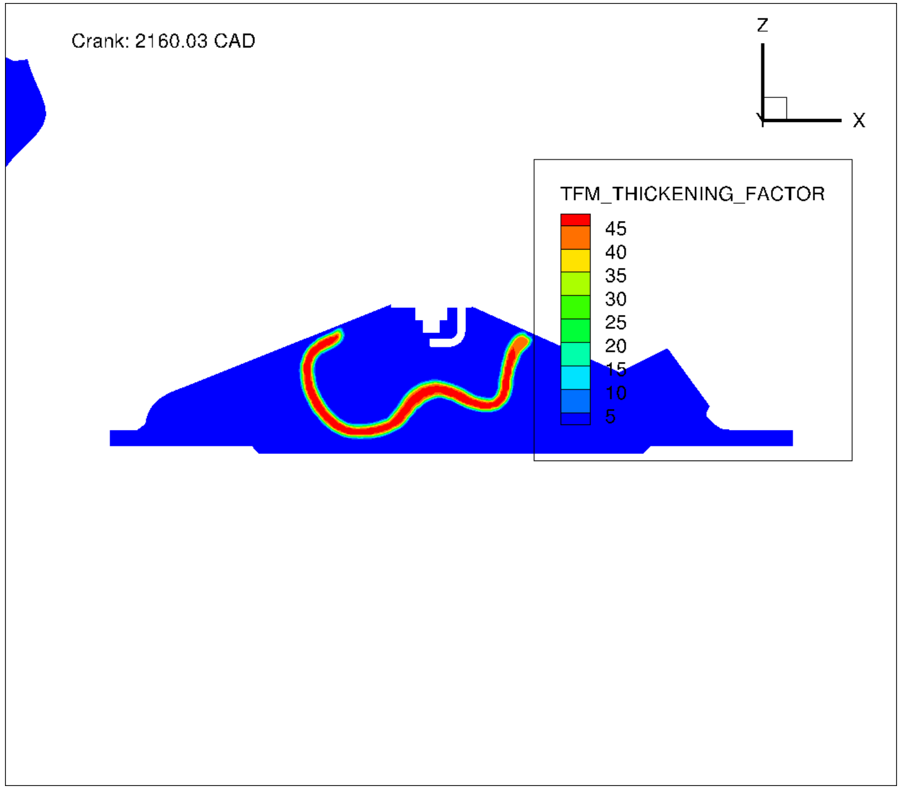
the 3D reaction rate is less than the 1D table value, so the 3D reaction rate is multiplied by the sensor_slope β

TFM formulation: flame sensor

Sensor slope β = 10



Sensor slope β = 30



TFM formulation: thickening options and AMR

Three options in CONVERGE:

1. Constant maximum thickening factor

$\mathrm{F} = constant \rightarrow \mathrm{n_{res}}$ and δ_F are calculated

2. Constant number of grid points across the flame

$\mathrm{n_{res}} = contant \rightarrow \mathrm{F}$ and δ_F are calculated

3. Constant thickened flame front and number of grid points across the flame

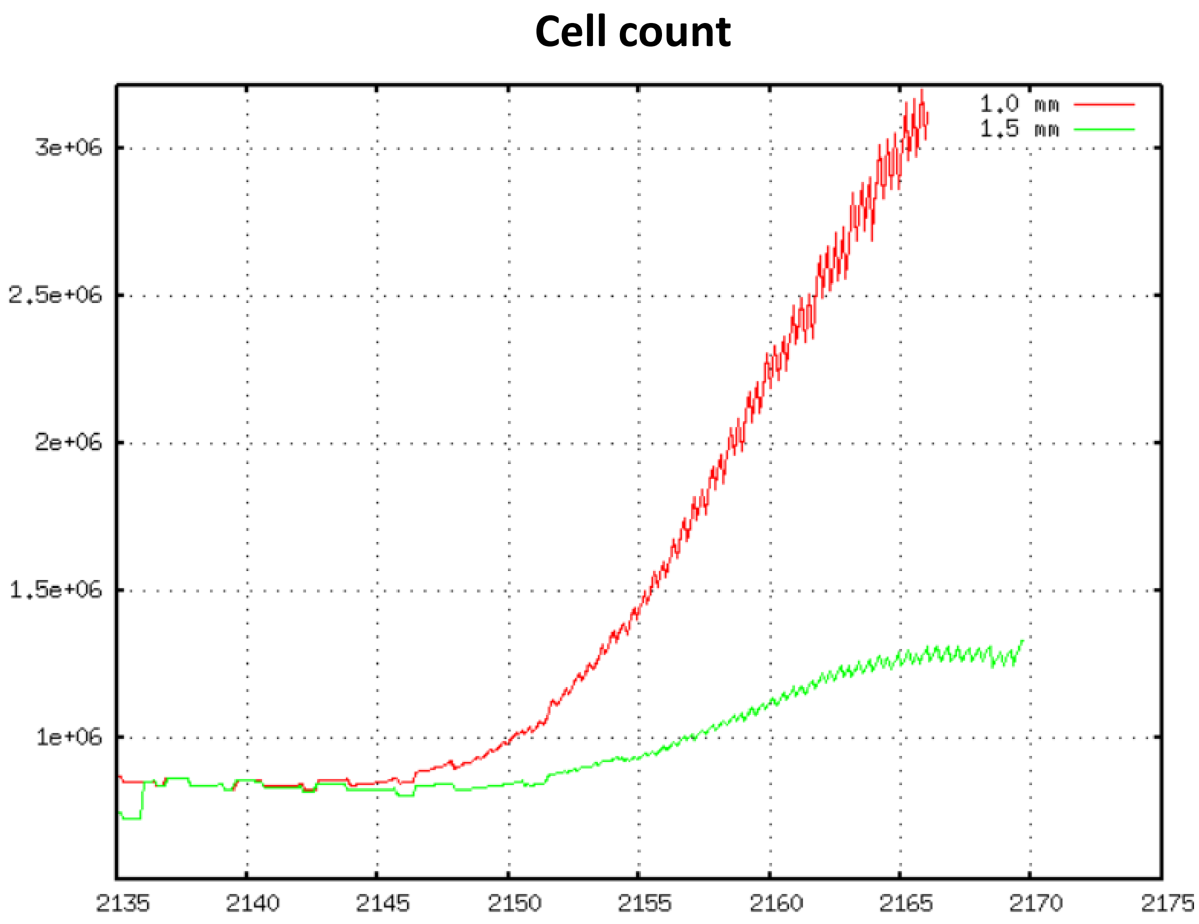
$\delta_\mathrm{F} = contant, \mathrm{n_{res}} = contant \rightarrow \mathrm{F}$ is calculated

$$\delta_\mathrm{F} = F * \delta_l^0$$

$$\mathcal{F}_{\text{target}} = \frac{n_{res}\Delta_x^{AMR}}{\delta_l^0(\phi)}$$

$$n_{AMR} = \text{int}\left[\frac{1}{\log(2)}\log\left(\frac{n_{\text{res}}\Delta_x^{\text{Base}}}{\delta_l^0(\phi)\mathcal{F}_{\text{target}}}\right)\right]$$

Effect of thickened flame value δ_F



tf_amr_thickness_target δ_F = 1.0 mm
and n_points_across_flame = 4

amr_level = 6 → 0.125 mm

tf_amr_thickness_target δ_F = 1.5 mm
and n_points_across_flame = 4

amr_level = 5 → 0.25 mm

TFM formulation: efficiency function

The efficiency function precursor Ξ_Δ is introduced to predict the turbulent flame propagation speed:

$$S_T = \Xi_\Delta S_l^0$$

Three options in CONVERGE:

1. Constant efficiency
2. Charlette's model $\Xi_\Delta = \left(1 + \min\left[\frac{\Delta}{\delta_l^0} - 1, \Gamma_\Delta\left(\frac{\Delta}{\delta_l^0}, \frac{u'_\Delta}{s_l^0}, \mathrm{Re}_\Delta\right)\frac{u'_\Delta}{s_l^0}\right]\right)^\beta$
3. Colin's model $\Xi_\Delta = 1 + \beta_{Colin} \frac{2\ln(2)}{3c_{ms}\left[\mathrm{Re}_t^{1/2} - 1\right]} \Gamma_{Colin}\left(\frac{\Delta}{\delta_l^0}, \frac{u'_\Delta}{s_l^0}\right)\frac{u'_\Delta}{s_l^0}$

u'_Δ is the sub-grid scale turbulent velocity, and in CONVERGE can be based on curl of the resolved velocity or based on subgrid tke

The efficiency function E is calculated by $E = \frac{\Xi\big|_{\delta=\delta_l^0}}{\Xi\big|_{\delta=F\delta_l^0}}$

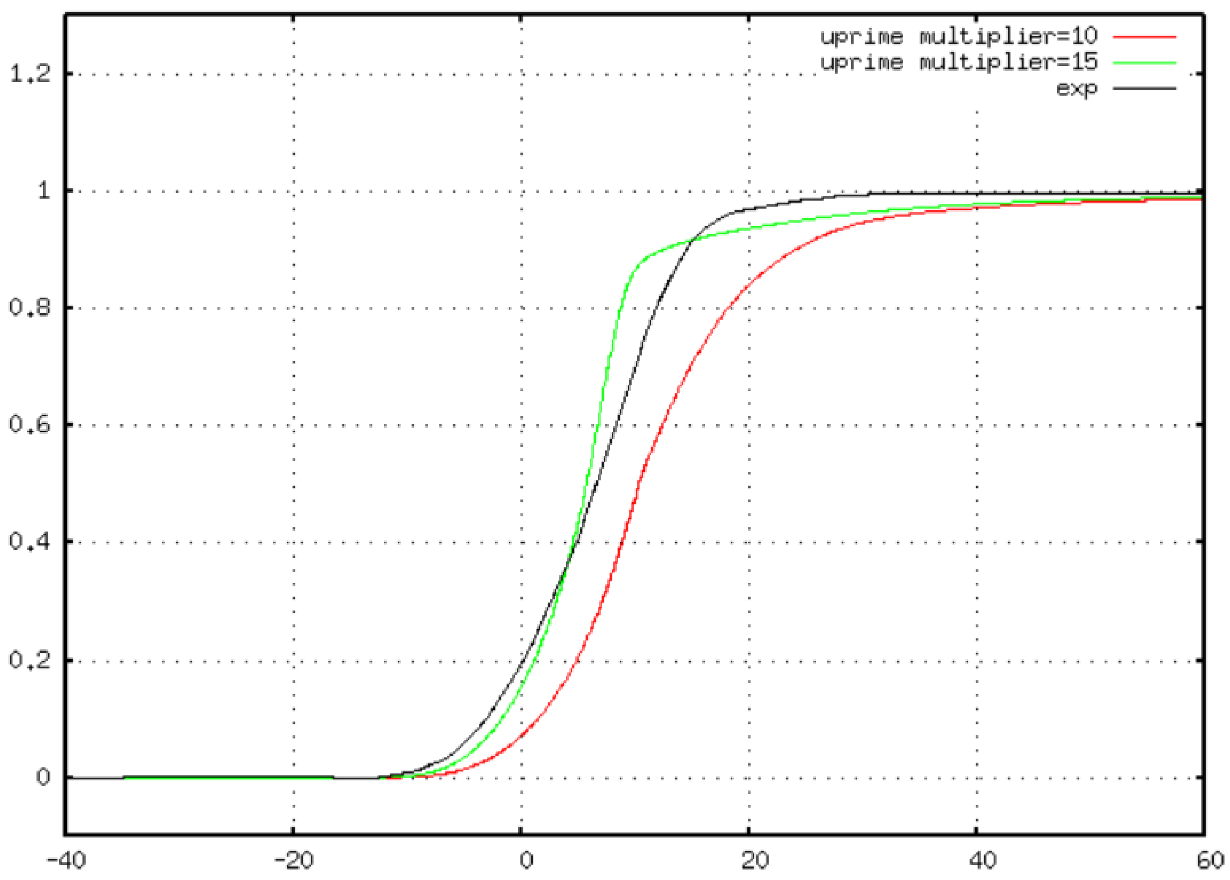
Effect of uprime_multiplier

LLNL mech with RON 95
SA = -23 CAD
TFM start = -20 CAD

beta_charlette = 0.65

uprime_multiplier
10
15

Mass fraction burned



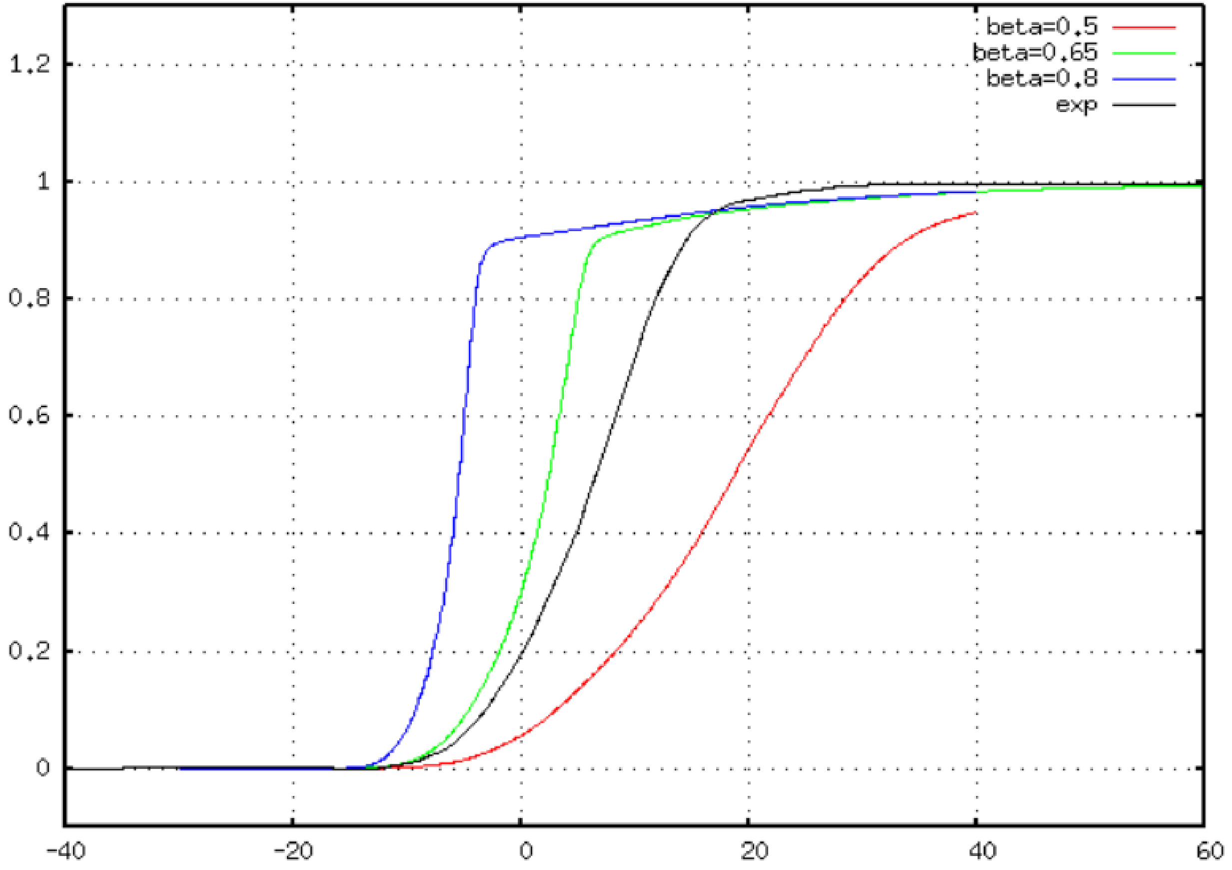
Effect of Beta_Charlette

LLNL mech with RON 95
SA = -23 CAD
TFM start = -20 CAD

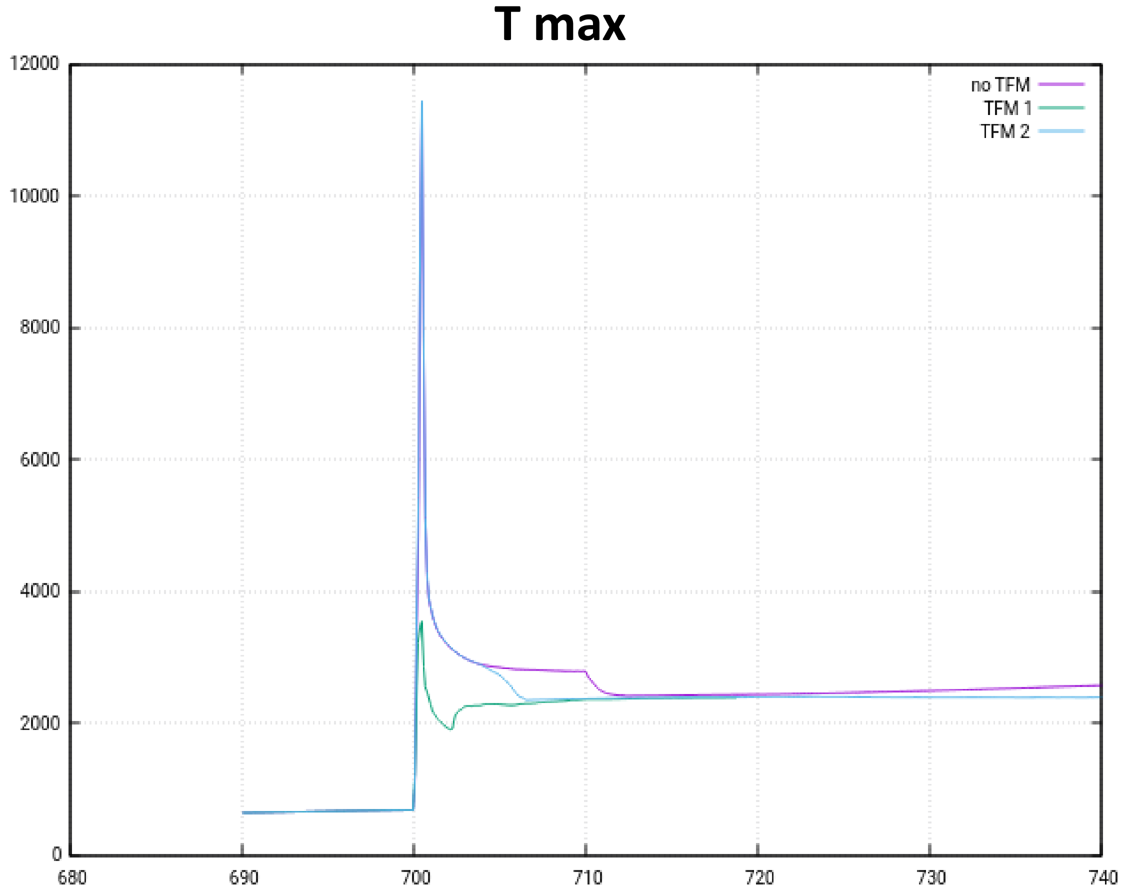
uprime_multiplier = 10

beta_charlette
0.5
0.65
0.8

Mass fraction burned



Effect of TFM start timing



SA = -20 CAD

TFM 1: TFM start timing = -20 CAD
TFM 2: TFM start timing = -17 CAD

- Thickened flame procedure affects the ignition, the max temperature decreases because more diffusion is added.
- The thickening procedure should be avoided when the flame kernel is not yet established.

The TFM start timing is set to 3 CAD after the ignition for all cases (manual)

Summary TFM setup

- TFM flame sensor: Jaravel's sensor methodology → sensor_slope β = 30

- TFM thickening option: Constant thickened flame front and number of grid points across the flame → tf_amr_thickness_target δ_F = 1.5 mm, n_pts_across_flame = 4 → flame resolution = 0.25 mm (amr_level = 5)

- TFM efficiency function: Charlette's model → uprime_multiplier = 10, beta_charlette = 0.6

- TFM start timing: manually set to 3 CAD after the ignition, for all cases

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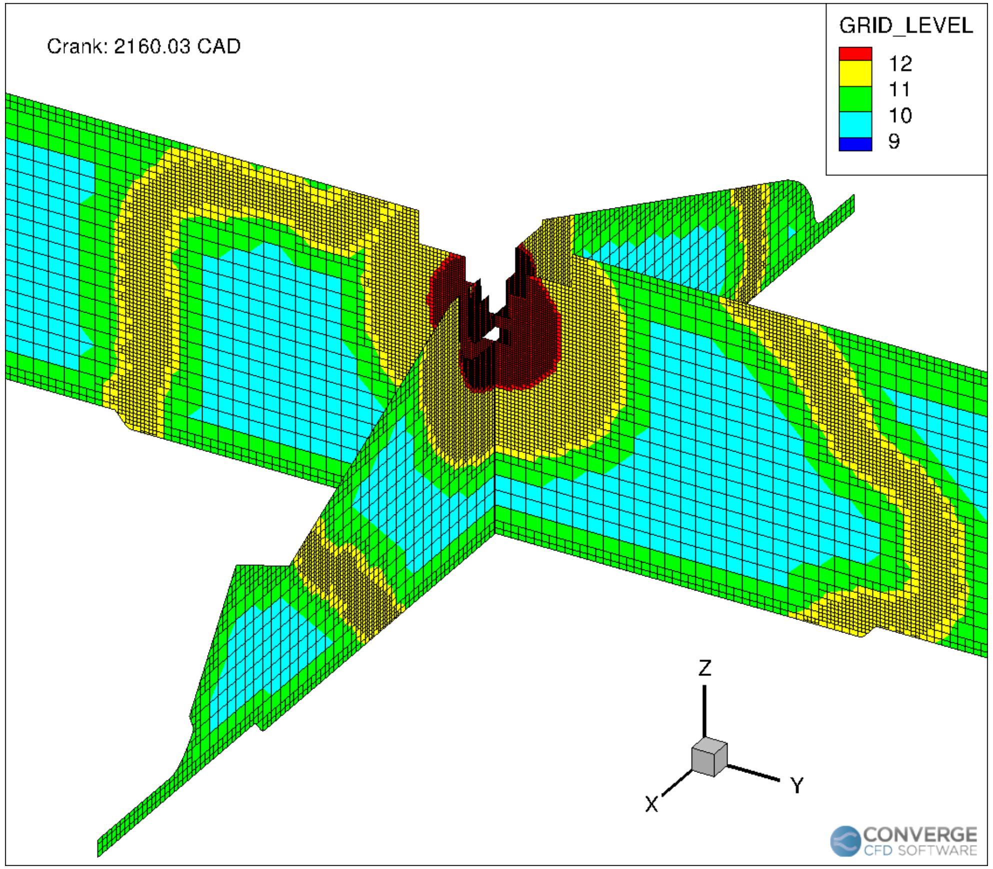
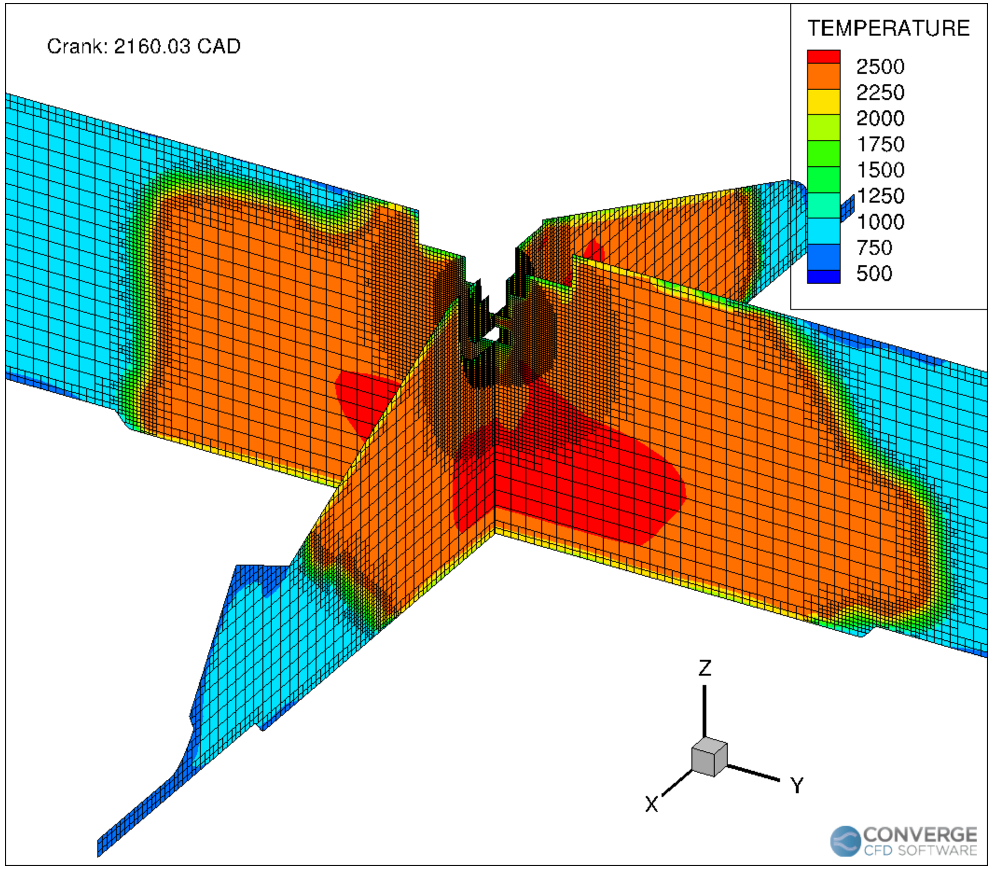
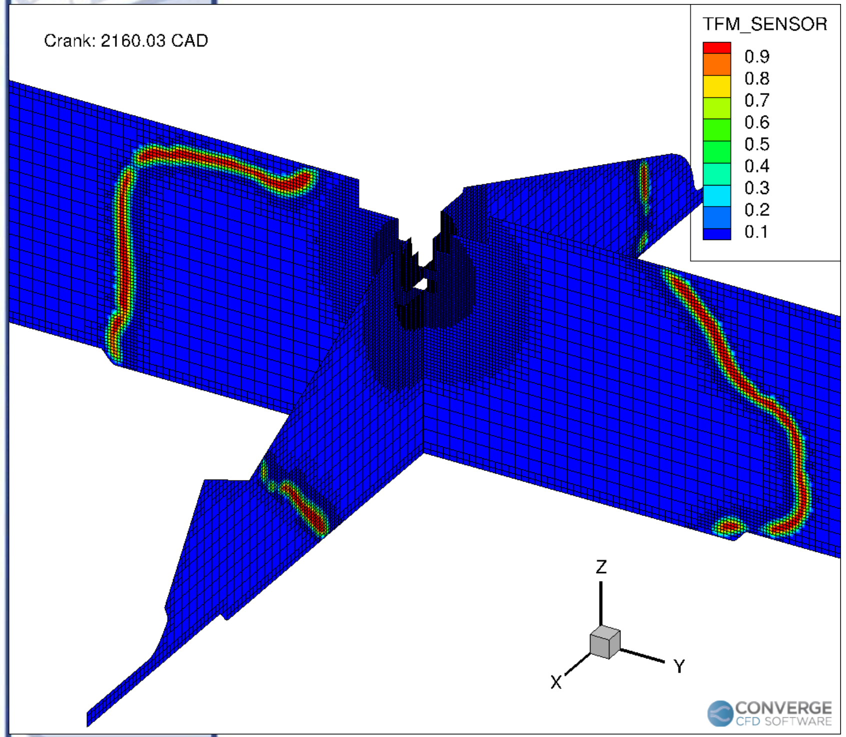
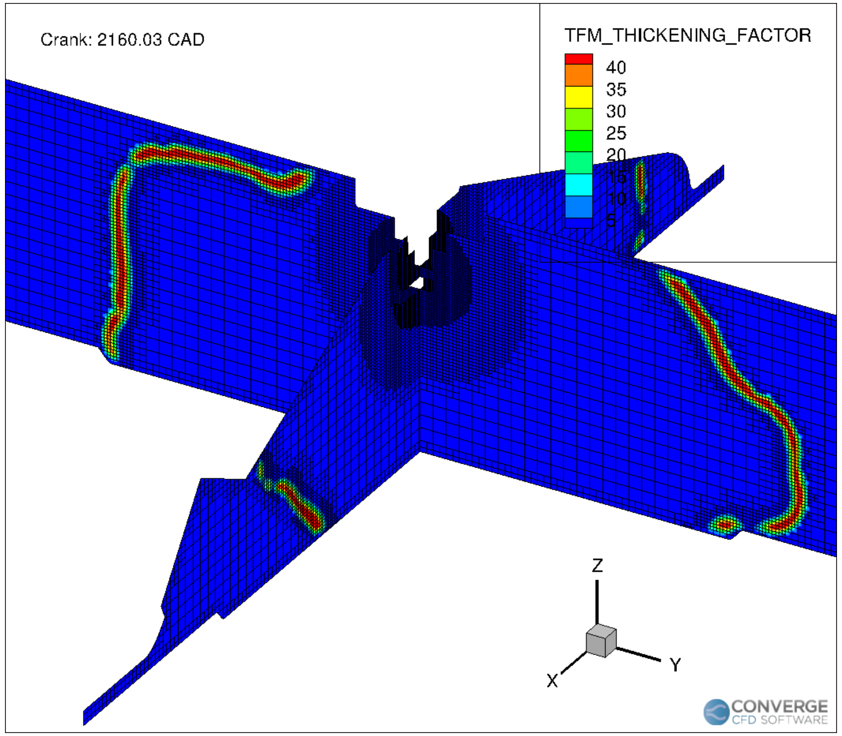
TFM 3D output

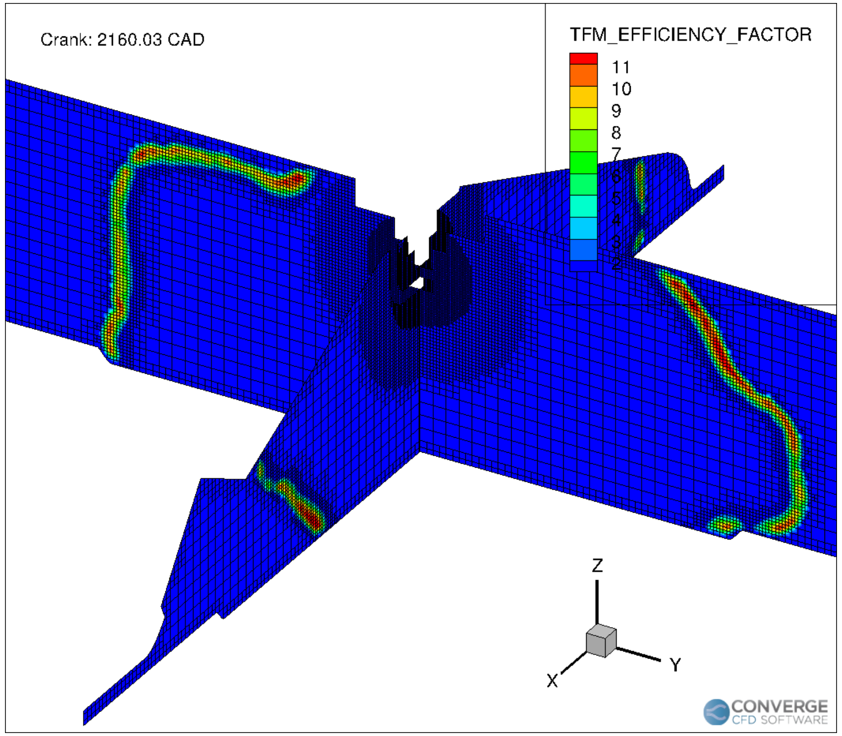




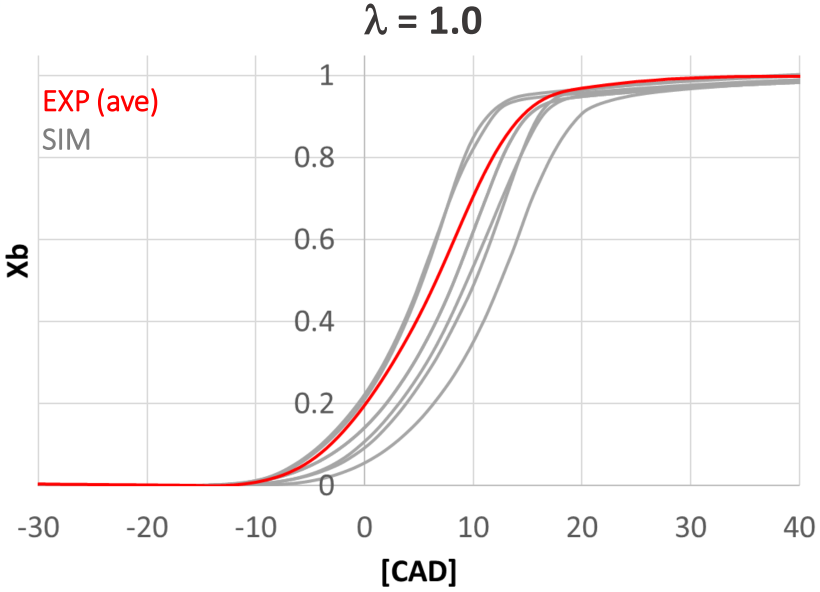
TFM 3D output

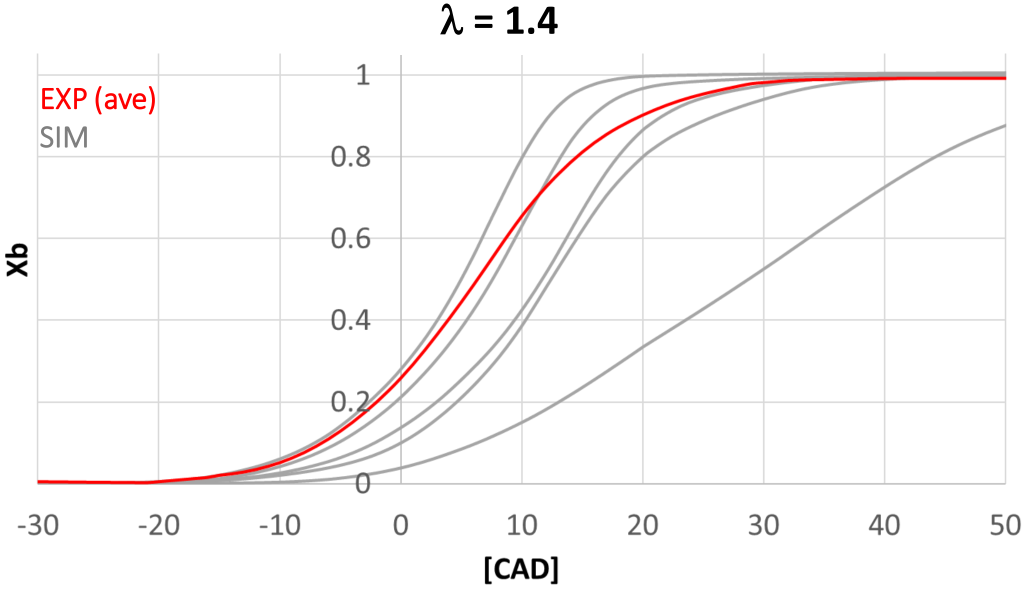






Mass fraction burned at different λ – Spark





CASE SETUP

Fuel: Gasoline RON95

Sensor slope: 30

Uprime_multiplier: 10

Beta_Charlette: 0.6

Spark energy: 5+5 mJ

- IT_exp: 20 CAD bTDCf
- TFM_start: 20 CAD bTDCf
- IT_num: 23 CAD bTDCf

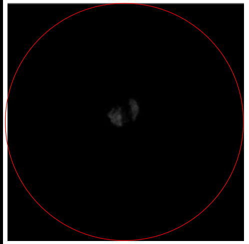
- IT_exp: 40 CAD bTDCf
- TFM_start: 40 CAD bTDCf
- IT_num: 43 CAD bTDCf

- Combustion rates are satisfactorily predicted

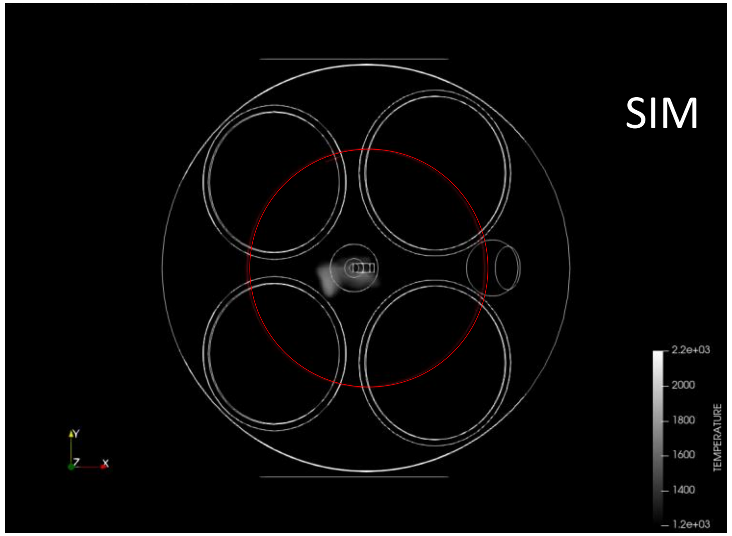
Flame imaging comparison – Spark λ=1.0

Timing
3 CAD
aIT

EXP



Timing
9 CAD
aIT



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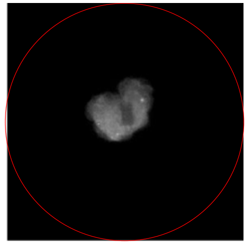
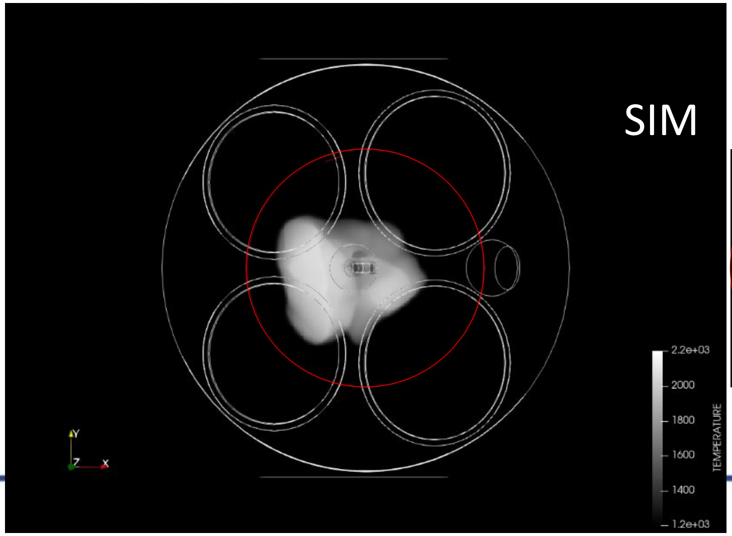


Timing
15 CAD
aIT



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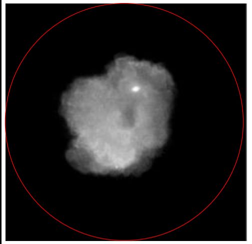
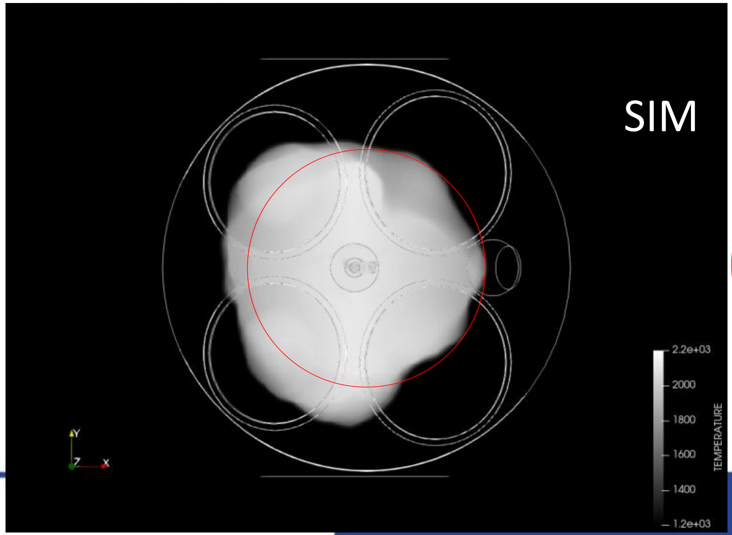


Timing
23 CAD
aIT



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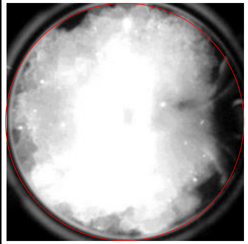
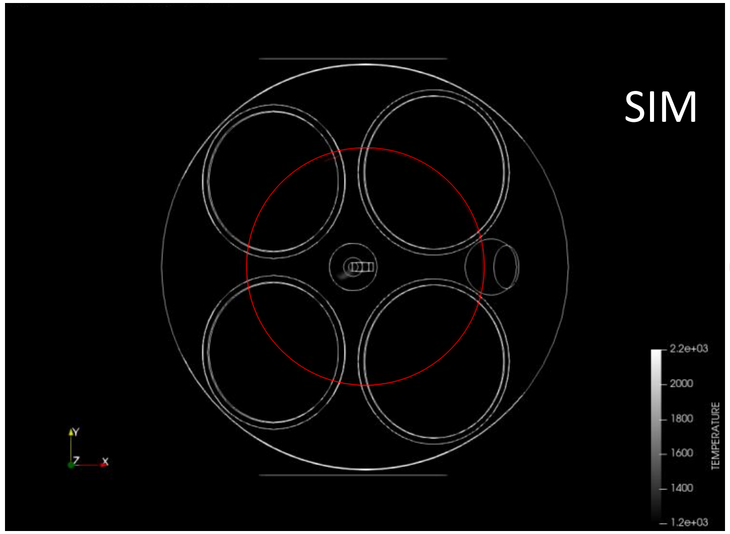


Flame imaging comparison – Spark λ=1.4

Timing
9 CAD
aIT

SIM



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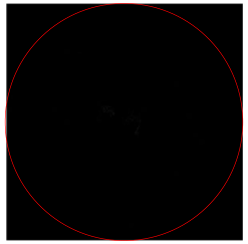
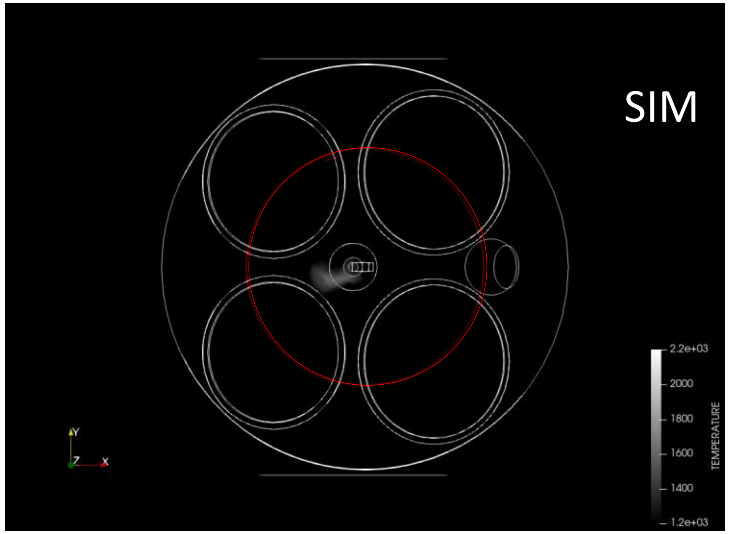


Timing
19 CAD
aIT

SIM



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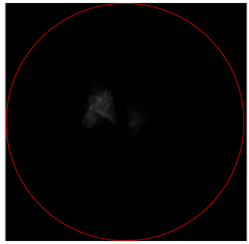
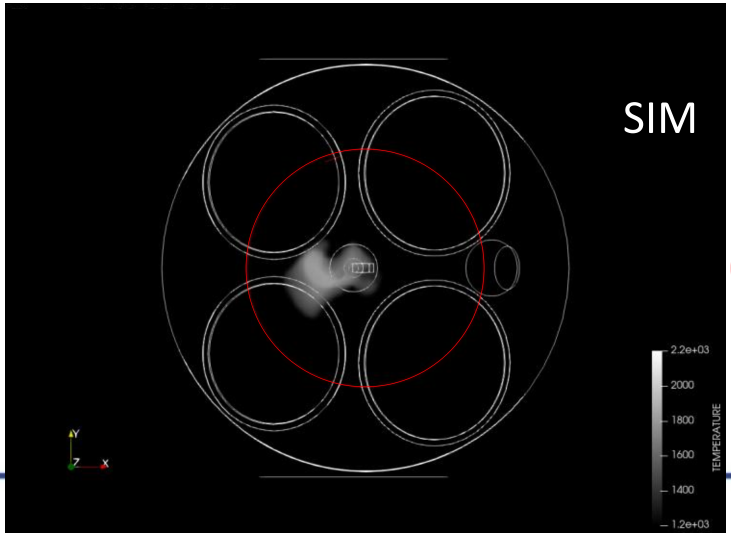


Timing
25 CAD
aIT

SIM



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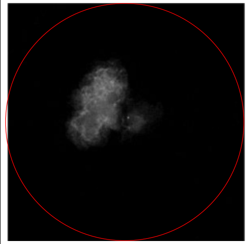
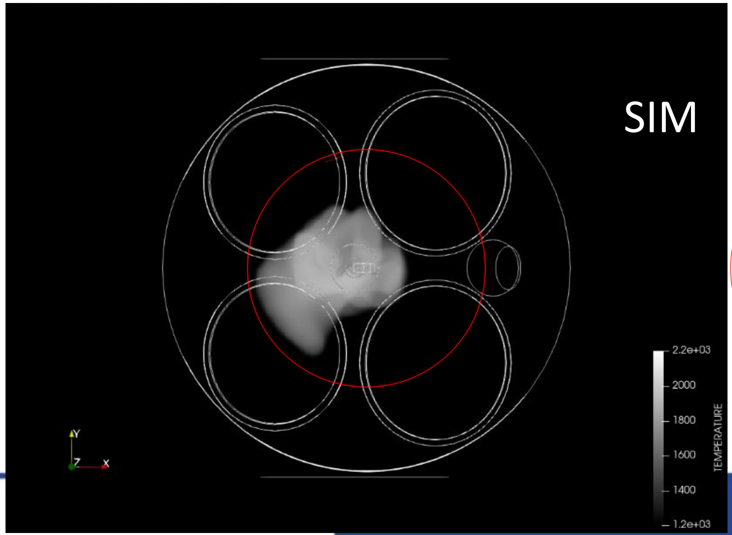


Timing
31 CAD
aIT

SIM



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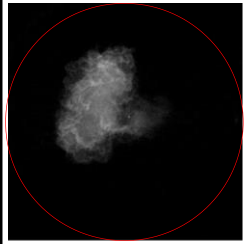
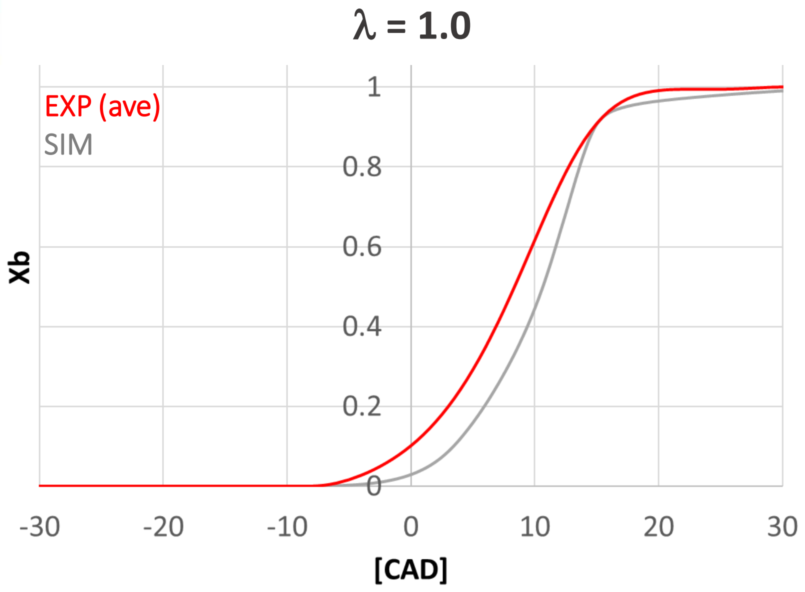
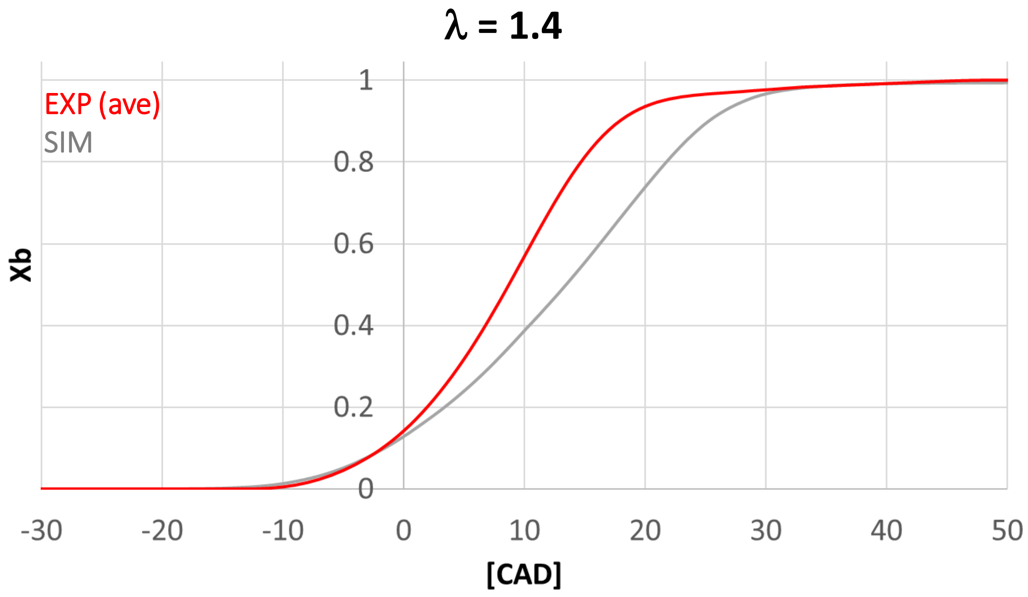


Mass fraction burned at different λ – ACIS





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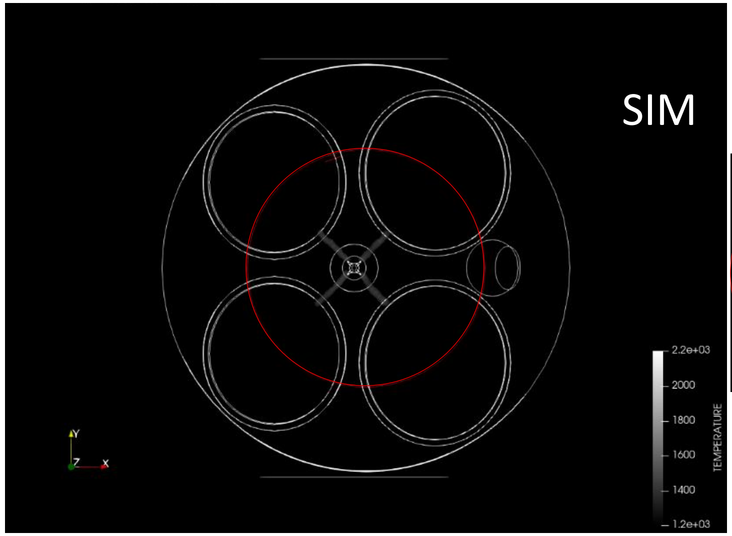
- IT_num: 16 CAD bTDCf

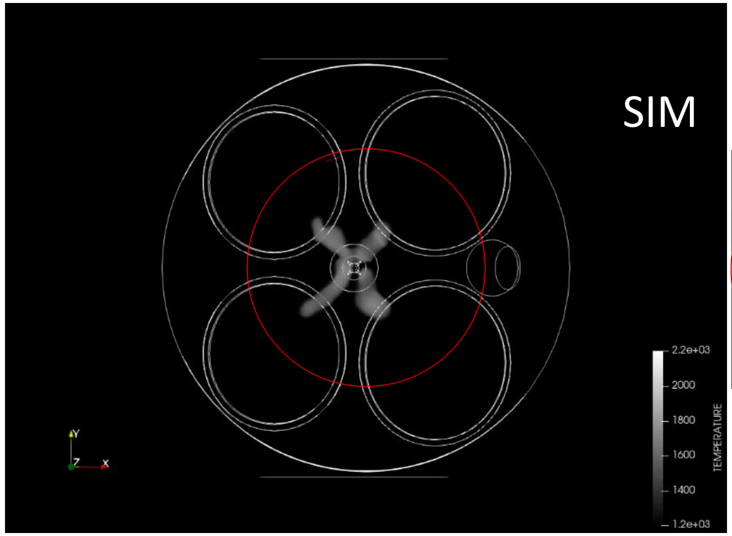
Flame imaging comparison – ACIS λ=1.0

Timing
1 CAD
aIT



EXP

Timing
5 CAD
aIT



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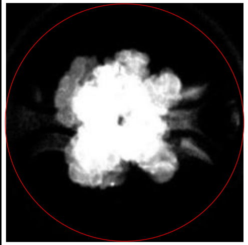
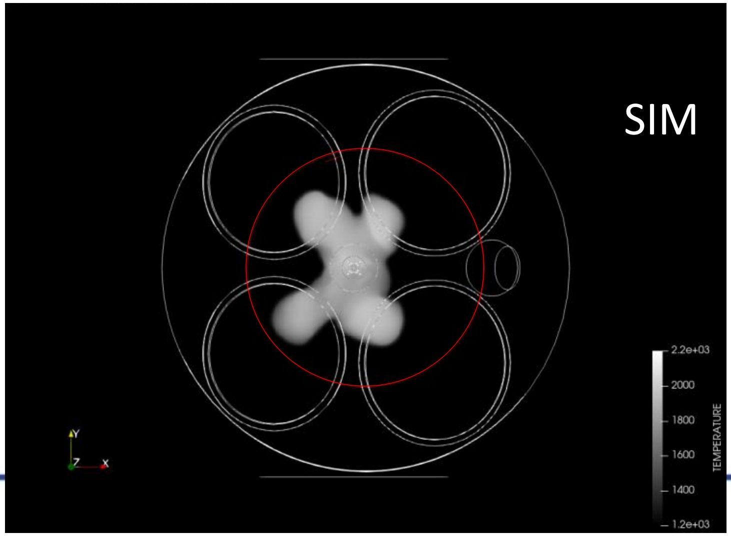


Timing
9 CAD
aIT



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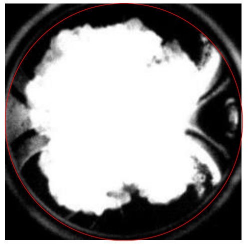

Timing
13 CAD
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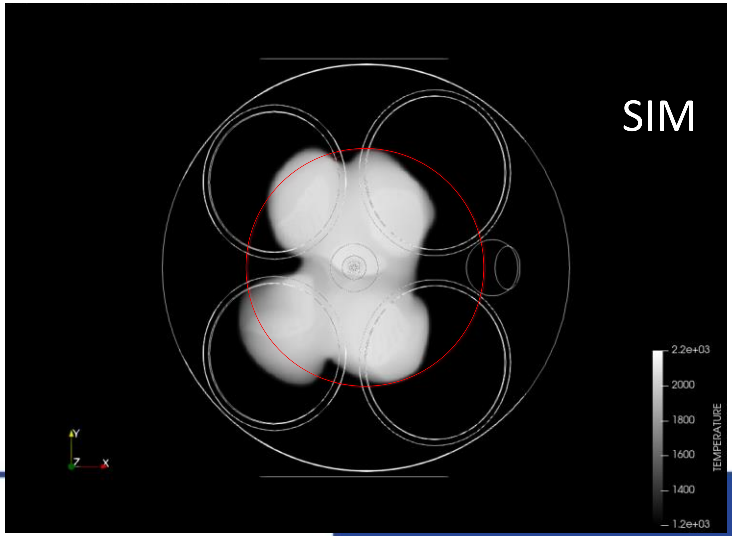

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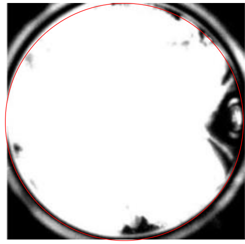
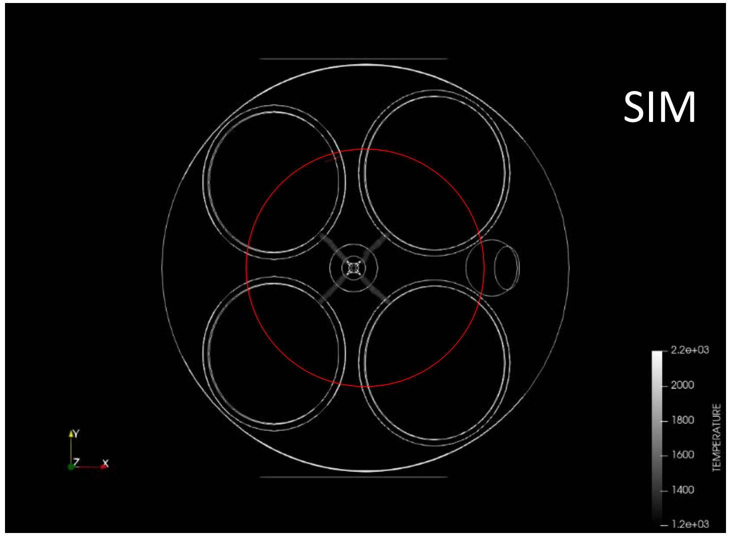


Flame imaging comparison – ACIS λ=1.4

Timing
1 CAD
aIT



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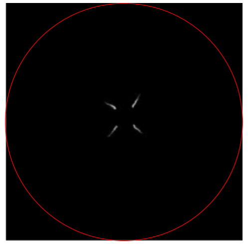
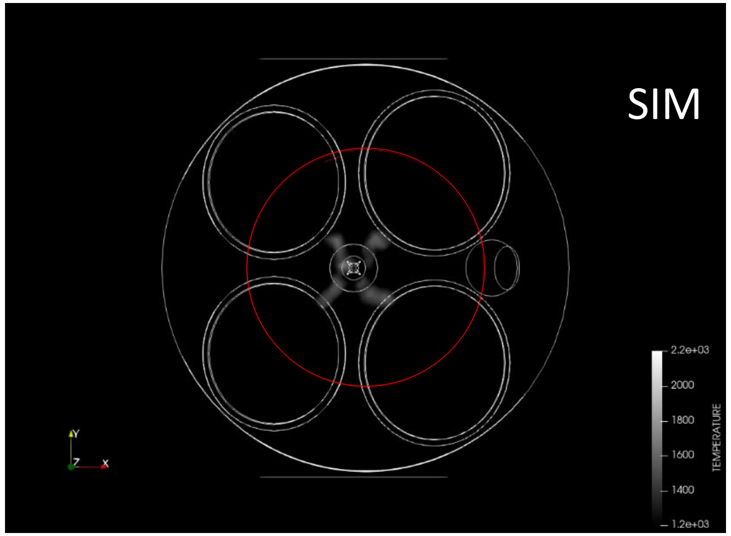


Timing
5 CAD
aIT



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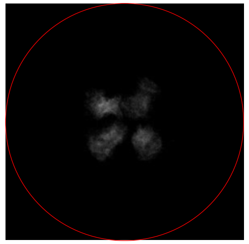
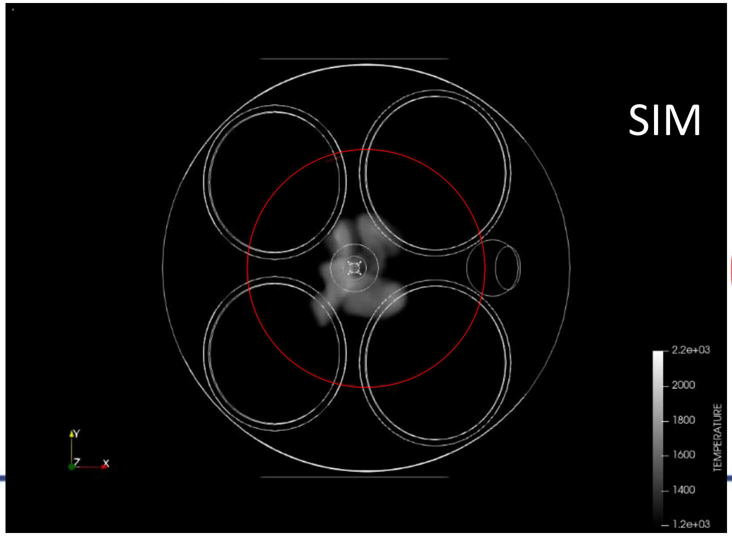


Timing
9 CAD
aIT



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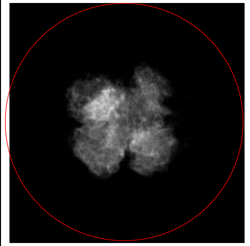
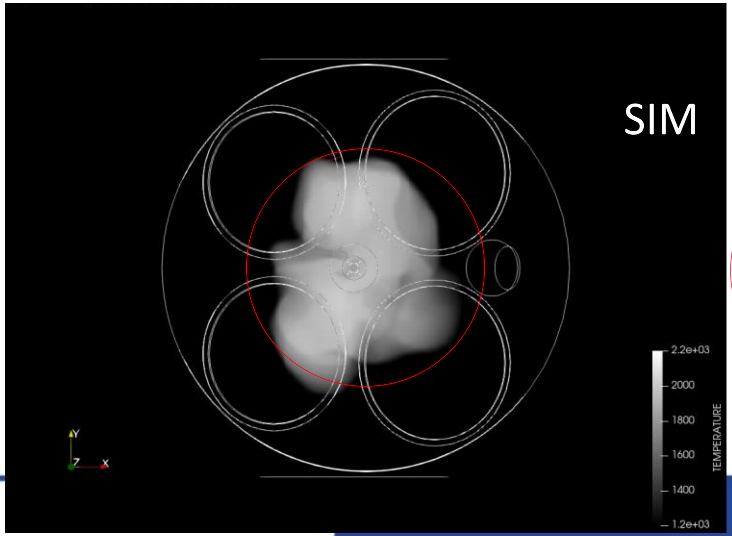


Timing
19 CAD
aIT



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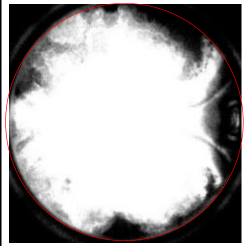

Outline

1. Experimental Setup
    - Optical access SI engine
    - Ignition systems tested in Perugia University

2. CFD Model Setup

3. TFM combustion model
    - Why TFM?
    - Flame sensor
    - Thickening options and AMR
    - Efficiency function
    - Effect of the calibration parameters

4. Cycle to cycle variability prediction
    - Multicycle LES simulations at different conditions
    - Mass fraction burned at different λ
    - Flame comparison at different λ

5. Conclusions and next steps

Conclusions

- The TFM combustion model is explored in detail
- A good setup has been defined
- Global (xb) and local (flame image) results are in good agreement with experimental data

Next Steps

- A sub-model to manage the transition and activation of the TFM is necessary
- The dynamic beta Charlette formulation could be implemented
- More cycles are needed to better understand the statistics and analyze the CCV

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