ASME Turbo-Expo, Vancouver, Canada, June 6-10, 2011

Panel Session 4-34 - LES Modeling of Combustors:

CERFACS Perspective

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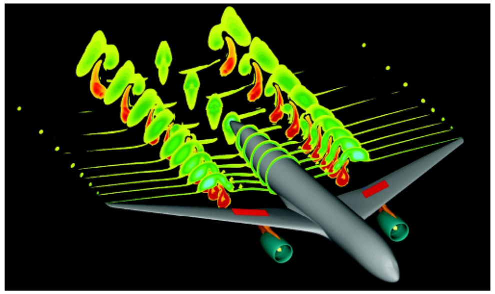
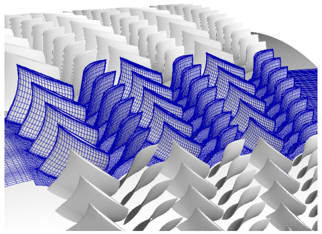
T. Poinsot[2]





[1] CERFACS - CFD Team, Toulouse
[2] IMFT, Toulouse

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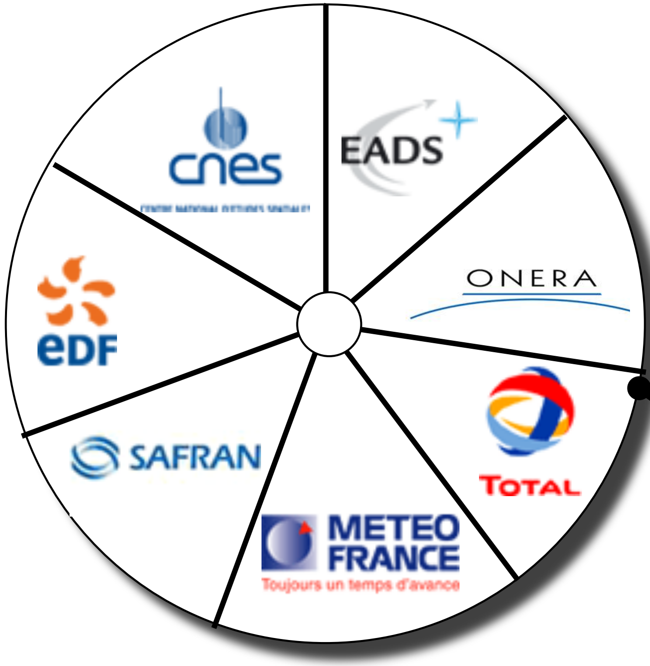
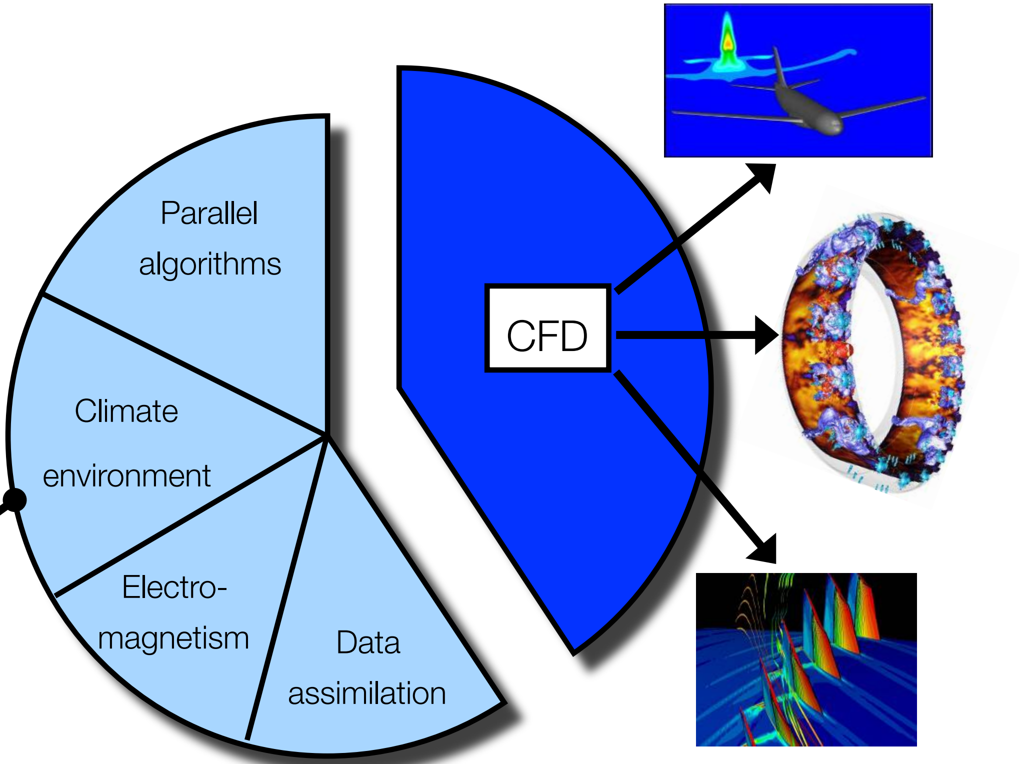
What's CERFACS?

CERFACS has seven shareholders

One hundred people in 5 teams



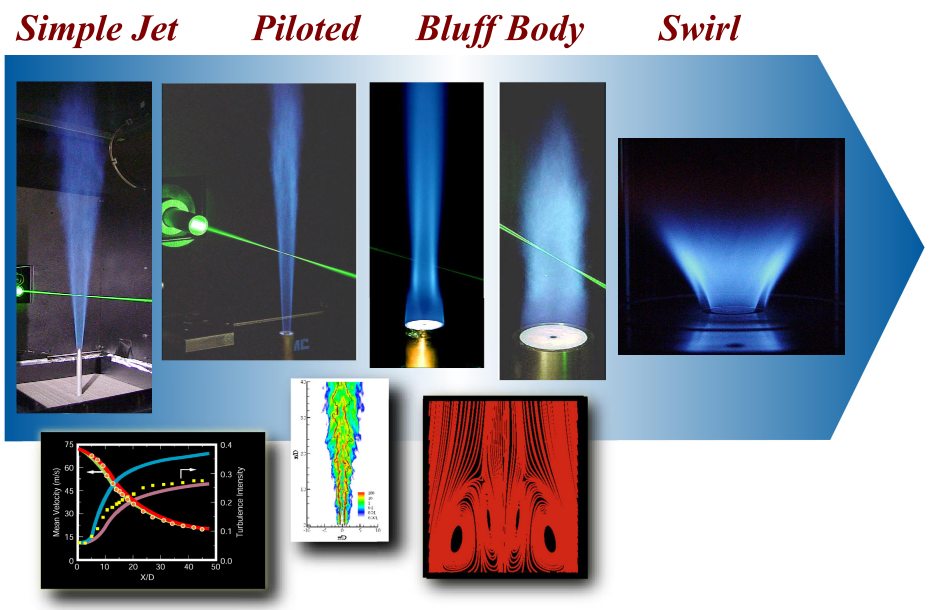


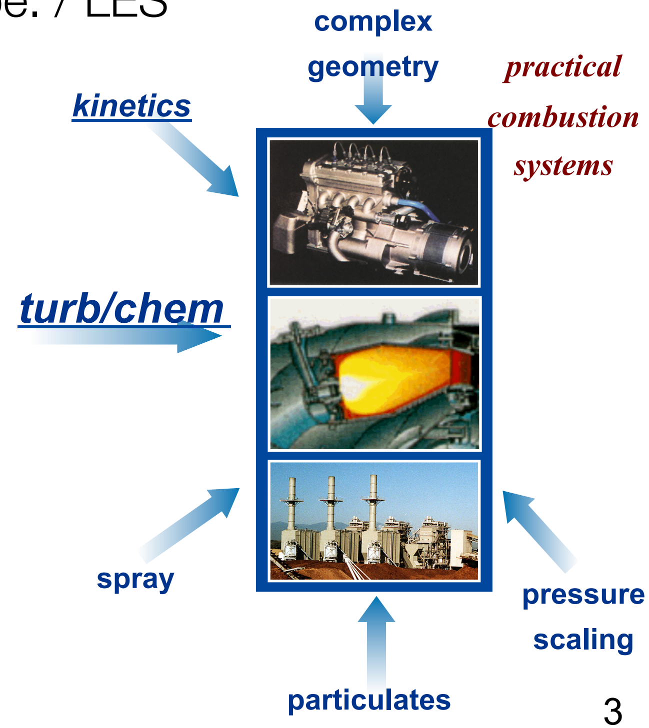
- **Expertise in scientific computation**
- **Access to large computational resources**

http://www.cerfacs.fr

CFD research in Turbulent reacting flows has massively transitioned to LES:

- 1996 – First TNFS workshop (Naples):
  => Construct an experimental data base to validate CFD modeling
- 1998 – Third TNFS workshop (Bolder):
  => First comparisons of simple flames – expe. / RANS
- 2010 – Tenth TNFS workshop (Beijing):
  => Detailed comparisons of expe. / LES





For the specific problem of Gas Turbines

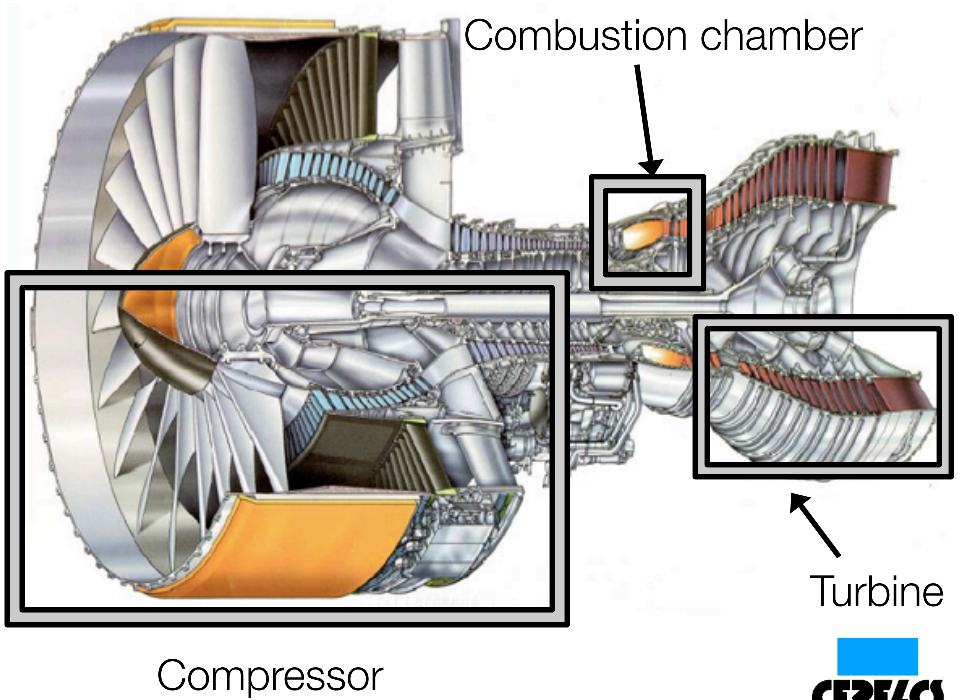
• ***Advanced CFD*** and ***Massively parallel*** computer architectures offer a clear potential for time and cost reductions of the design chain while providing ***more accurate predictions***

• CFD modeling needs to be specifically addressed for the three engine components:

=> **Compressor** – RANS (URANS / LES)

=> **Burner** – RANS / LES

=> **Turbine** – RANS (URANS / LES)



• Each component is the locus of distinct flow physics and adding **multi-physics** may greatly contribute to the predictions

=> Flow separation and transition

=> Multi-phase flows

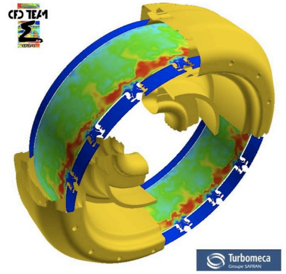
=> Chemical reaction

=> Mixing, cooling

=> Heat transfer

…

I] Recent contributions of LES to Combustor design:

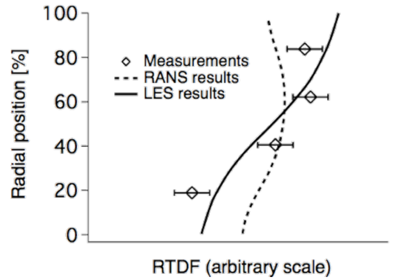


=> Real scale applications

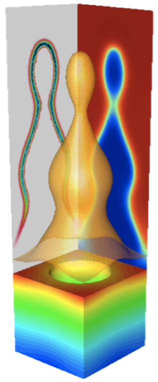
--> comparison against RANS predictions

--> mesh sensitivity analysis

=> Thermo-acoustic instability prediction

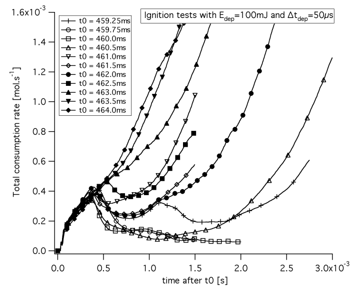


II] LES perspectives and applications:



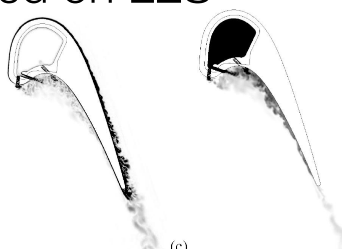
=> LES modeling and code validations

=> Transient reacting flows: ignition process understanding



III] Perspectives:

=> Towards multi-physics CFD based on LES



IV] Conclusions:

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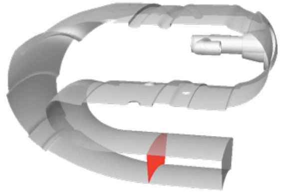

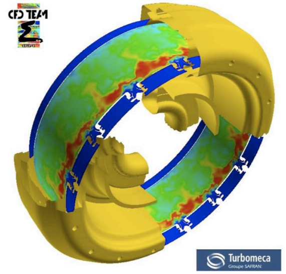

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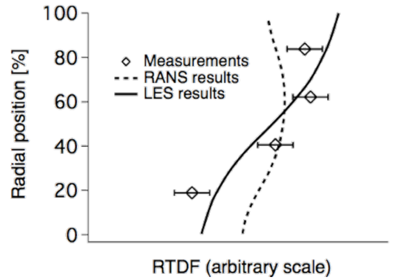

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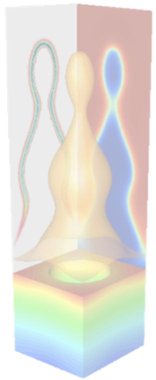

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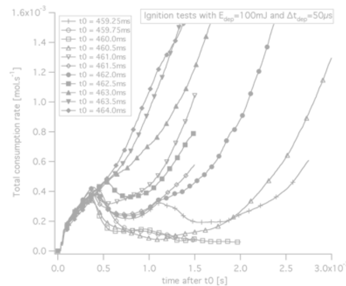

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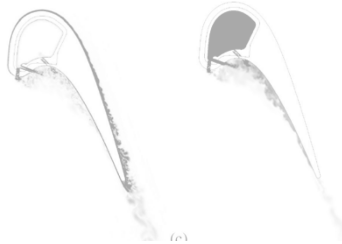
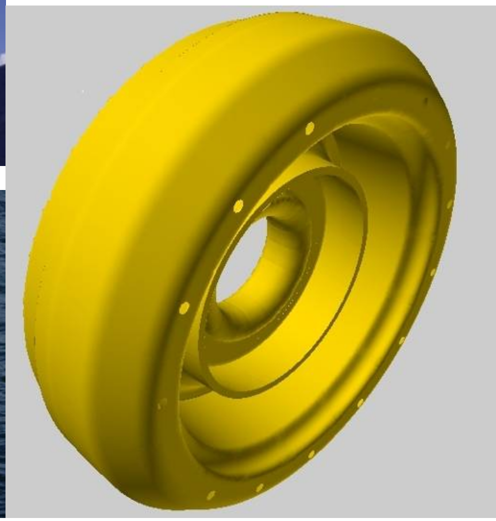
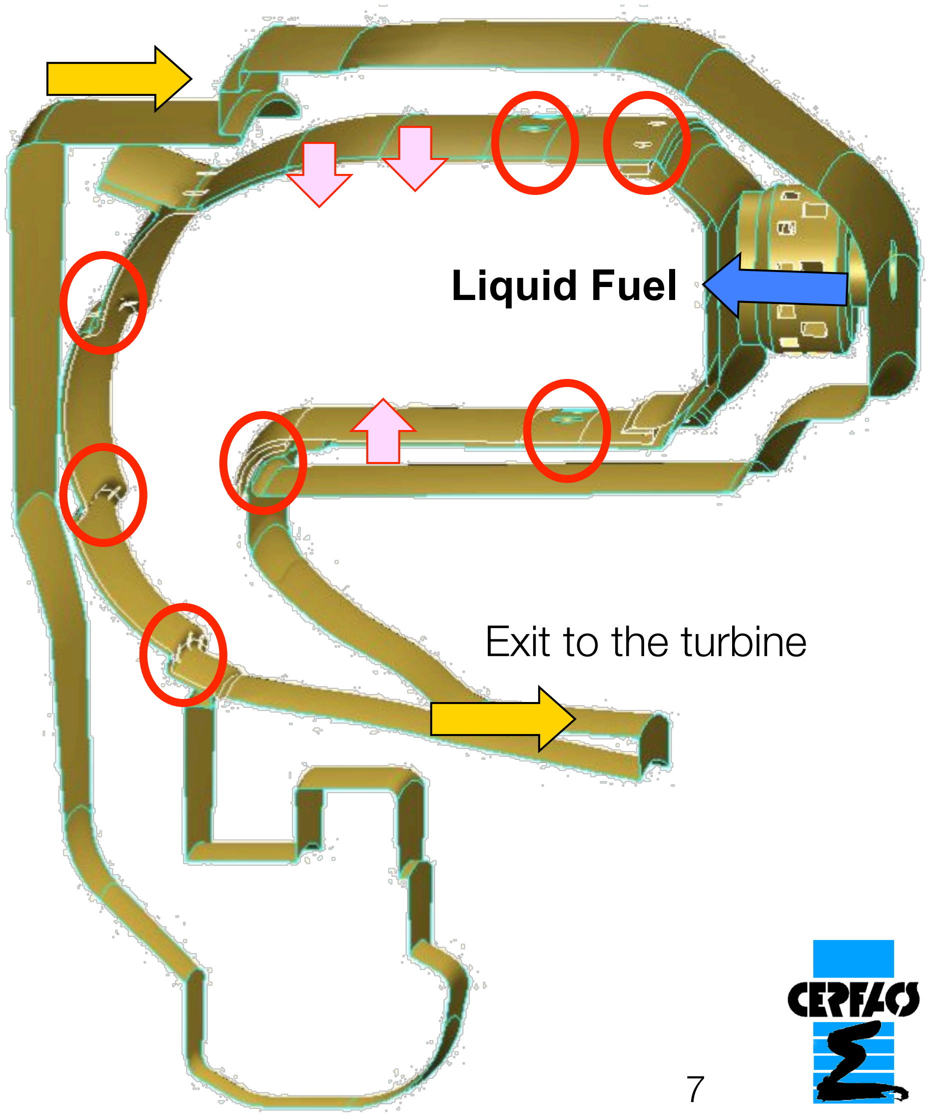


IV] Conclusions:

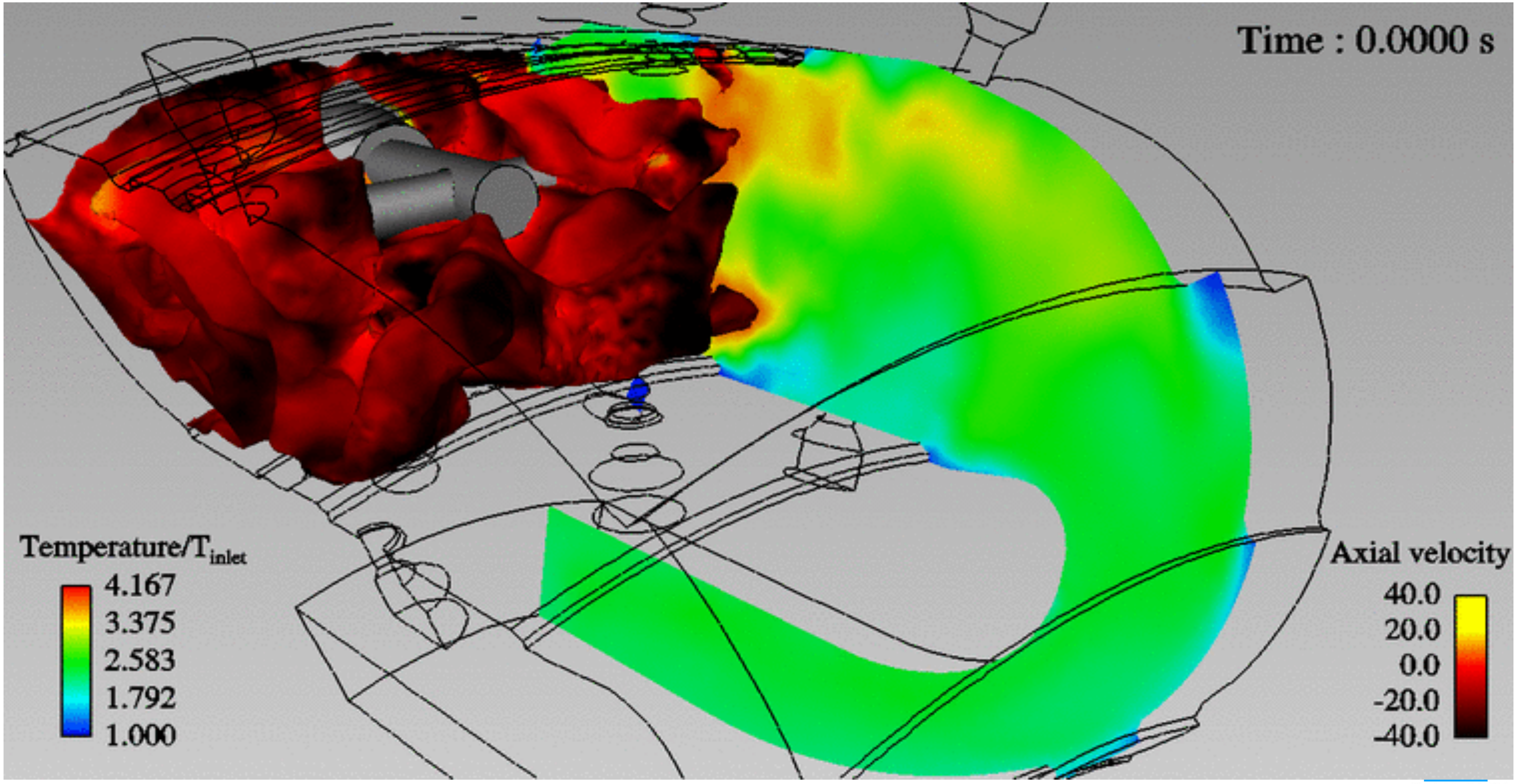
Target configuration: a helicopter combustion chamber at cruise conditions

Annular burner





<u>Target configuration</u>: Single sector gaseous (partially premixed) LES [1]

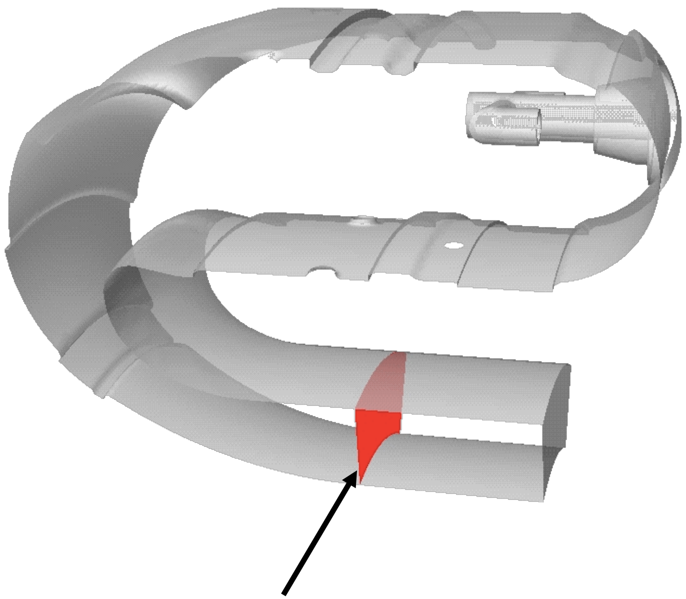


[1] G. Boudier et al., Comb. Inst., 31(2):3057-3082, 2007.

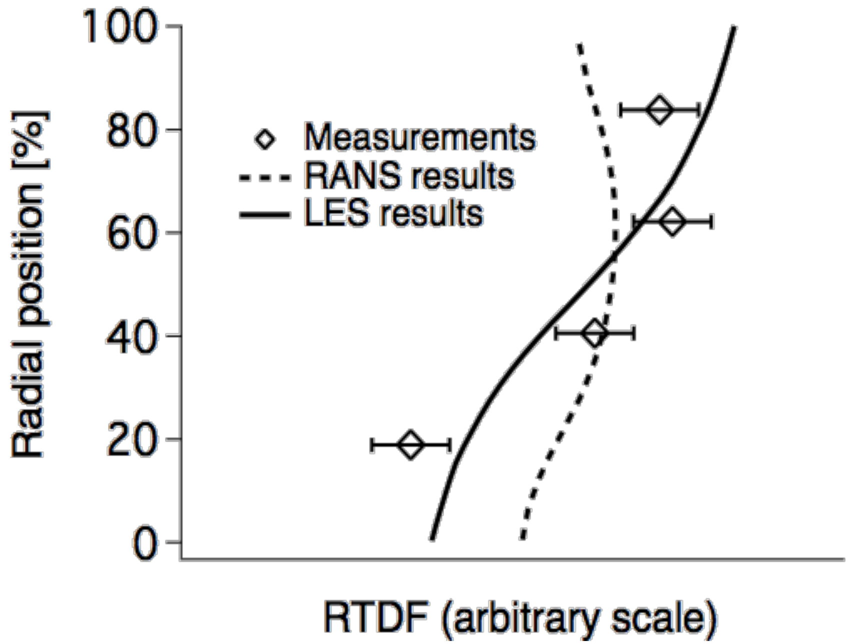
RANS versus LES : Impact on a design criterion (i.e. RDTF) [1,2,3]

$$RTDF(r) = \frac{\left\langle \overline{T}(r,\theta) \right\rangle_{\theta} - \left\langle \overline{T}(r,\theta) \right\rangle_{\theta r}}{\left\langle \overline{T}(r,\theta) \right\rangle_{\theta r} - \overline{T}_{inlet}}$$

RTDF(r) profile measures the radial temperature heterogeneities through the exit plane of the chamber ⇒ controls the turbine lifetime !!



Plane of interest



[1] G. Boudier et al., Comb. Inst., 31(2):3057-3082, 2007.
[2] G. Boudier et al., INCA workshop, 2005.
[3] S. James et al., AIAAJ, 44:674-686, 2007.

Effect of grid resolution: overview for a real combustor application [1,2]

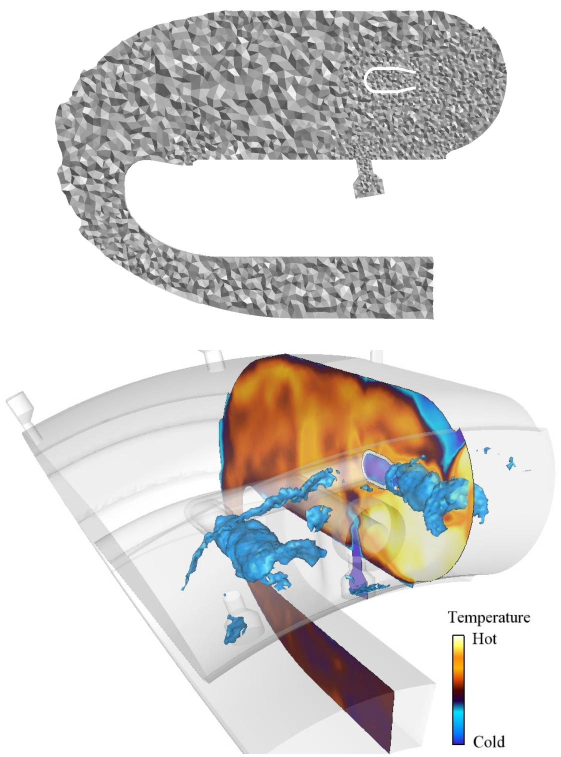
LES in a single sector burner

[1] G. Boudier et al., C&F., 155:196-214, 2008.

[2]. G. Boudier et al., QLES, Leuven, 2007.

Coarse mesh

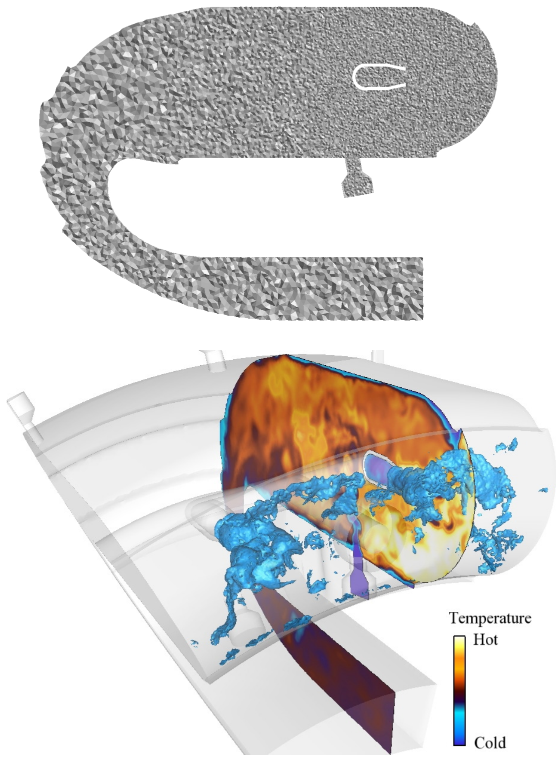
(1.2 M cells)



315 CPU hours

Intermediate mesh

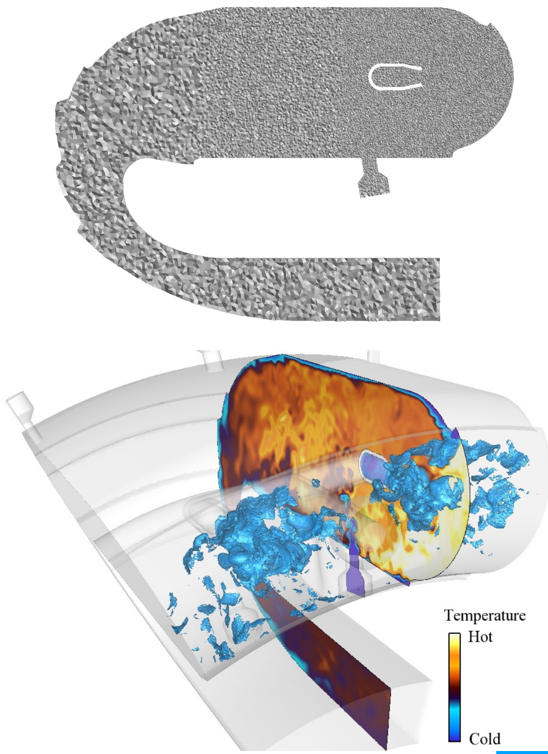
(10.6 M cells)



4,550 CPU hours

Fine mesh

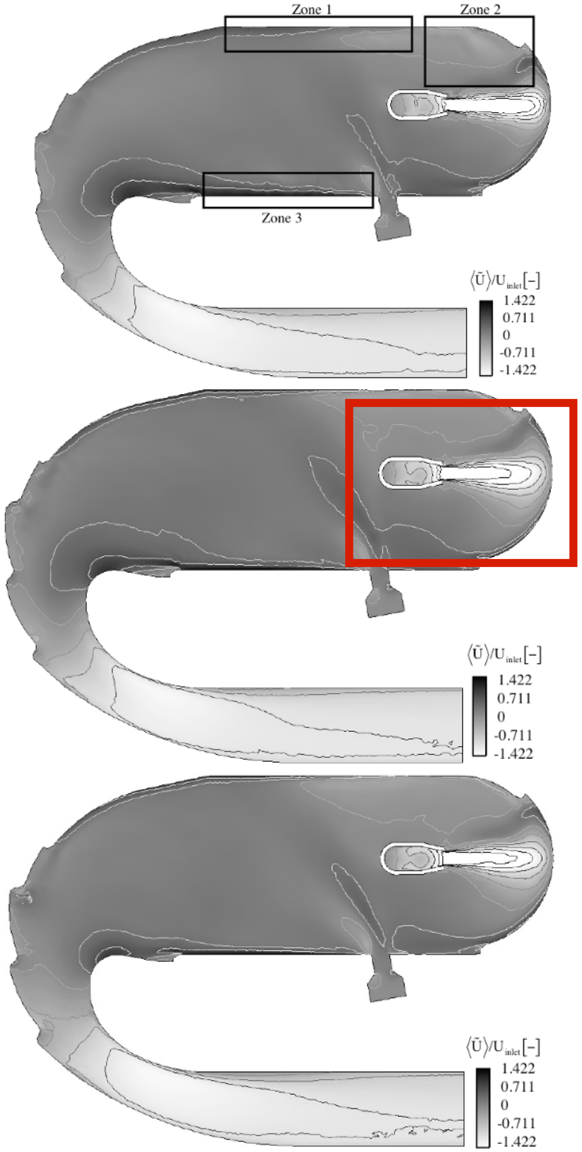
(43.9 M cells)

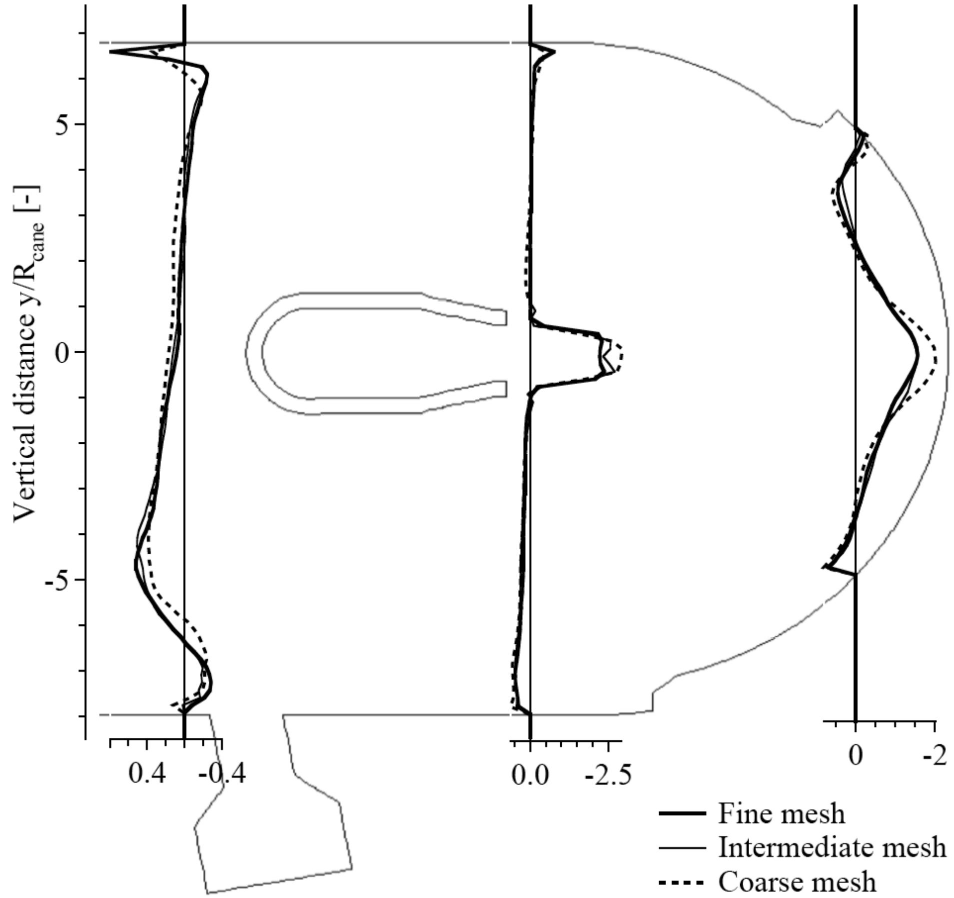


30,200 CPU hours

Effect of grid resolution: overview for a real combustor application [1,2]

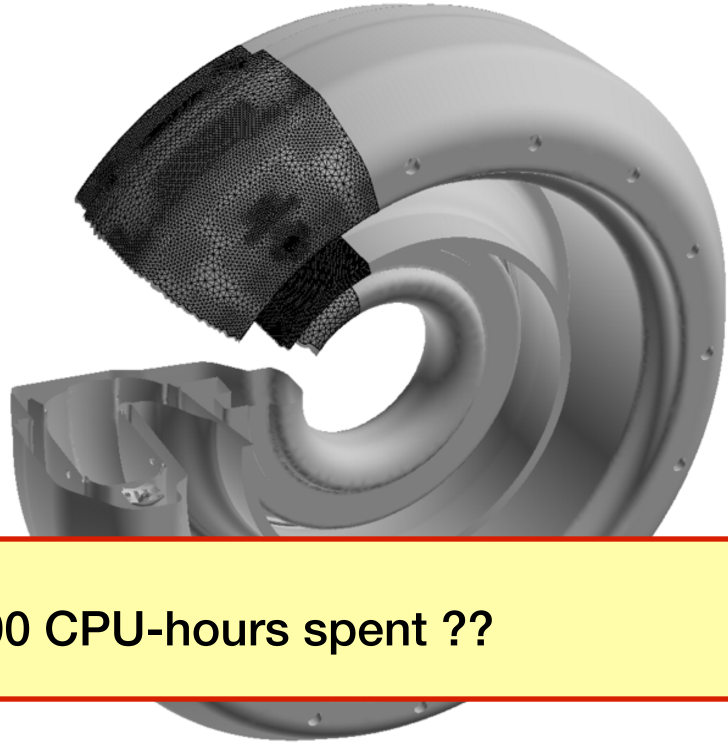
Increasing mesh resolution





[1] G. Boudier et al., C&F., 155:196-214, 2008.
[2]. G. Boudier et al., QLES, Leuven, 2007.

Extending to the full annular burner: thermo acoustic instabilities



• **Numerical aspects:**

- 3D compressible LES (AVBP),
- reactive Navier-Stokes solver,
- TTGC convective scheme (3rd order),
- Smagorinsky model [1],
- NSCBC boundary conditions [2],
- Initial conditions from statistically converged mono-sector results.

What do you get out of the 1,000,000 CPU-hours spent ??

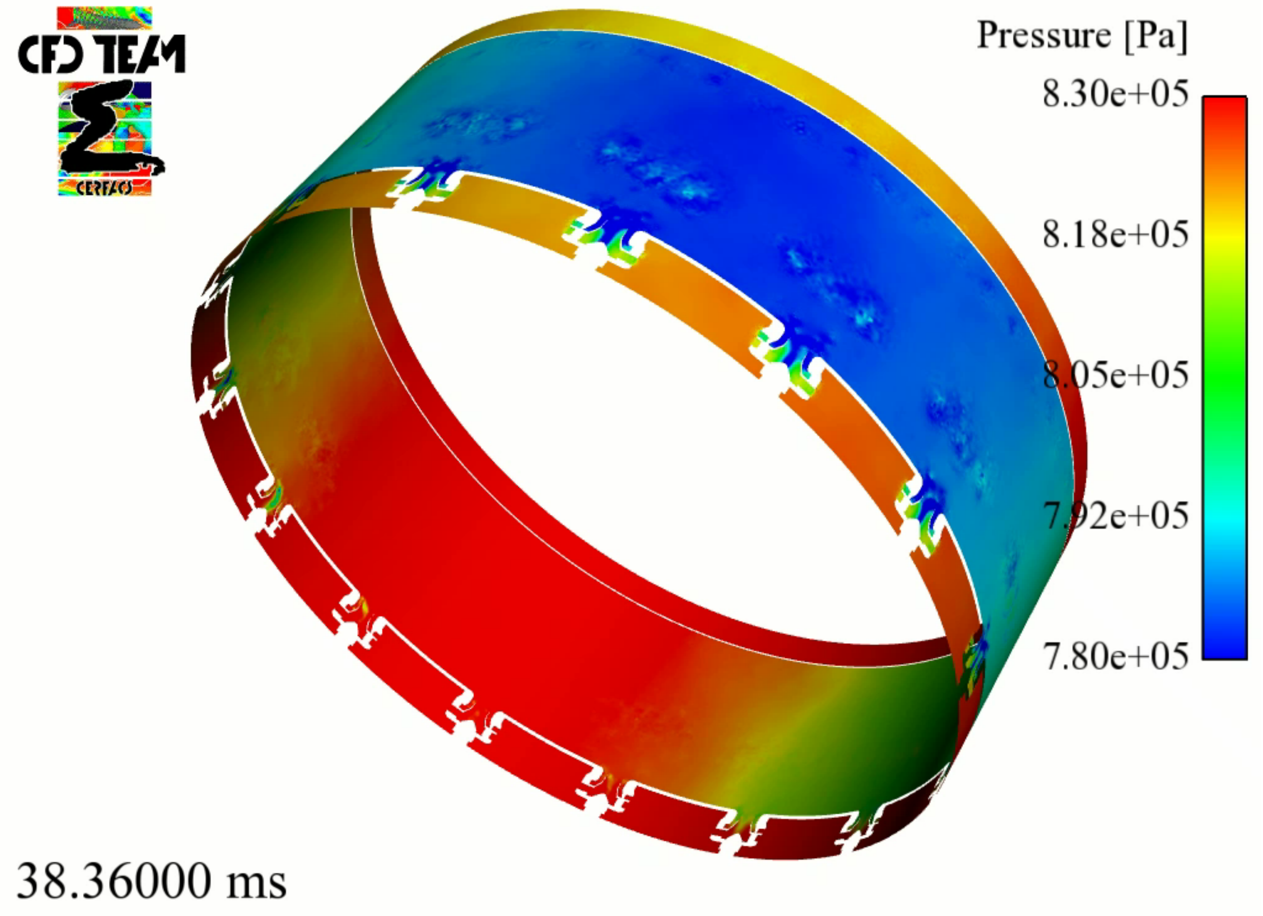
• **Chemical aspects:**

- JP10 1-step fitted mechanism (surrogate for kerosen [3])
- Dynamic Flame Thickening [4].

[1] Smagorinsky et al., 1963
[2] Poinsot et al., 1992
[3] Légier et al., 2001
[4] Colin et al., 2000

G. Staffelbach et al., 2008
G. Boufier et al., IJ Aeroacoustic, 2007

Application to full annular burner: impact on pressure



- Temporal evolution of pressure typical of the expression of two counter-rotating pressure waves: self-sustained azimuthal thermo-acoustic instability.

<u>Application to full annular burner:</u> impact on temperature

First numerically observed azimuthal thermo acoustic instability…

=> *no external forcing source*: the instability naturally arises when you start the full LES.

=> *mesh independent results*.

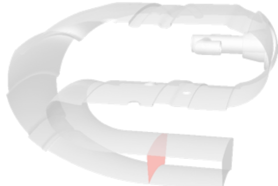
=> results *coherent with reported frequencies* observed on exp. benches and on the engine demonstrator.

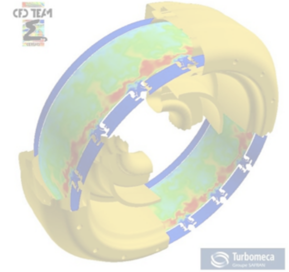
Need to capitalize to **produce knowledge on the triggering mechanisms** to eventually **anticipate such instabilities before computing it** or constructing the entire engine…

38.36000 ms

- Unexpected implication of the instability: azimuthal oscillation of combustion and the temperature field.

Outline of the talk





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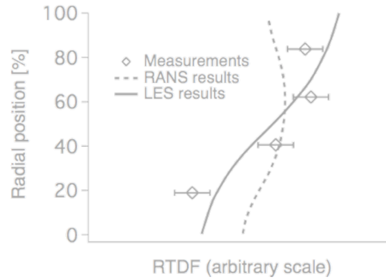

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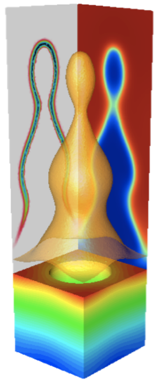

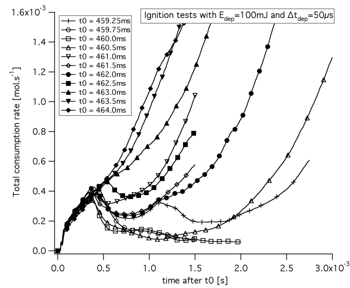

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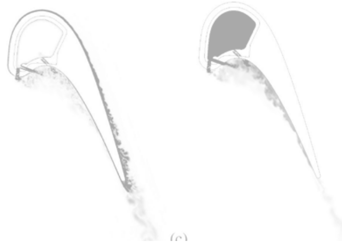


IV] Conclusions:

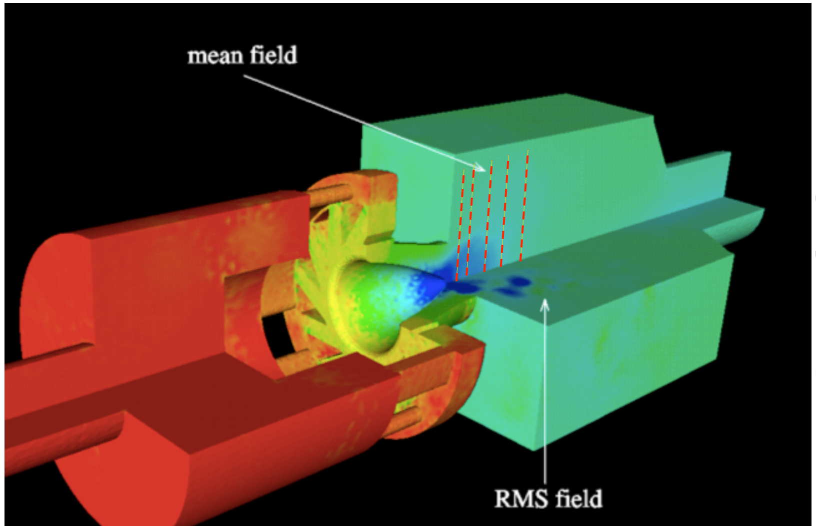
I.1] LES modeling and code validations

Gaseous turbulent combustion validation: Premixed combustion

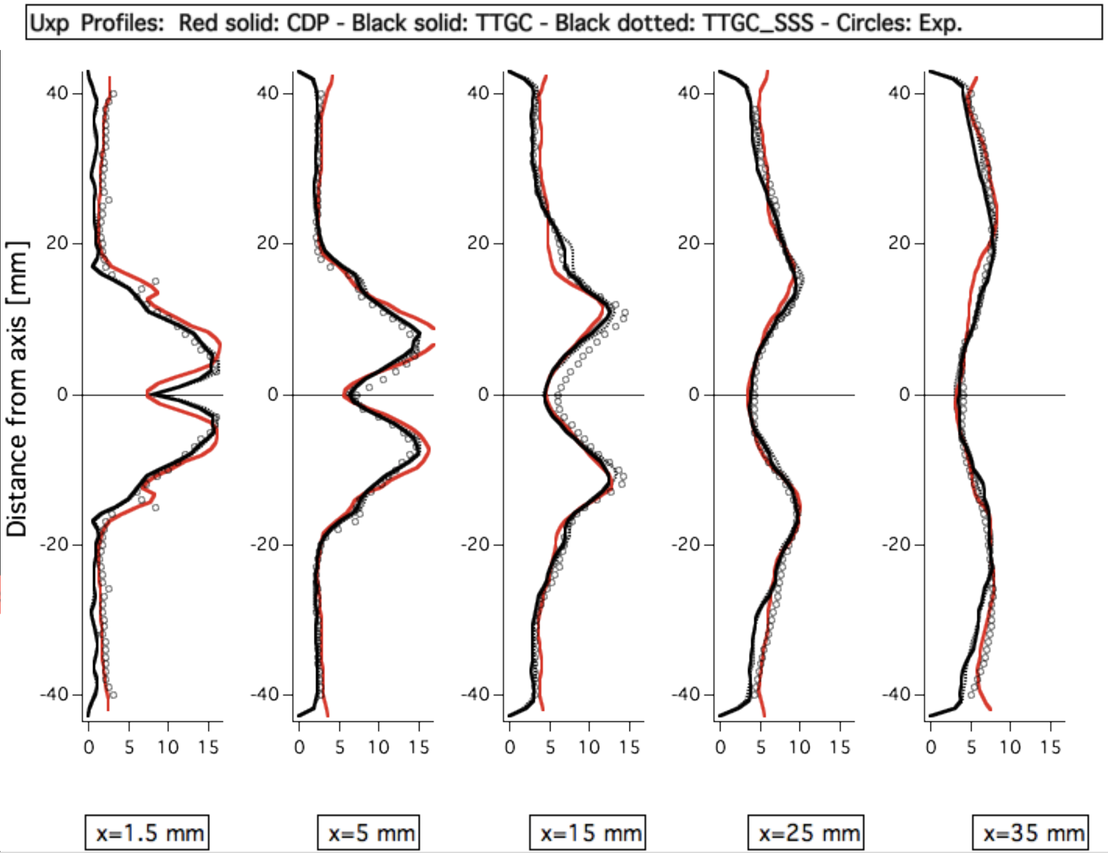
PRECCINSTA burner [1,2]: atmospheric rig targeted to understand thermo-acoustic instabilities

--> Measured profiles of Velocity (LDV), Species and Temperature fields (Raman) for different operating cdts (i.e. equivalence ratio – stable & unstable combustion)

Axial velocity RMS profiles [3-6]:*(Φ=0.8)*



3 millions cell



[1] P. Weigand et al., ASME Turbo-Expo, 2006.

[2] P. Meier et al., C&F 150(1-2), 2-26, 2007.

[3] S. Roux et al., C&F 141, 40-45, 2005.

[4] J. Galpin et al., C&F 155(1-2), 247-266, 2008.

[5] B. Fiorina et al., C&F 157, 465-475, 2010.

[6] V. Moureau et al., C&F 158, 1340-1357, 2011.

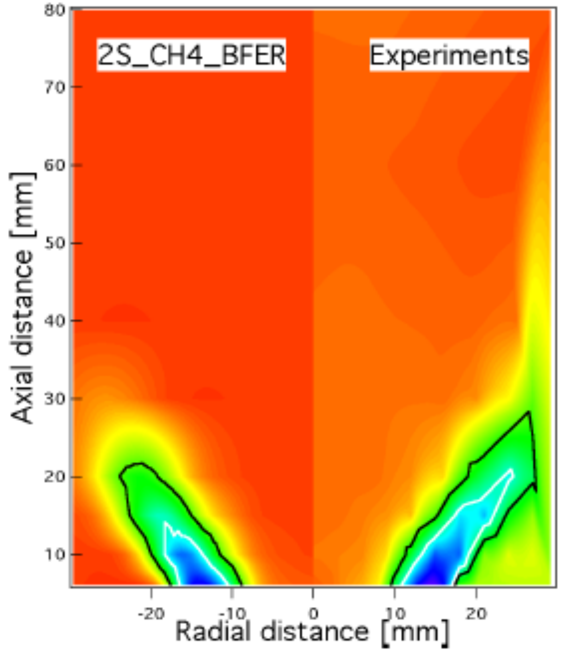
One difficulty for LES when faced with these setups is to go after more specific quantities: intermediate species of reactions & pollutant formations…

=> what model / chemical scheme to use and how ??

[1] B. Franzelli et al., C&F, 157:1364-1373, 2010.
[2] W.P. Jones et al., C&F 73:222-233, 1988.
[3] N. Peters, Vol. 241, Springer, Berlin, 1985.

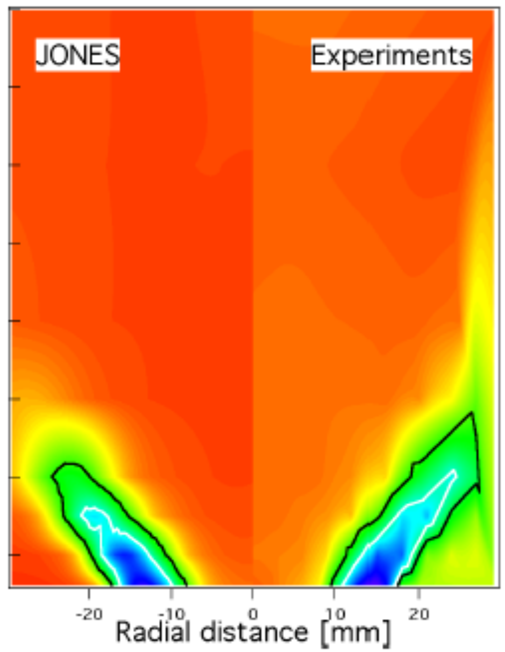
2 step reduced scheme [1]

$$CH4 + 1.5\ O_2 \quad => \quad CO + 2\ H_2O$$
$$CO + 0.5\ O_2 \quad <=> \quad CO_2$$



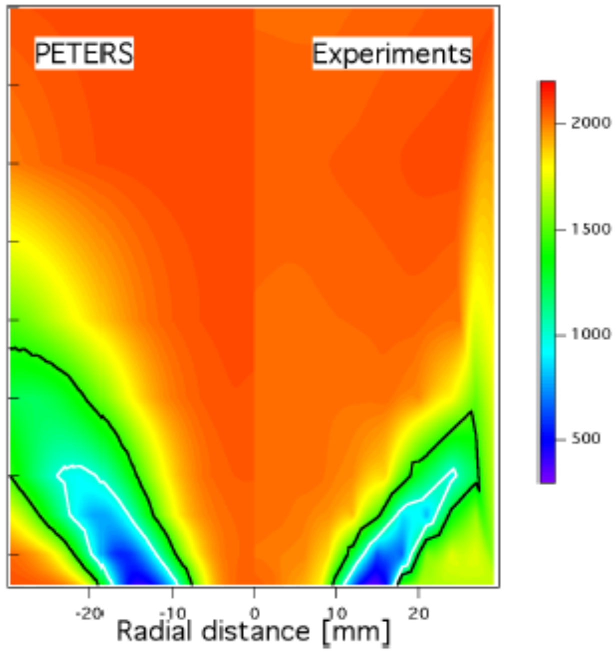
4 step reduced scheme [2]

$$CH_4 + 0.5\ O_2 \quad => \quad CO + 2\ H_2$$
$$CH_4 + H_2O \quad => \quad CO + 3\ H_2$$
$$CO + H_2O \quad <=> \quad CO_2 + H_2$$
$$H_2 + 0.5\ O_2 \quad <=> \quad H_2O$$



4 step reduced scheme [3]

$$CH_4 + 2\ H + H_2O \quad => \quad CO + 4\ H_2$$
$$CO + H_2O \quad <=> \quad CO_2 + H_2$$
$$2\ H + M \quad <=> \quad H_2 + M$$
$$3\ H_2 + O_2 \quad <=> \quad 2\ H + 2\ H_2O$$



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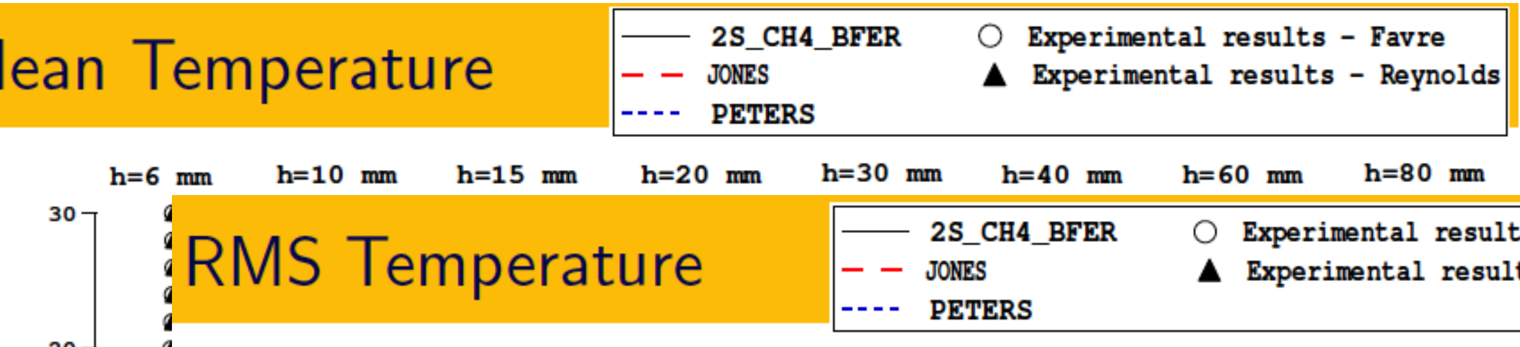
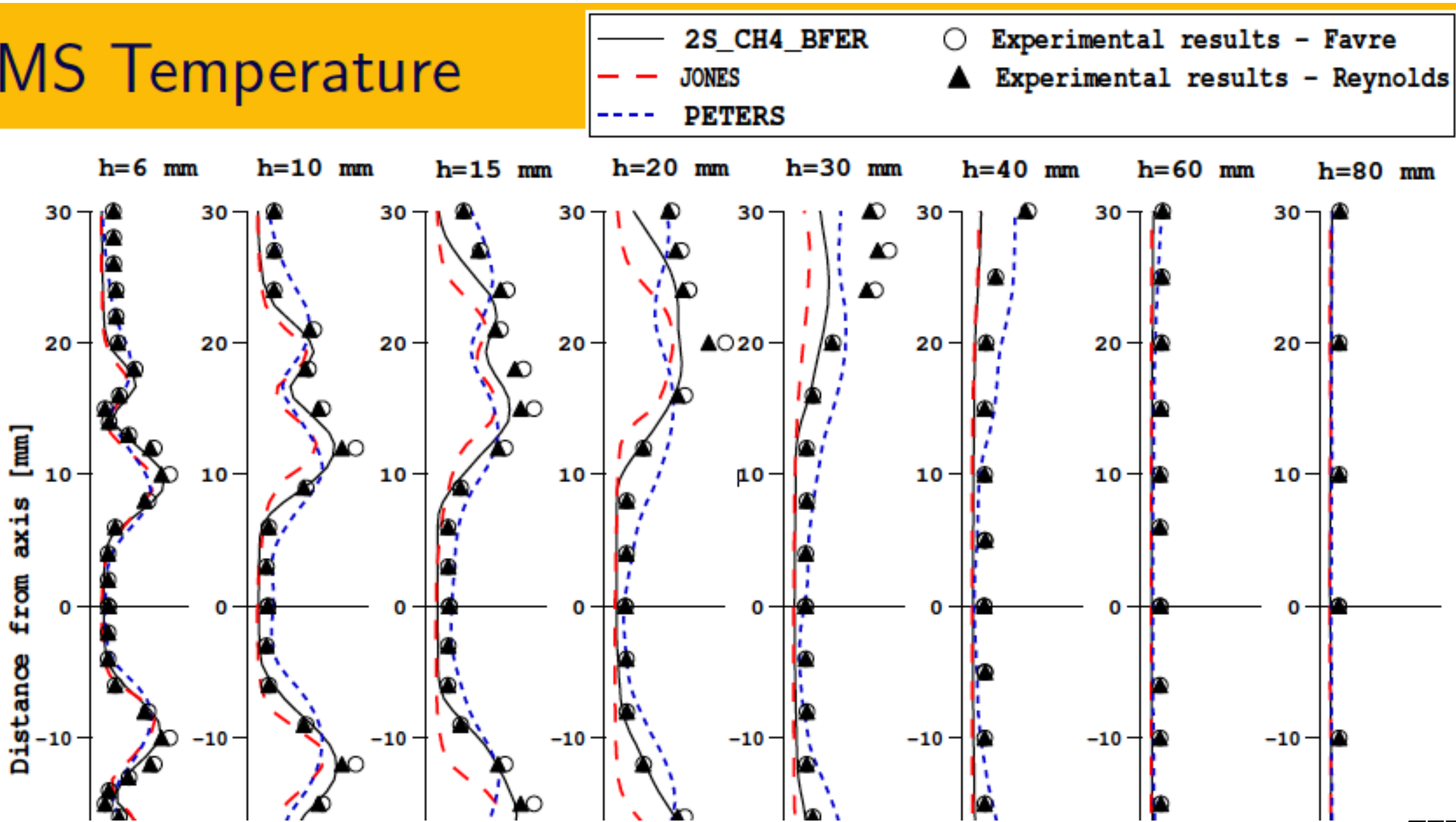
[2] W.P. Jones et al., C&F 73:222-233, 1988.
[3] N. Peters, Vol. 241, Springer, Berlin, 1985.

Mean Temperature

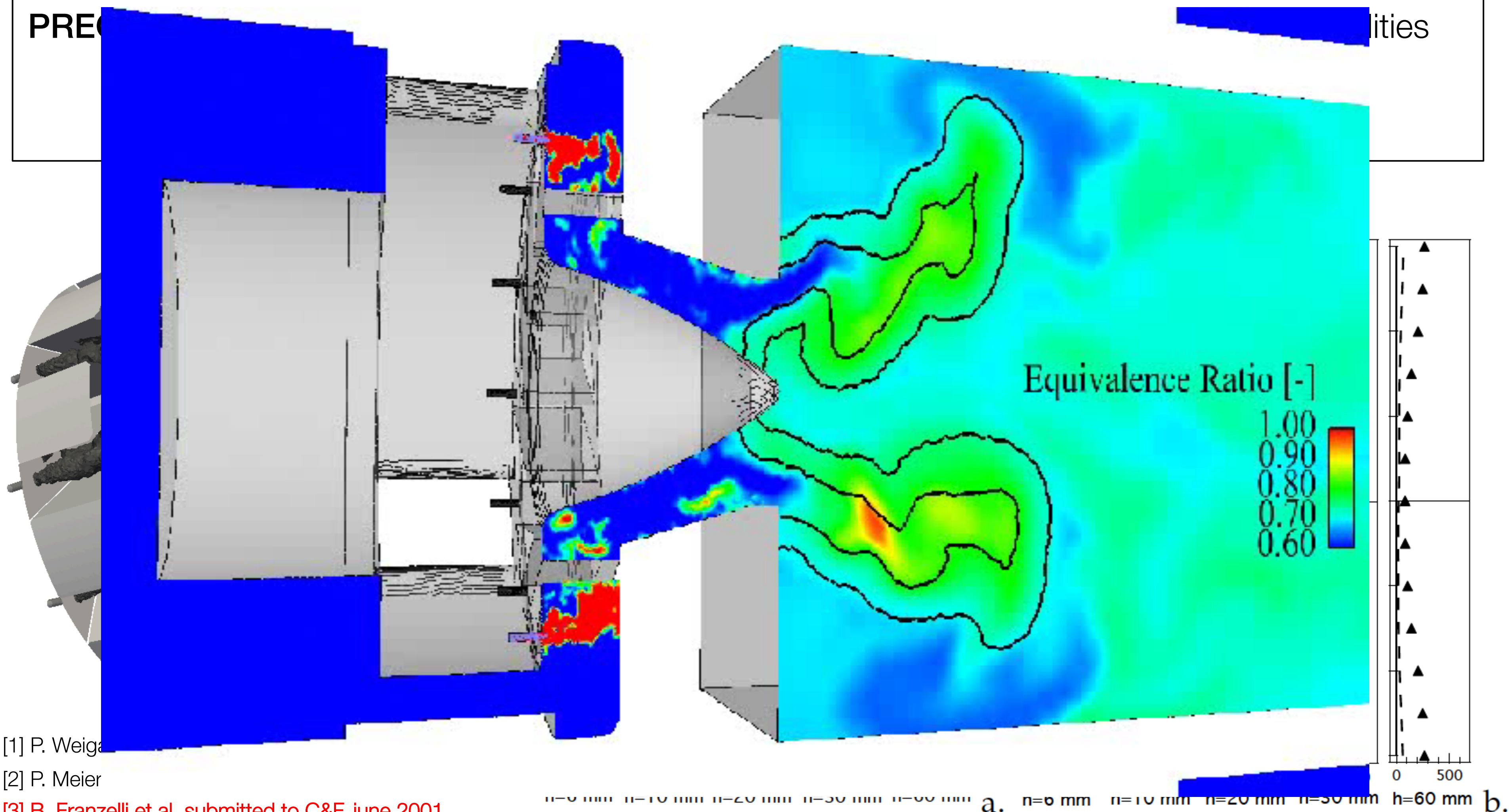


RMS Temperature



Gaseous turbulent combustion validation: Partially-premixed combustion

PRE ... ities



[1] P. Weig
[2] P. Meier
[3] B. Franzelli et al, submitted to C&F, june 2001,

LES is by construction a temporally dependent CFD solution:

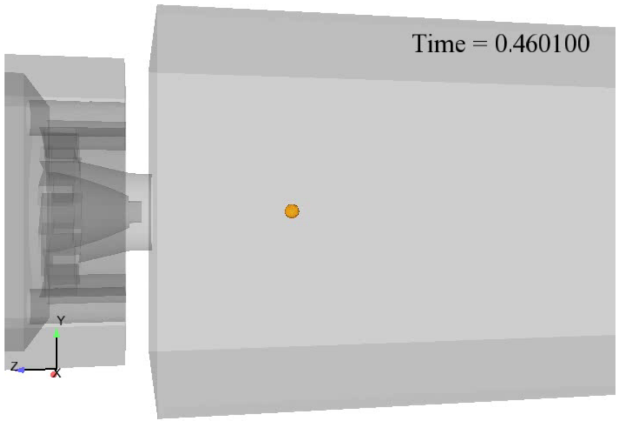
By construction large scale transient flow phenomena issued by LES will be representative of the physics controlling this single flow realization, i.e.:

1/ set of BC's and IC's

2/ careful with the modeling (loss of causality and locality at the sub-grid and nearby scales…)

Successful ignition

CTRZ region

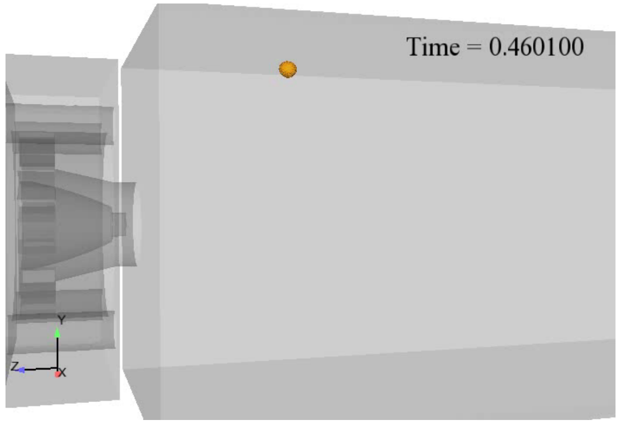


Successful ignition

Near wall region

Failed ignition

Near wall region



In the initial phase following the energy deposit: successful vs failed

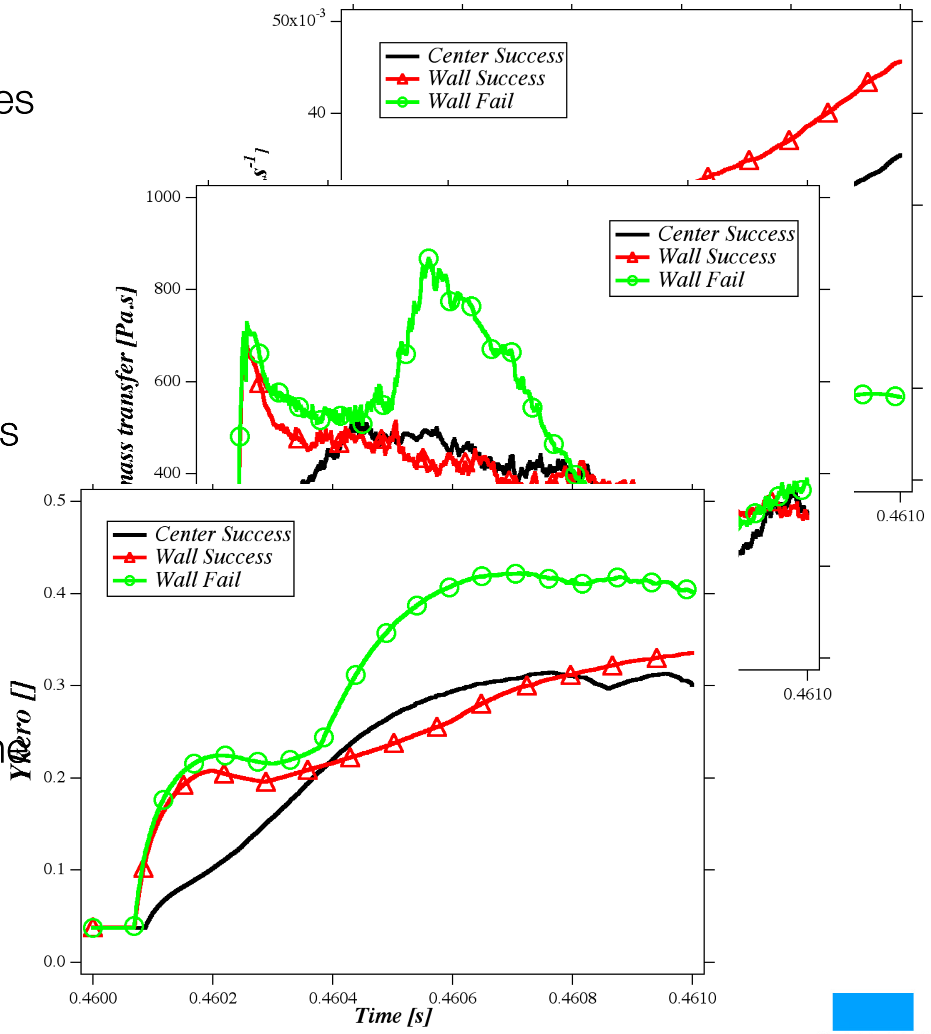
=> Change in slope of the fuel consumption rates

=> **Failed case**: most of the flame heat is used to evaporate the surrounding liquid fuel until a sudden drop.

=> **Successful case**: slow evolution of the mass transfer rate.

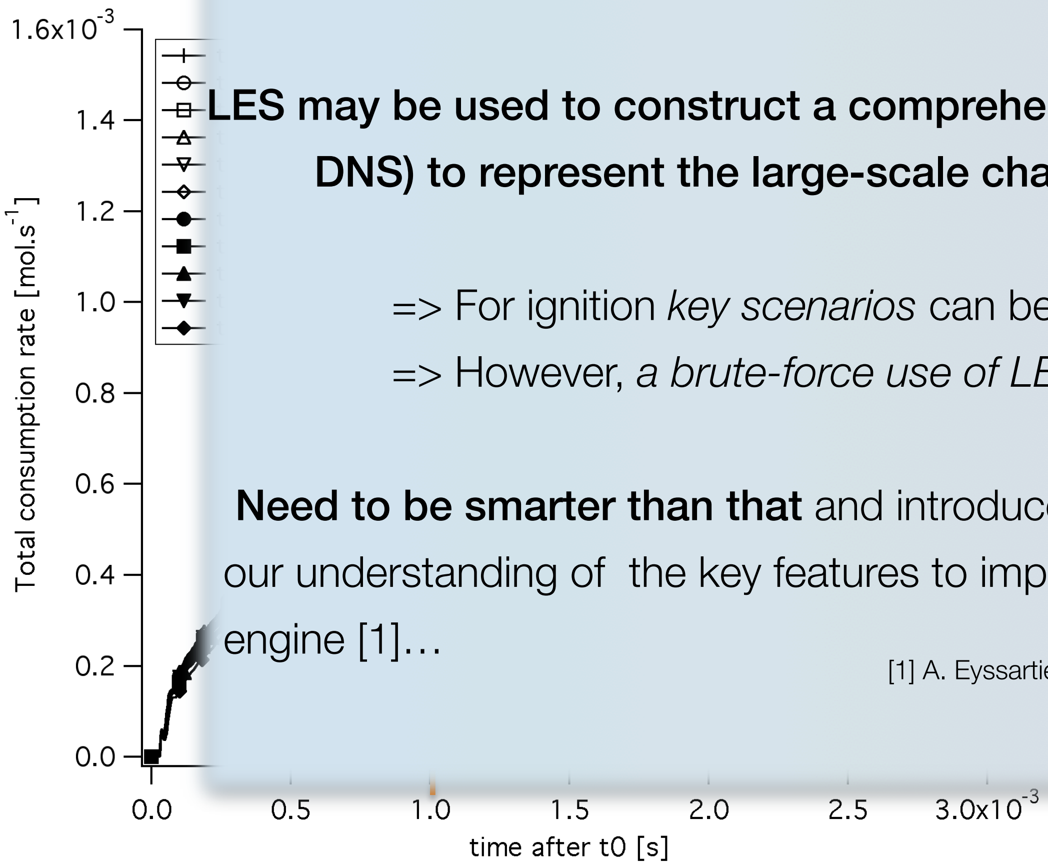
=> Major differences in the local values of the gaseous fuel mass fraction:

- **Failed case**: too rich to fully evaporate the liquid fuel crossing the flame kernel
- **Successful case**: local variations at the flame kernel position ensure full ignition



For modeling and understanding you need different realizations of the ignition sequence:

=> use of statistically stationary cold LES and start the energy deposit at different instants



LES may be used to construct a comprehensive numerical data-base (just like DNS) to represent the large-scale chain of events of transient flows

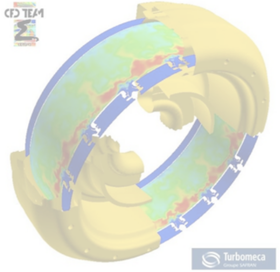
=> For ignition *key scenarios* can be observed and evaluated

=> However, *a brute-force use of LES* (like shown here) is not realistic...

Need to be smarter than that and introduce **a statistical tool** that can improve our understanding of the key features to improve the ignition success of a real engine [1]…

[1] A. Eyssartier et al., submited to C&F, june 2011.

Outline of the talk



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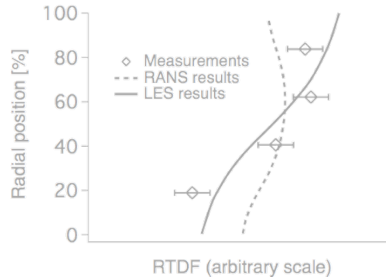
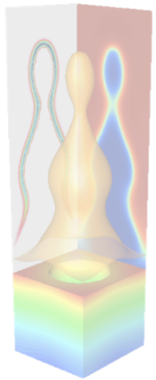
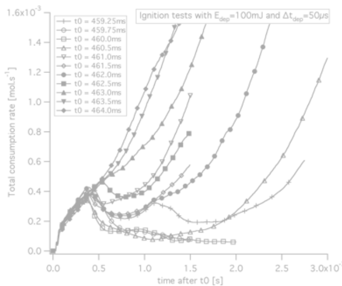


II] LES perspectives and applications:



=> LES modeling and code validations

=> Transient reacting flows: ignition process understanding



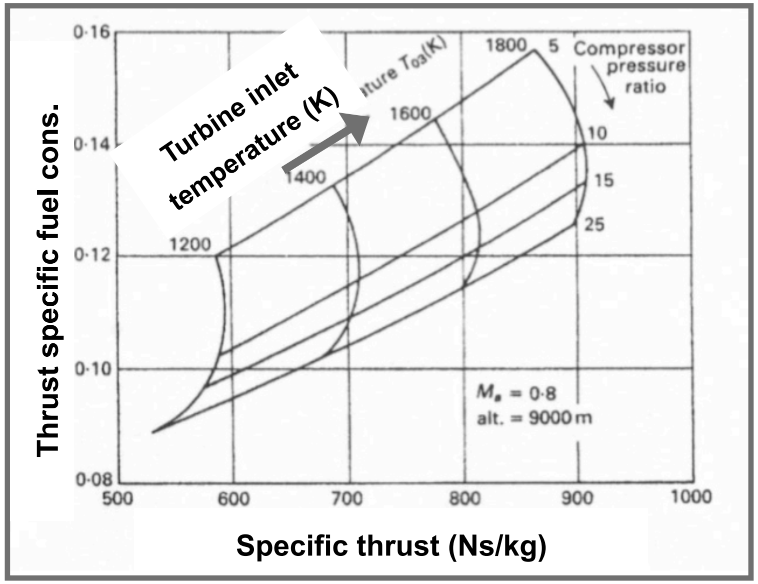
III] Perspectives:

=> Towards multi-physics CFD based on LES

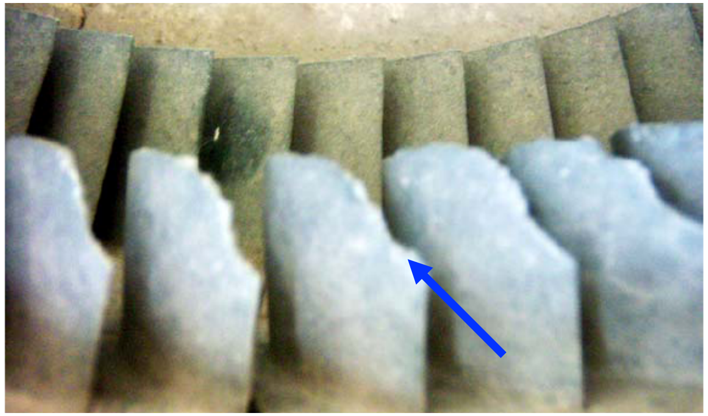
IV] Conclusions:

Engine design: increase the engine efficiency, reduce fuel consumption and pollutant emissions

- Efficiency:



However a 15 K increase at the turbine blade surface decreases the turbine lifetime by 2



- Low NOx design: increase the amount of air going through the fuel injection system to increase premixing and lean combustion

=> highly prone to combustion thermo acoustic instabilities

=> less 'fresh' air to dilute the hot gases entering the turbine…

LES imposes constraints:

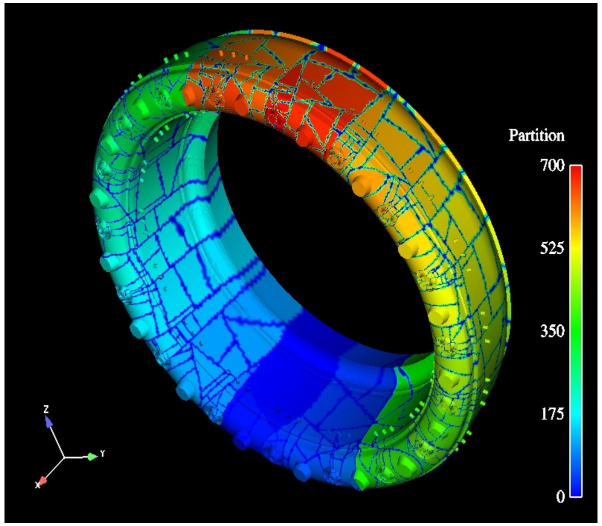
Natural pre-requisites:

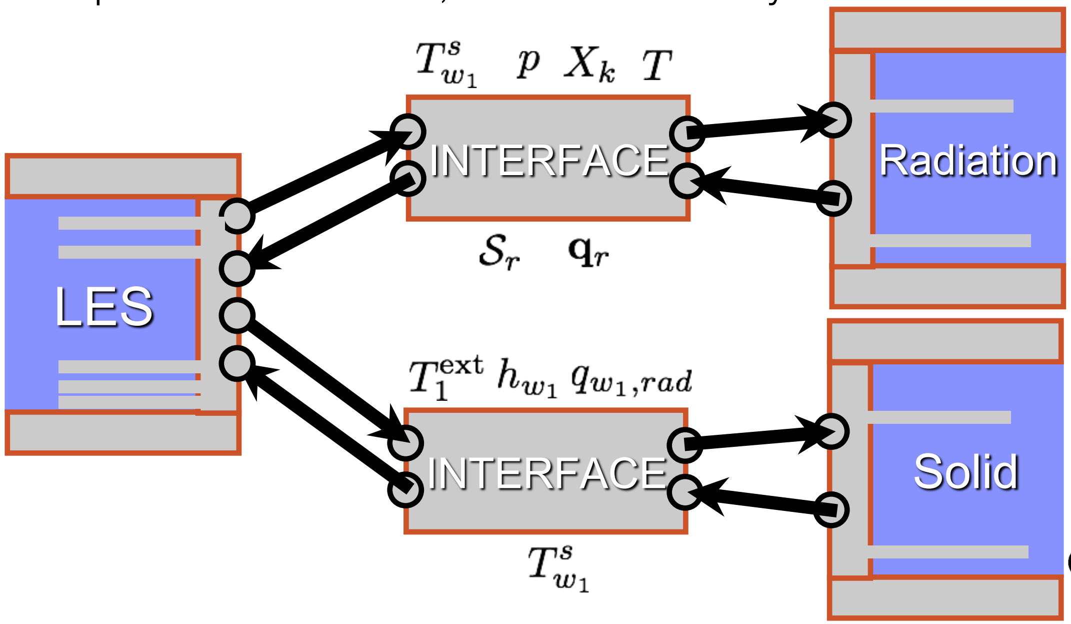
=> Interfacing massively parallel codes while preserving their respective scalability

=> Preserve the overall CPU cost of the new massively parallel application

Co-lateral scientific issues:

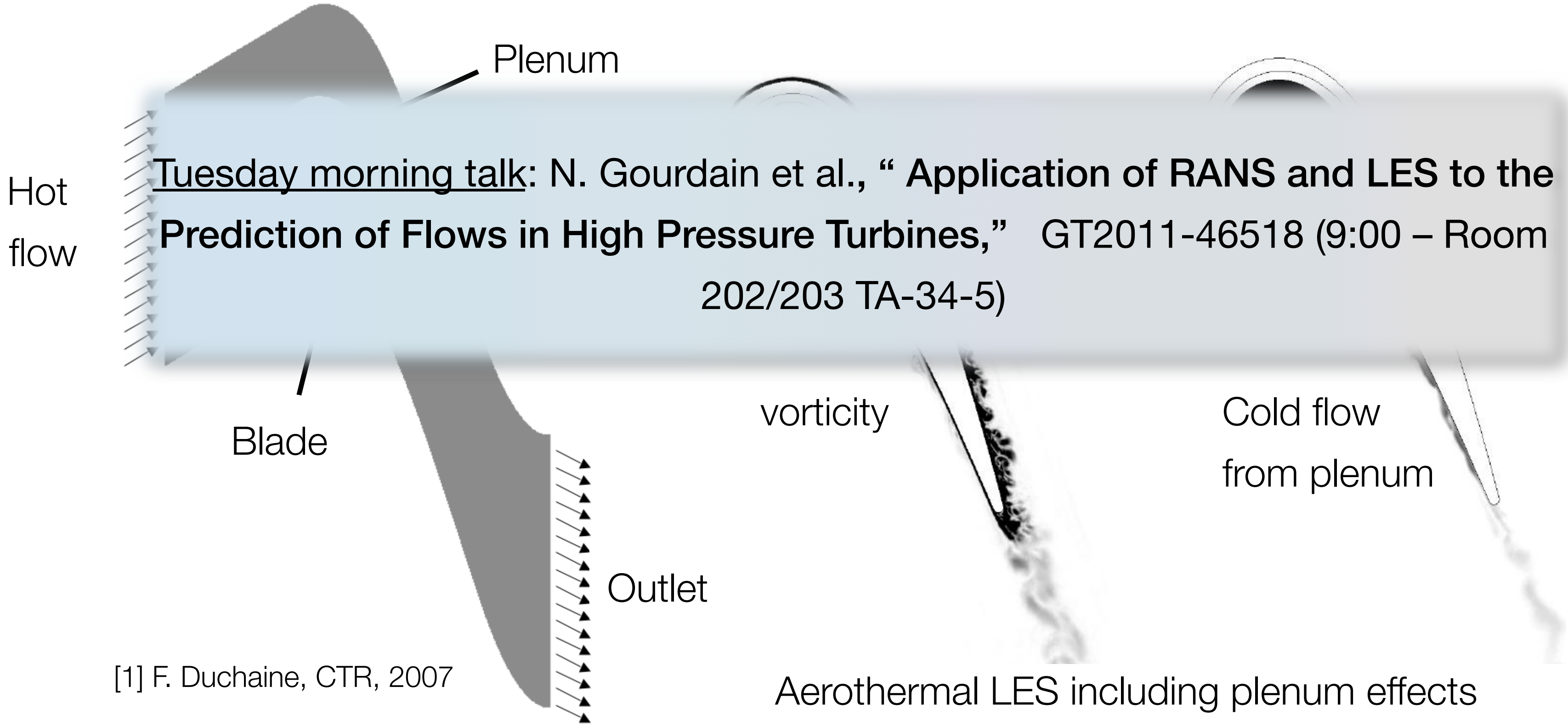
=> non-coincident meshes, interpolations schemes, numerical stability…





Aerothermal coupling simulations

- T120D configuration (VKI),
- **AVBP/AVTP coupling simulation [1],**
- Mesh is 6,5 millions of cells.
- Outlet Mach number: 0.87,
- Re = 4.0 10^5,
- scheme: TTGC (3^{rd} order),
- WALE turbulence model.

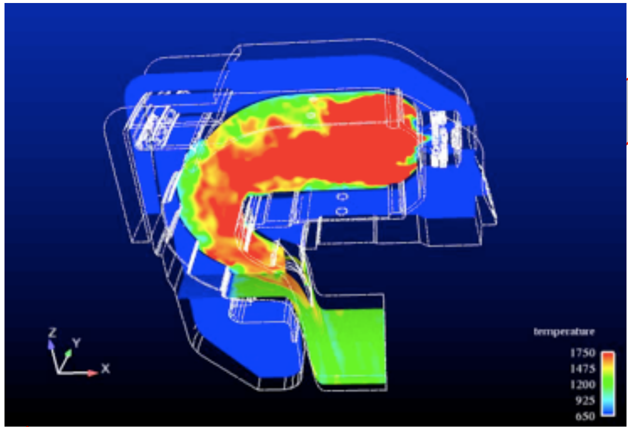


Tuesday morning talk: N. Gourdain et al., " **Application of RANS and LES to the Prediction of Flows in High Pressure Turbines,"** GT2011-46518 (9:00 – Room 202/203 TA-34-5)

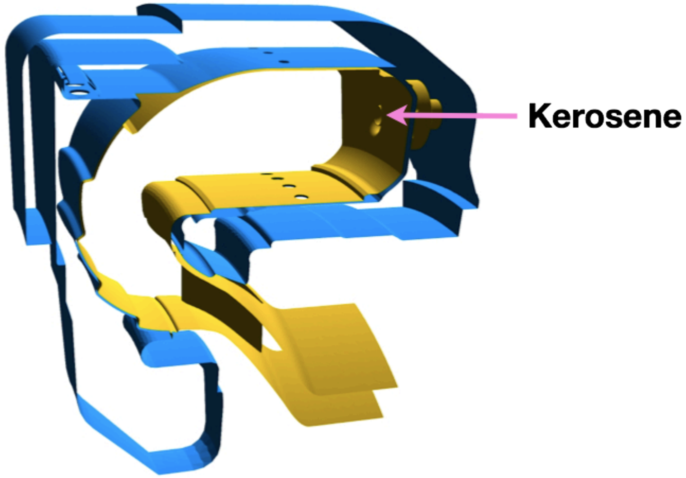
[1] F. Duchaine, CTR, 2007

Aerothermal LES including plenum effects

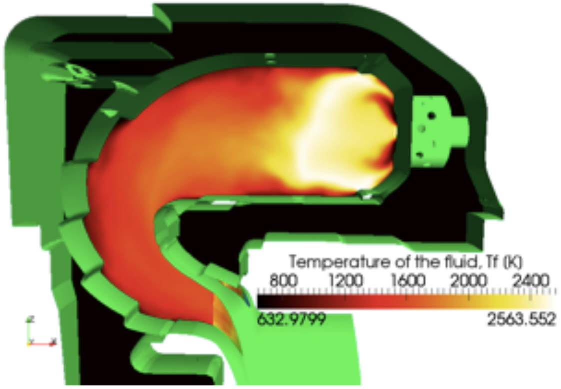
Helicopter engine application



Combustion LES solver AVBP



High Pressure Stator

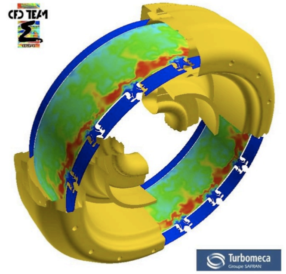


Radiation solver PRISSMA

O-Palm

Conduction solver AVTP

I] Recent contributions of LES to Combustor design:

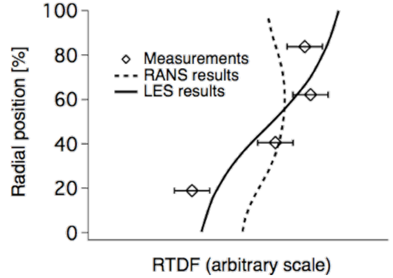


=> Real scale applications

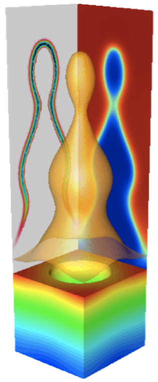
--> comparison against RANS predictions

--> mesh sensitivity analysis

=> Thermo-acoustic instability prediction

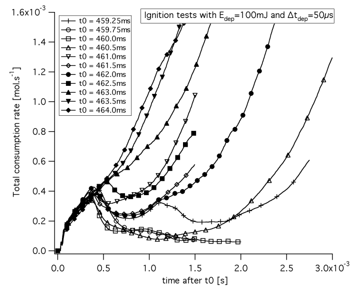


II] LES perspectives and applications:



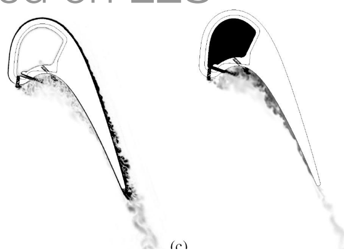
=> LES modeling and code validations

=> Transient reacting flows: ignition process understanding

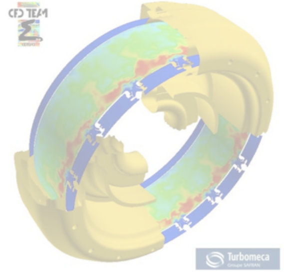


III] Perspectives:

=> Towards multi-physics CFD based on LES



IV] Conclusions:

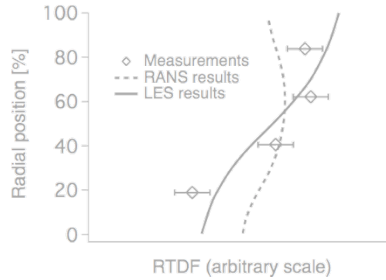


LES of industrial burners:

=> intermediate resolution and simple models seem sufficient

=> difficulties are in the cooling system modeling and introduced to be able to produce de computations (careful!!)

=> brute force LES is also possible but costly

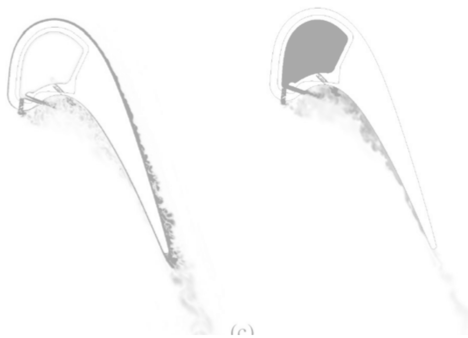


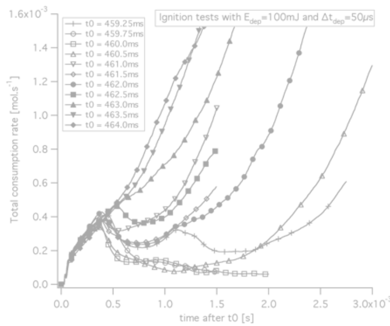
LES perspectives and applications:

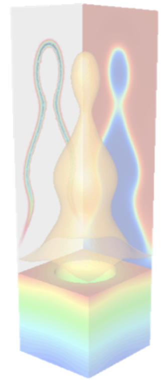
=> LES modeling and code validations is still needed: two-phase flows!!

=> Transient reacting flows: ignition process understanding

=> Towards multi-physics CFD based on LES



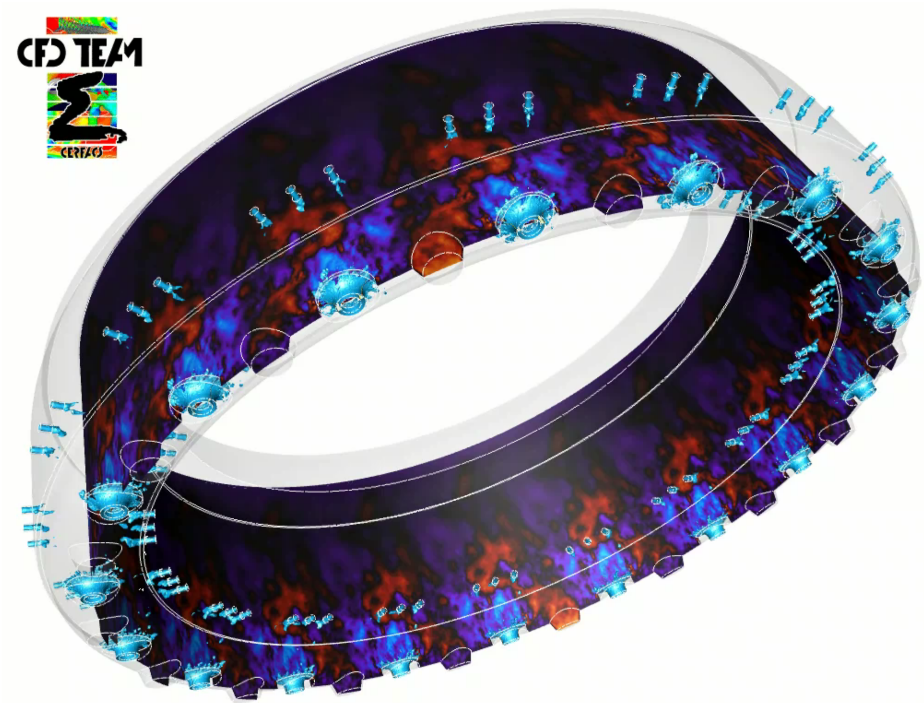




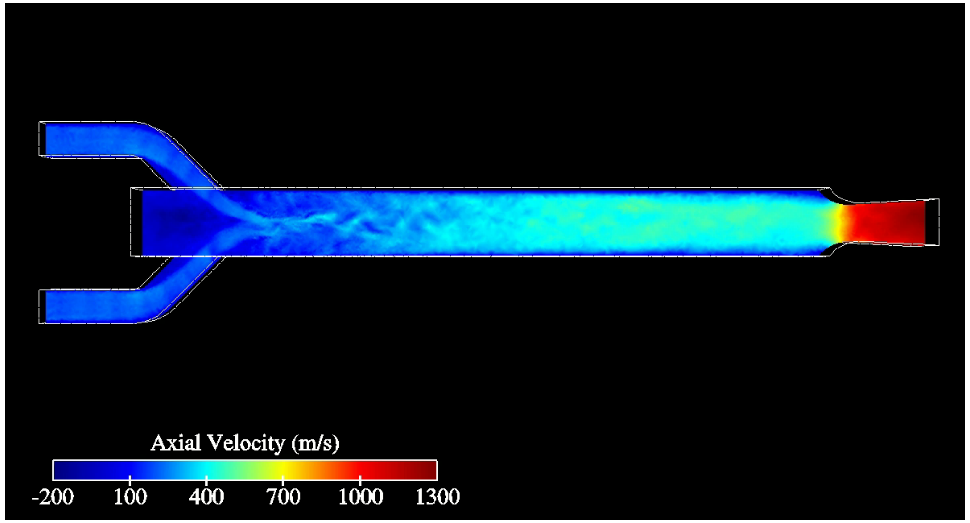
Thanks for your attention

Any questions?

Helicopter engine ignition sequence



Thermo-acoustic oscillation in ramjet burner

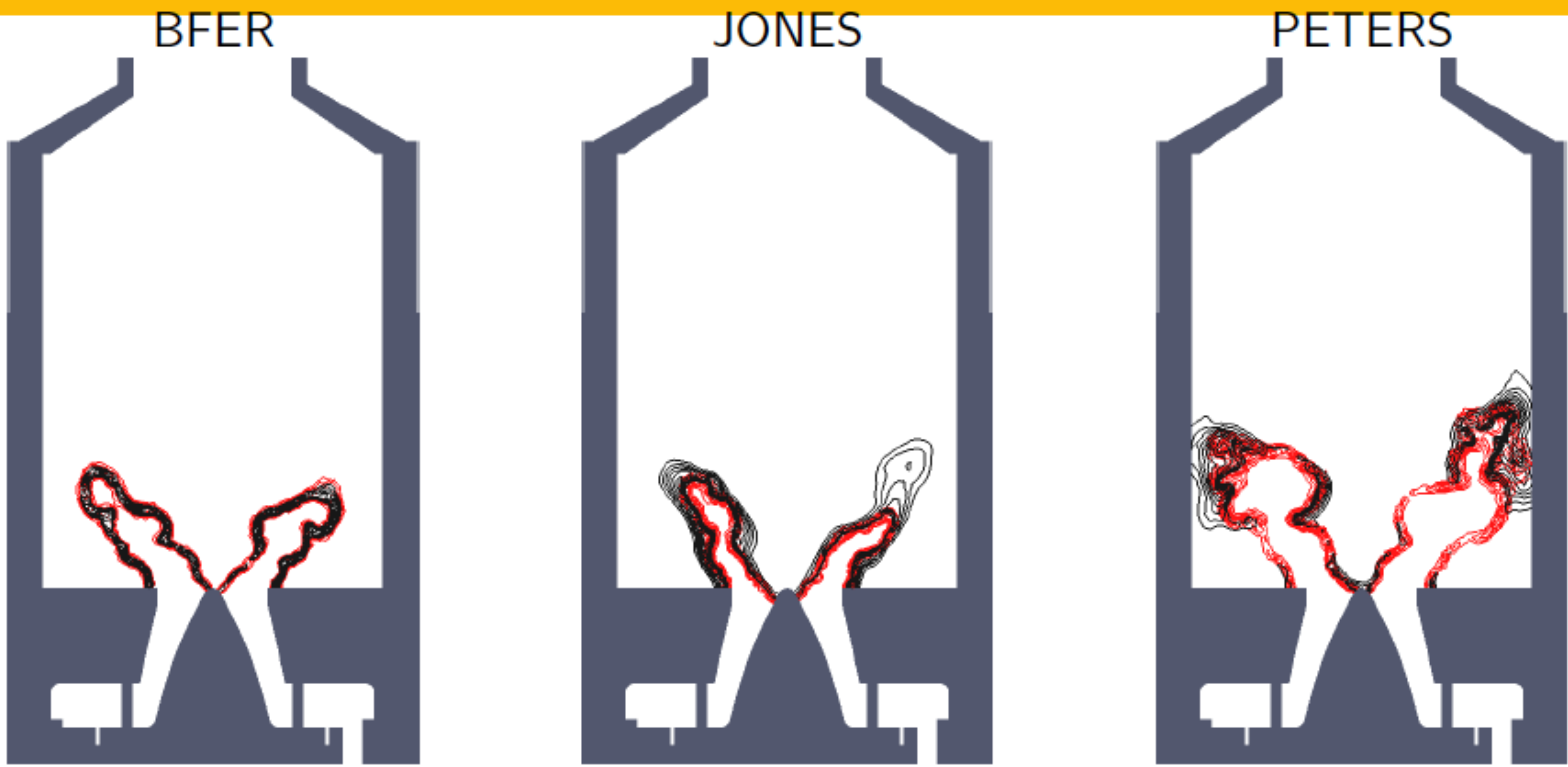


Thanks to the CERFACS-CFD team and our partners!

http://www.cerfacs.fr/~lgicquel
Laurent.Gicquel@cerfacs.fr

[1] B. Franzelli et al., C&F, 157:1364-1373, 2010.
[2] W.P. Jones et al., C&F 73:222-233, 1988.
[3] N. Peters, Vol. 241, Springer, Berlin, 1985.

Instantaneous CH4 oxidation and CO-CO2 recombination



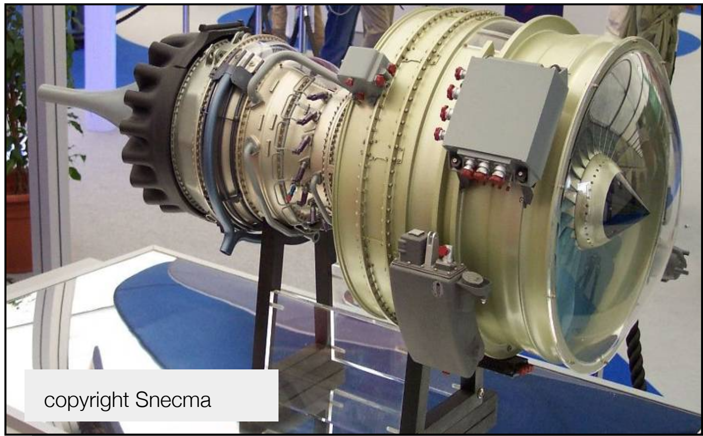
The aeronautic context

- CO_2 emissions from 1990 to 2025[1]: +100-600% (2008: 2.2% of the total).

- European objectives for 2020[2]:
  - ➢ reduce pollutant emissions (NO_x: -80%, CO_2: -50%),
  - ➢ reduce the noise emissions (-10dB).

- Economical constraints:
  - ➢ cut the engine costs (today it represents 30% of the aircraft cost).

copyright Airbus



copyright Snecma

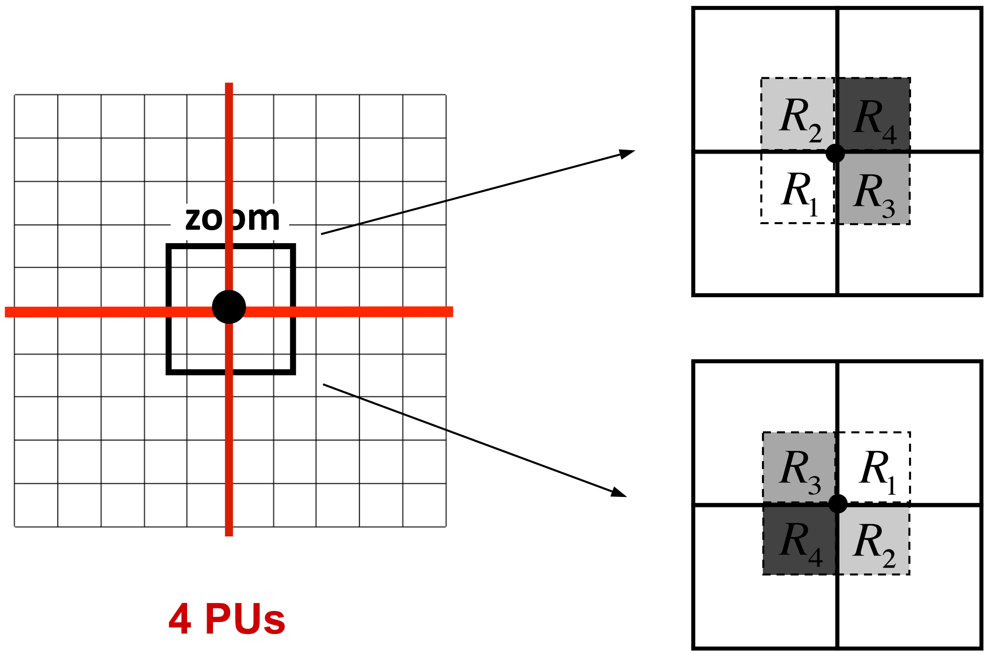
[1] INRETS, 2004
[2] ACARE recommendations

Economical and environmental constraints impose technical and technological changes!

Communication strategy: MPI non-blocking calls

How to compute a residual at partition interfaces?

Like this…



$$\frac{1}{4}\left\{R_4+\left[R_3+\left(R_2+R_1\right)\right]\right\}$$

D C B A

$$\neq$$

$$\frac{1}{4}\left\{R_1+\left[R_2+\left(R_3+R_4\right)\right]\right\}$$

A B C D

…or like this…

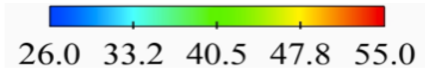
Problem: non-blocking communications induce a non-deterministic behavior

Impact of rounding errors on LES

Consequence of the lack of associativity property (Floating point arithmetic):

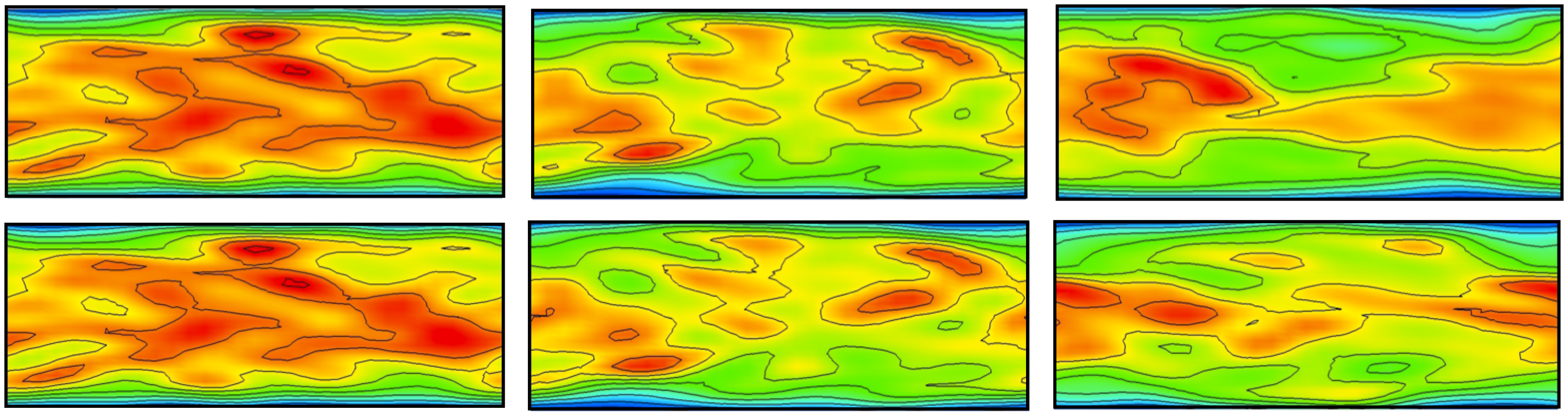
- illustration on a temporally evolving turbulent channel (AVBP).

Instantaneous axial velocity fields (m/s)



4 PUs

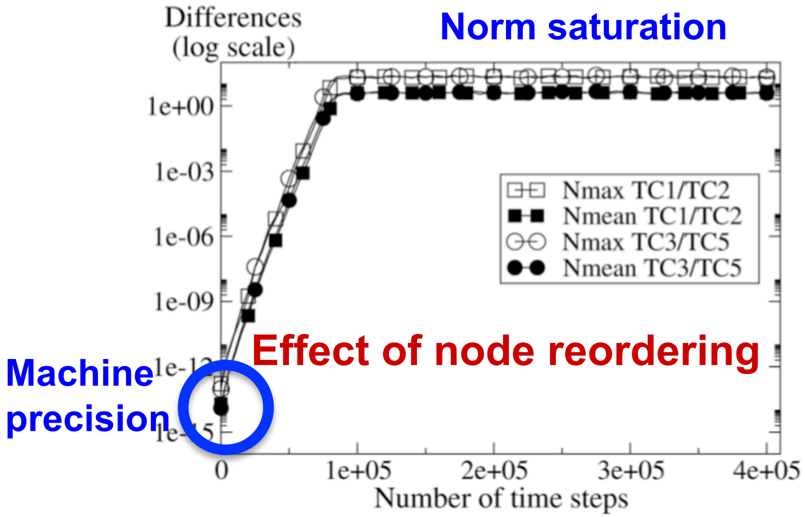
8 PUs

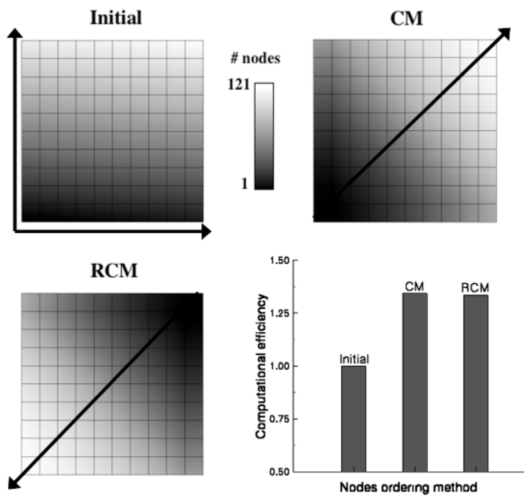


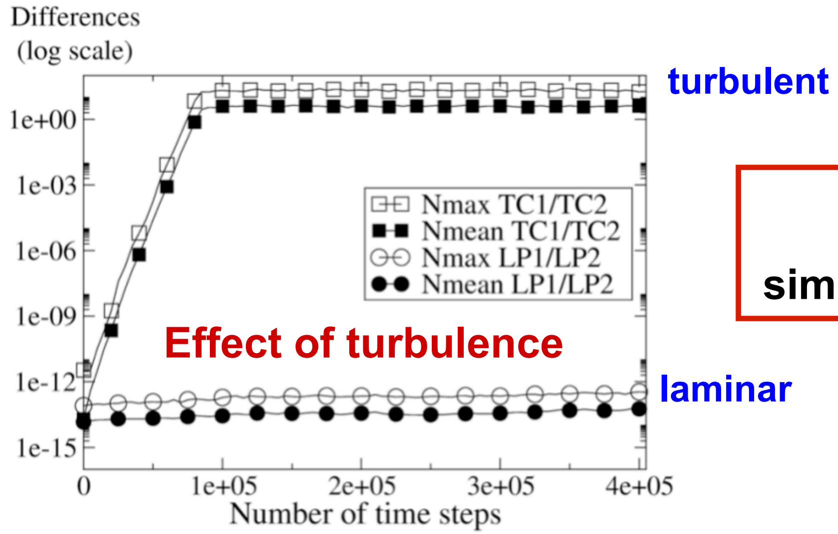
t_1 < t_2 < t_3

Senoner et al., 2008

Impact of rounding errors on LES







These results are not induced by parallel simulations (calc. performed with a single core!)

Senoner et al., 2008

Impact of mesh-partitioning

- Non-blocking communications participate to rounding errors (non-deterministic behavior),
- Blocking communications are good for deterministic behavior,
- Any sufficiently turbulent flow computed in LES exhibits significant sensitivity to small perturbations, leading to instantaneous solutions which can be totally different,
- The divergence of solutions is explained by 2 combined factors:
  - ➢ exponential separation of trajectories in turbulent flows,
  - ➢ propagation of rounding errors induced by domain partitioning and scheduling operations that can be different.
- Implicit stages done on a block basis can result in different convergence/instantaneous solutions:
  - ➢ in practice, this also impacts RANS convergence history… However since the solution is unique (?) and stationnary there should be no degradation of solution observed.

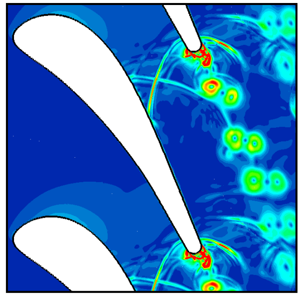
Validation of LES code after modifications may only be based on statistical fields!

1 Introduction
- Context

2 Numerical developments for HPC
- Flow solver examples
- Speed-up and Mesh-partitioning
- Communication, Impact on numerical solutions

3 Application to aeronautic challenges
- Civil aircrafts
- Compressor
- Combustion chambers
- **Turbines**

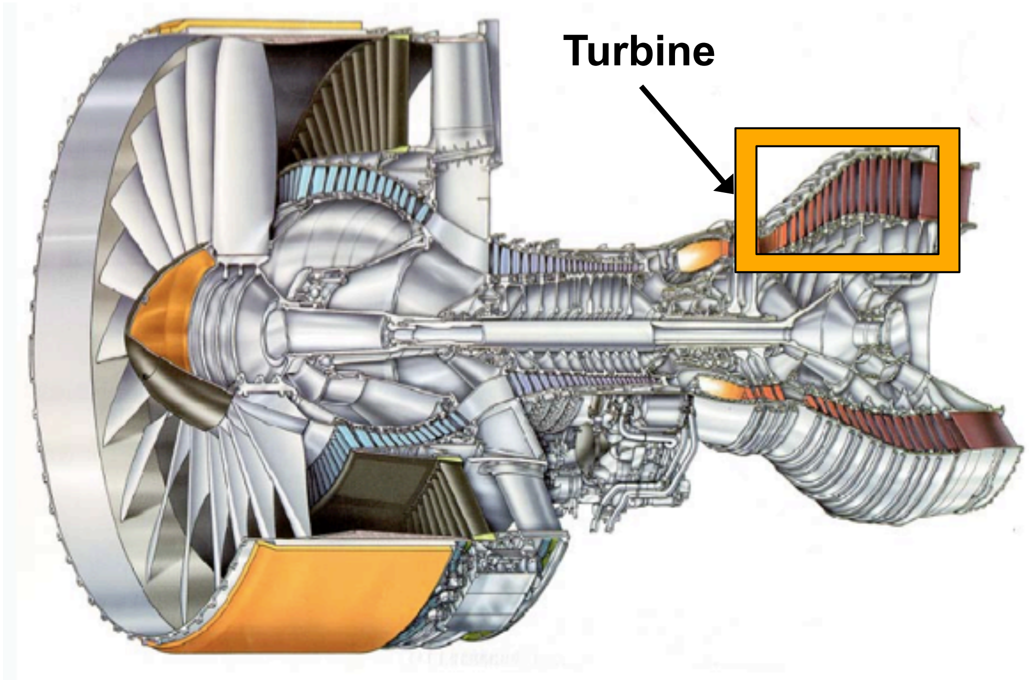
4 Conclusion and perspectives



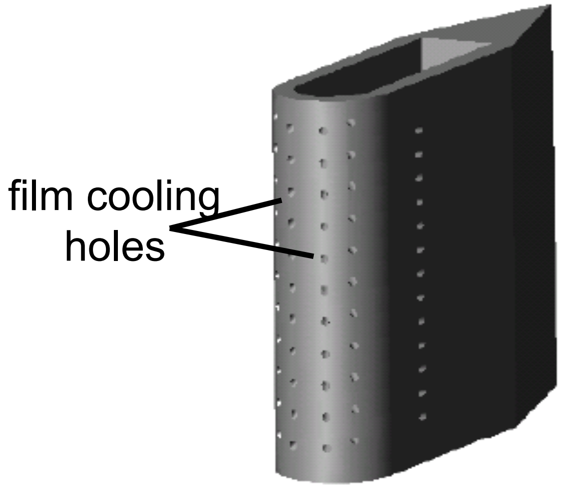
Turbines

<u>Objectives</u>

- As for compressors, unsteady flows are still not well understood,
- Main reasons are also computational cost, size and complexity of the configurations,
- Challenges today for turbine designers is the prediction of heat transfer:
    - a 15 K difference on the temperature prediction leads to a reduction of its life duration by a factor 2,
    - (U)RANS methods are not adapted to complex flows.

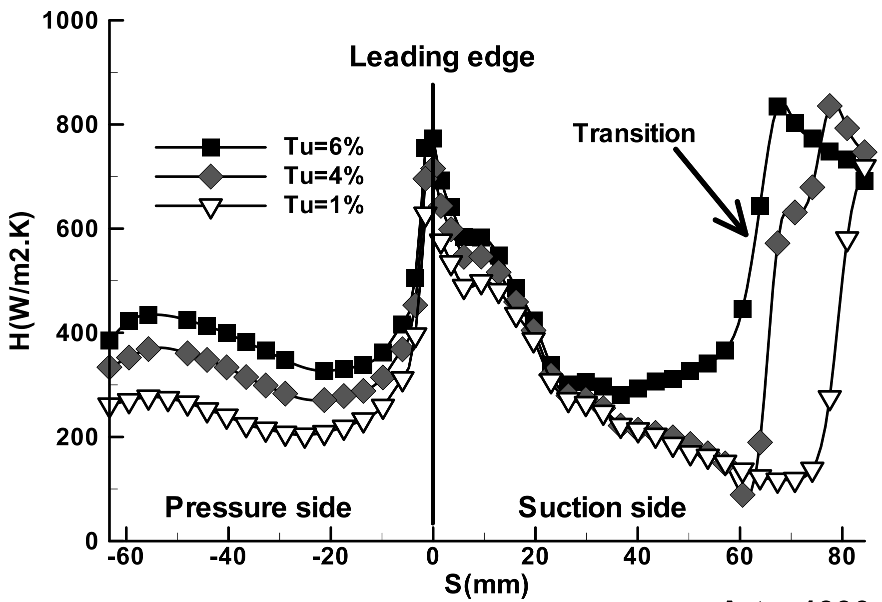


Aerothermal in turbine blades: overview

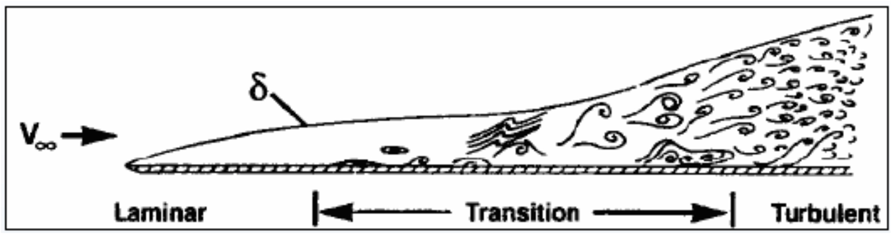


Complex flows that can not be efficiently computed with a (U)RANS method:

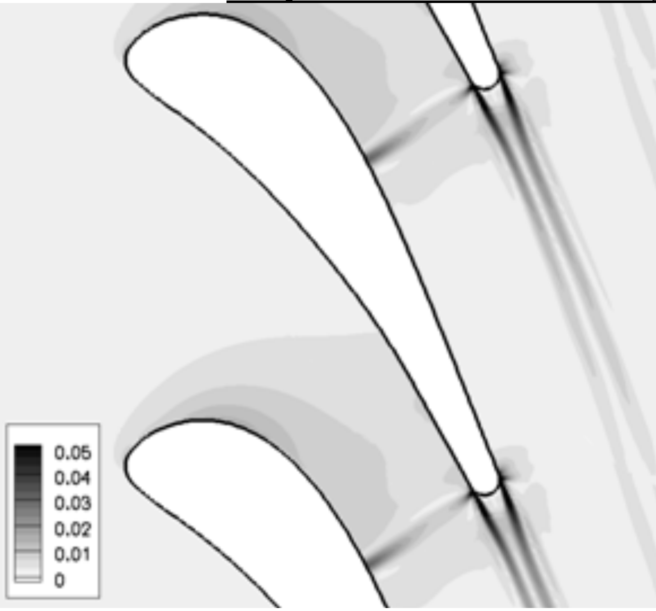
- laminar to turbulent transition,
- hot spot incoming from the combustion chamber,
- aero-thermal interactions (adiabatic is not true).

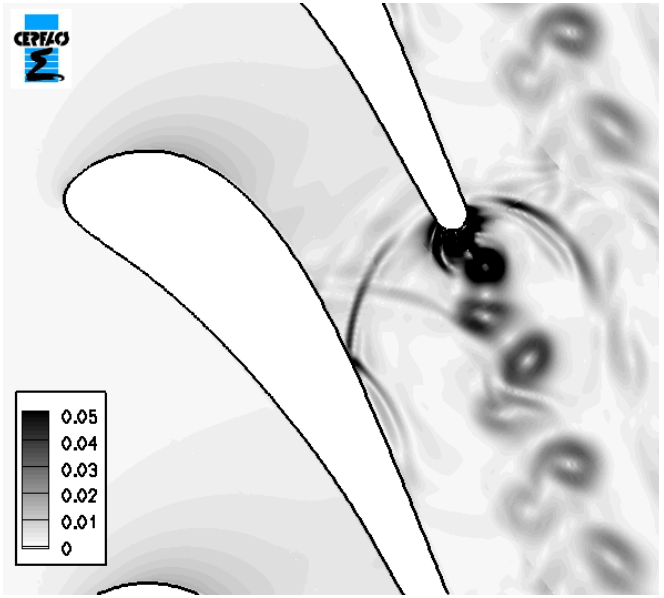


Arts, 1990

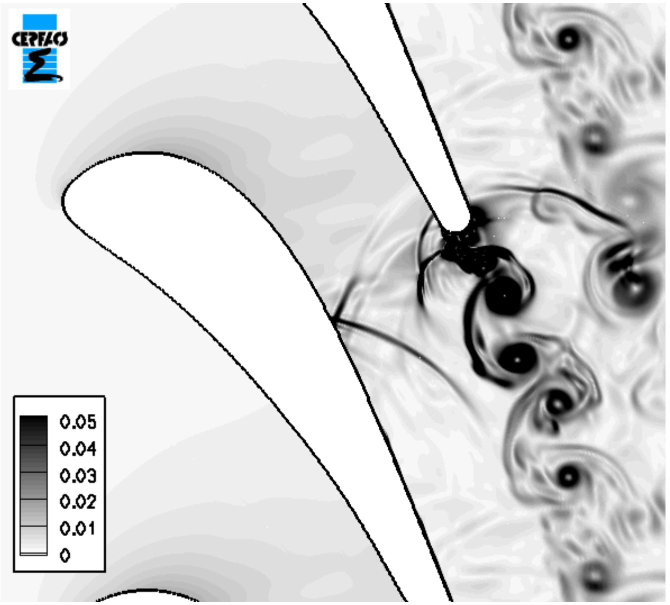


Impact on unsteady aerodynamic performance





T. Léonard et al., in ASME Turbo-Expo, Glasgow, 2010.



Instantaneous gradp flow field (*elsA*)

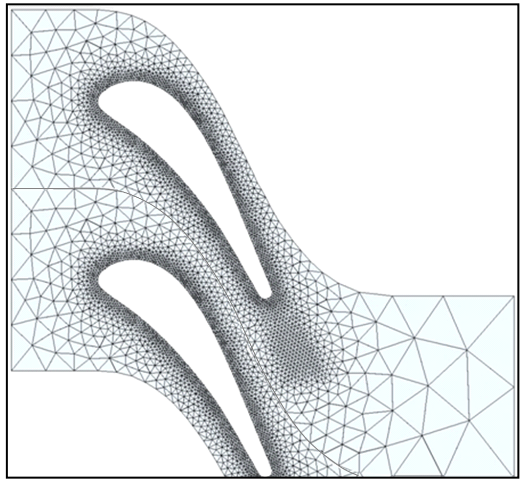
- RANS predicts a non-physical shock-wave,
- URANS predicts the vortex shedding but flow features are damped by artificial viscosity,
- LES demonstrates its capacity to transport flow vortices and acoustic waves.

CFD research in Turbulent Reacting Flows has massively transitioned LES:

- the continuous increase of computing power
- code developments to ensure scalability of the solvers

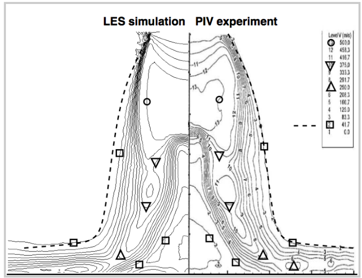
AVBP: An unstructured LES flow solver:

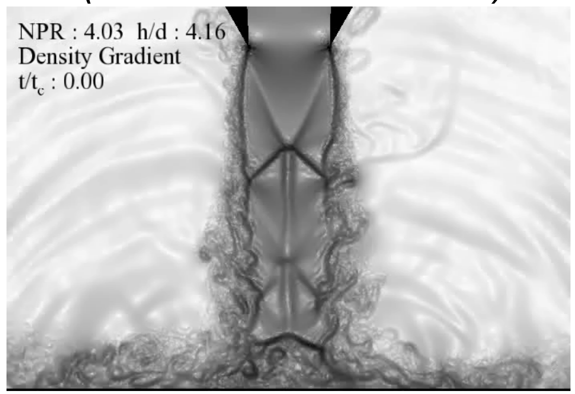
- Developed by CERFACS and IFP-EN,
- External/internal flows,
- Fully compressible turbulent reacting flows,
- DNS/LES approaches,
- Unstructured hexaedral, tetraedral, prisms & hybrid meshes,
- Massively parallel,
- C/Fortran languages,
- SPMD approach.
- Multi-phase solvers (Lagrangian & Eulerian)

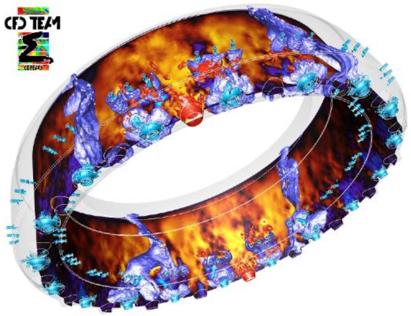


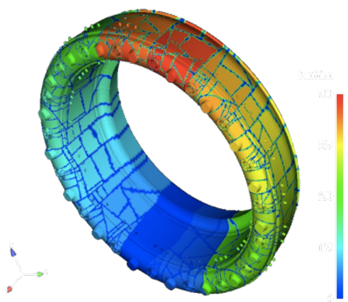
Unstructured grid

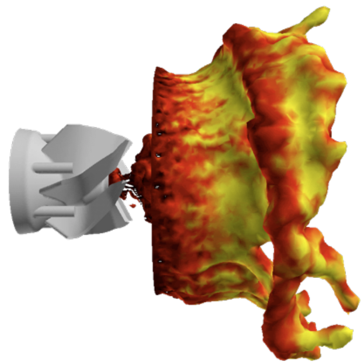
(Coincident interfaces)

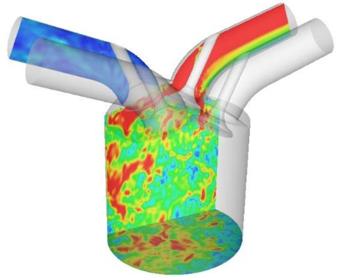








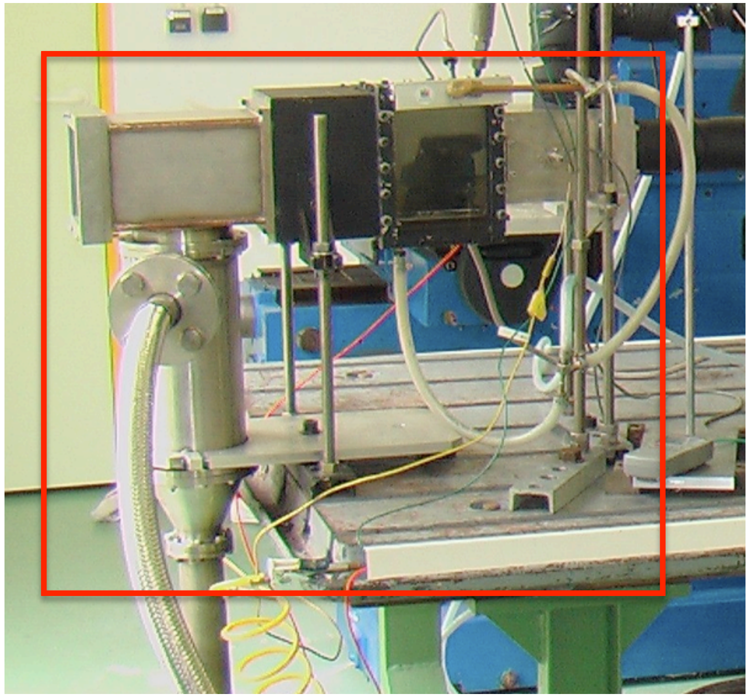




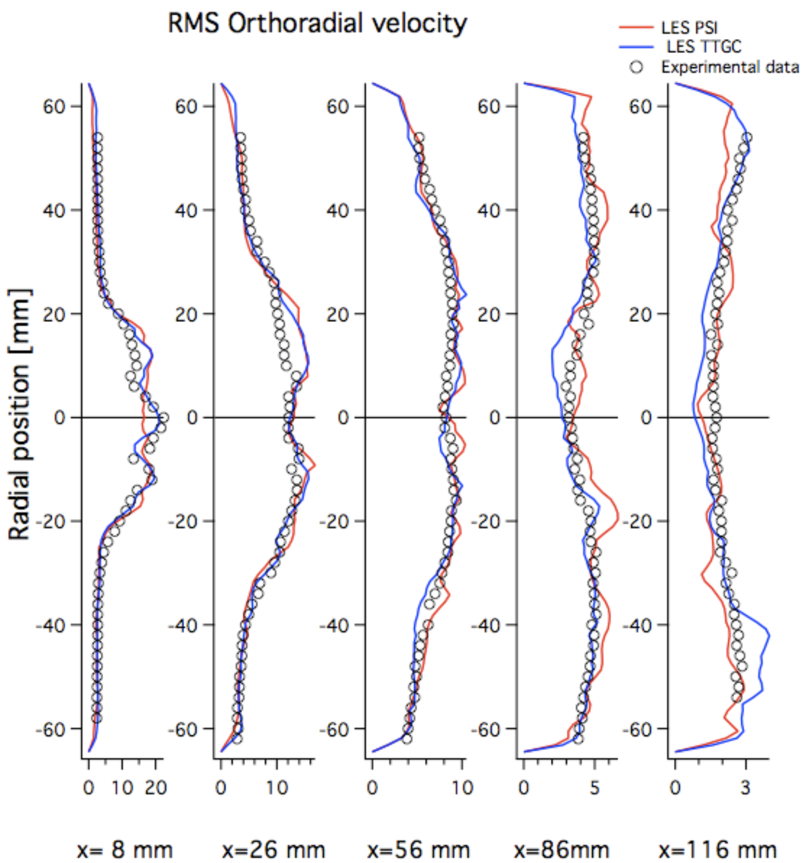
Gaseous turbulent combustion validation: Two-phase flow combustion

MERCATO burner [1,3]: atmospheric rig targeted to understand two-phase flow combustion

--> Measured profiles of Velocity (PIV), Droplet particle size & velocity in cold/reactg cdts

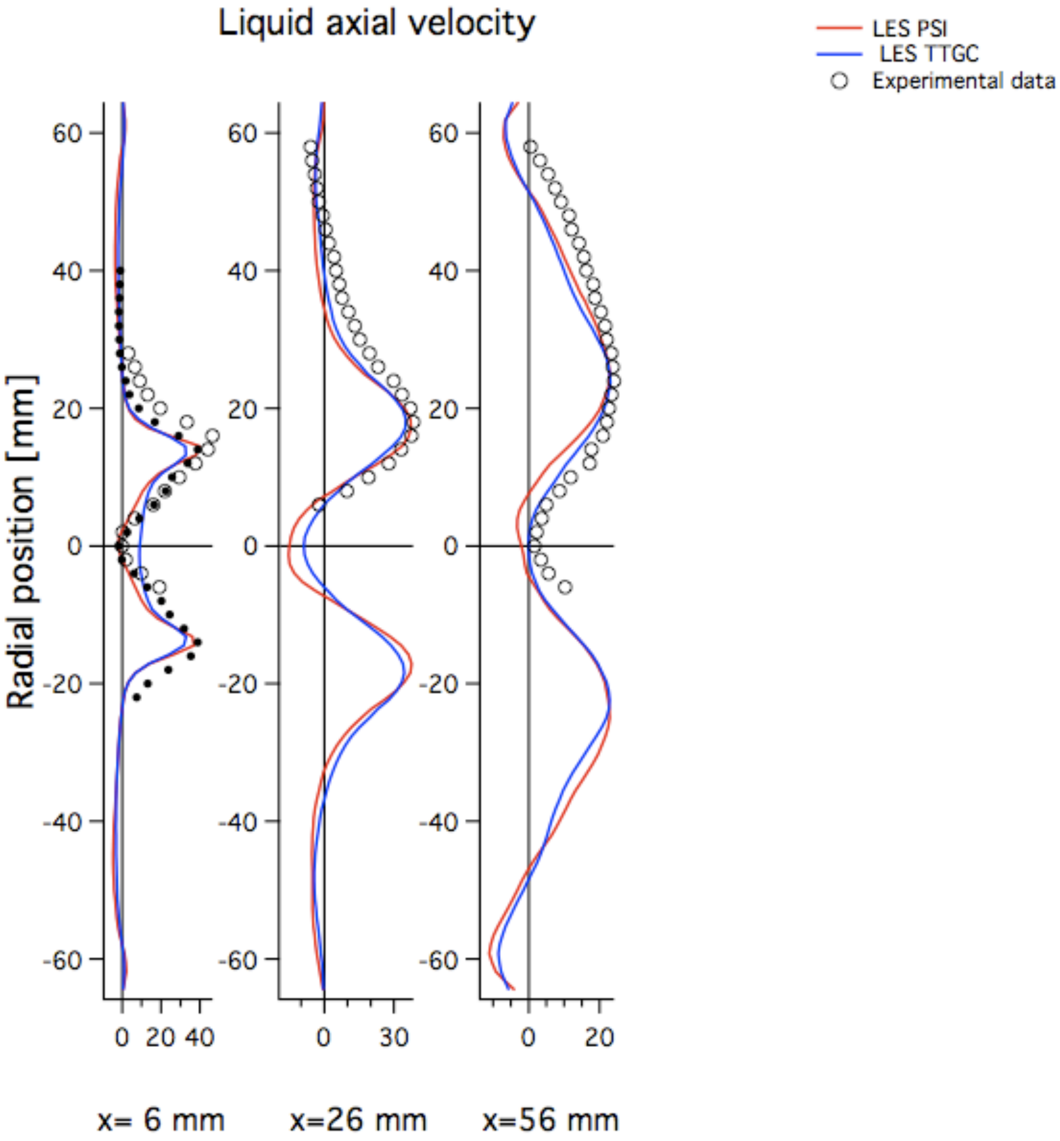


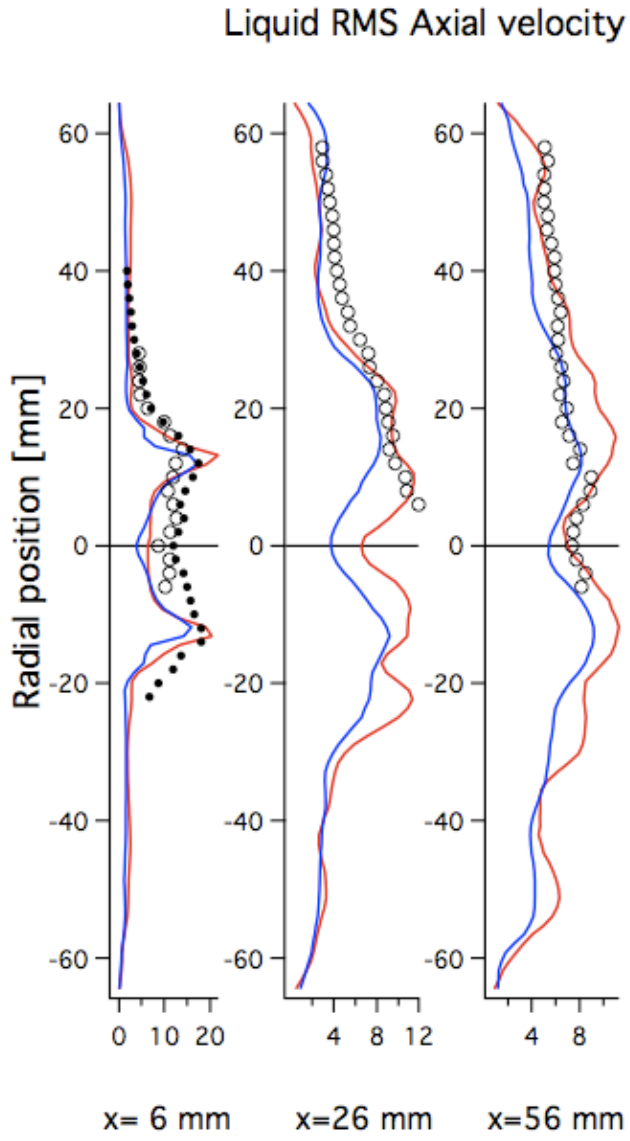
Cold gaseous flow predictions



[1] R. Lecourt et al, .
[2] M. Sanjose et al.
[3] M. Sanjose et al, CTR, 2007.

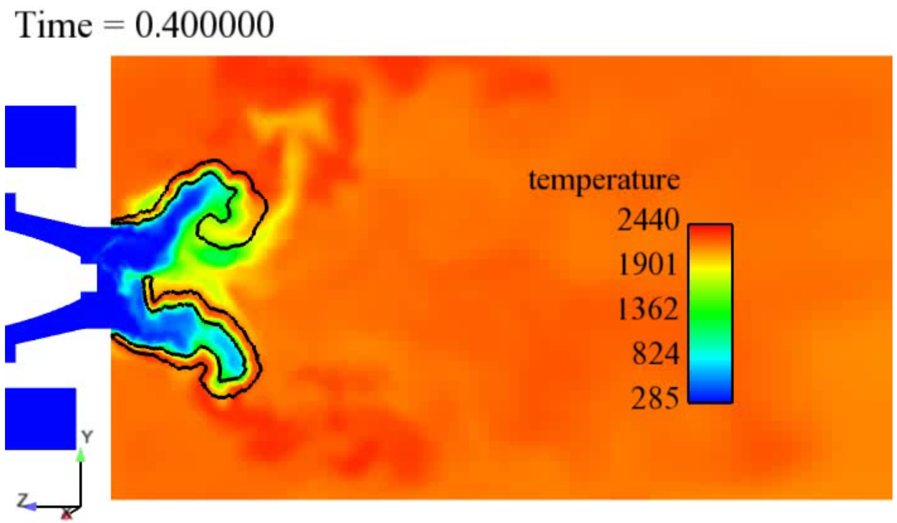
Liquid phase predictions



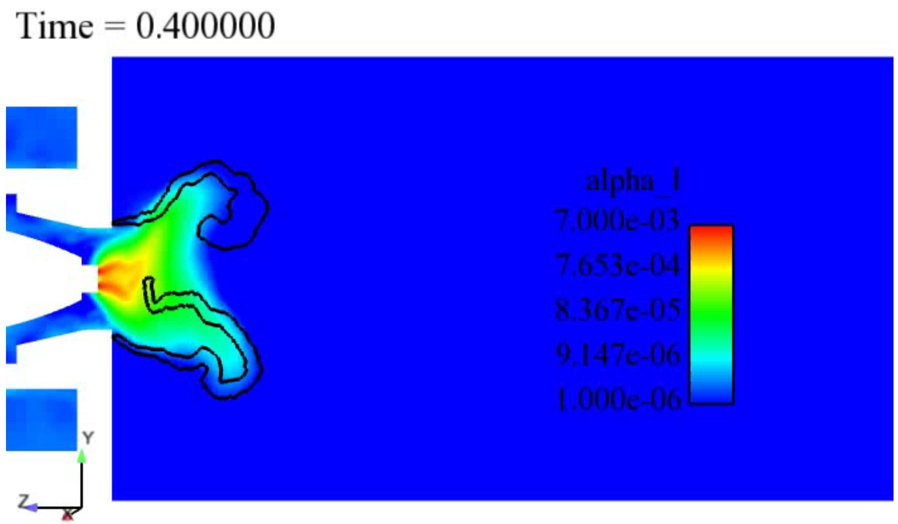


Two-phase reacting flow predictions

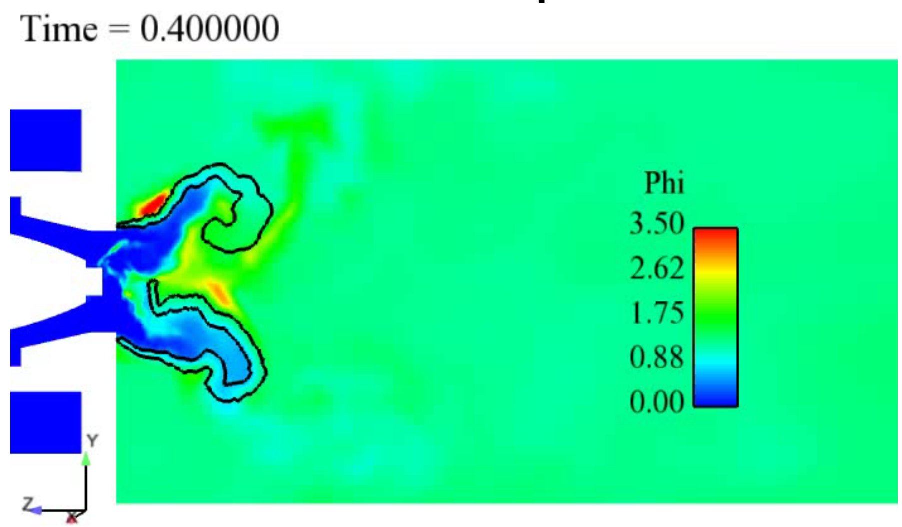
Gas Temperature



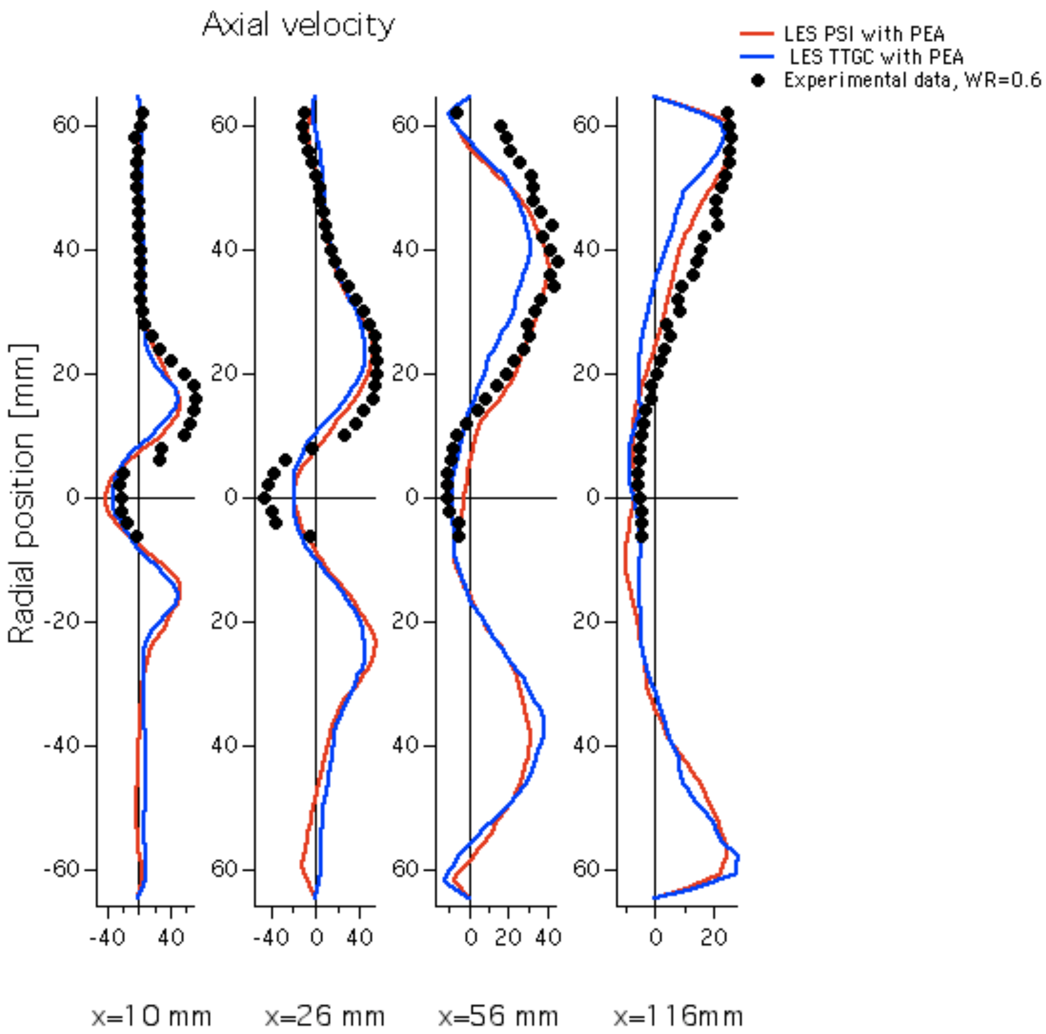
Droplet mass fraction

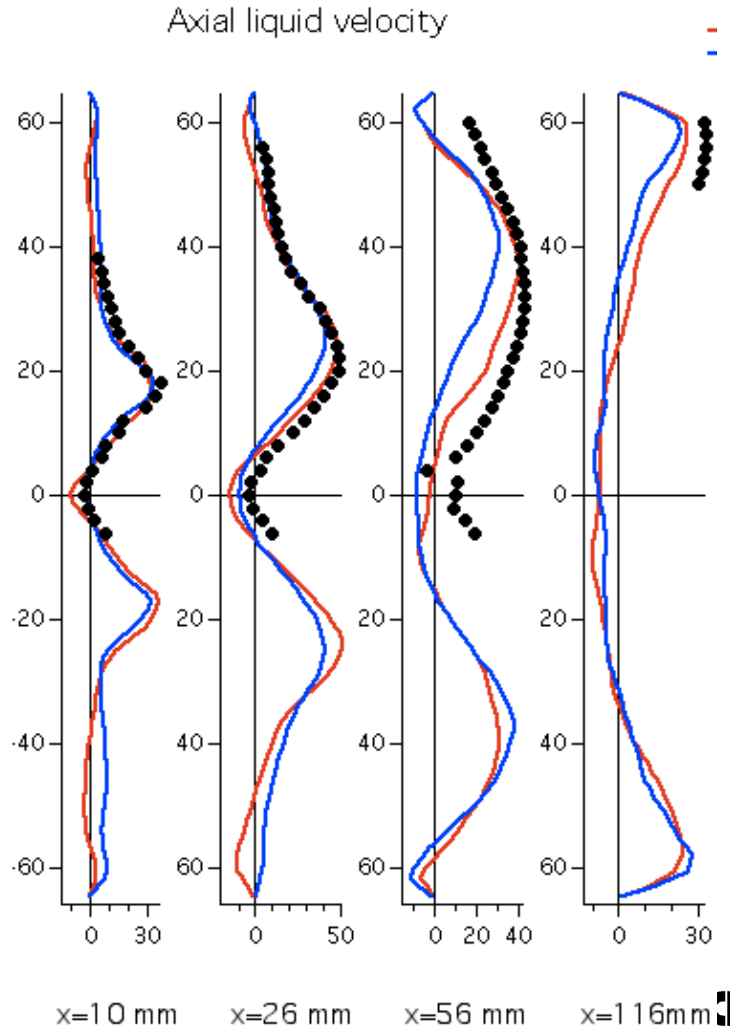


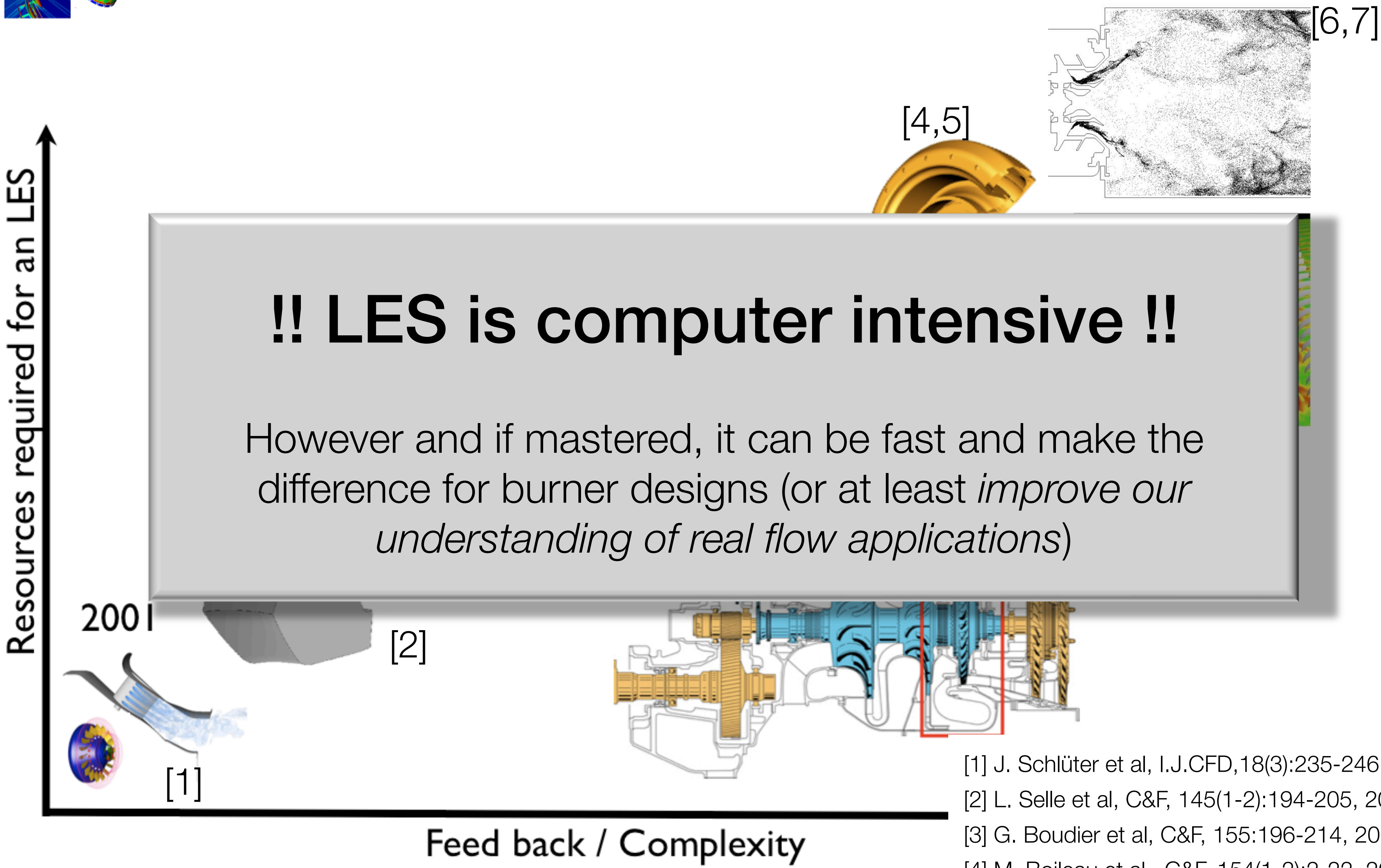
Gas equivalence ration



Two-phase reacting flow predictions





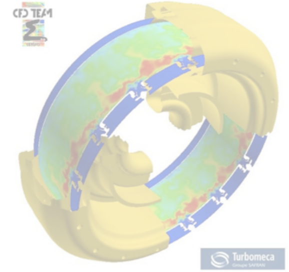


!! LES is computer intensive !!

However and if mastered, it can be fast and make the difference for burner designs (or at least *improve our understanding of real flow applications*)

[1] J. Schlüter et al, I.J.CFD,18(3):235-246, 2004.
[2] L. Selle et al, C&F, 145(1-2):194-205, 2006.
[3] G. Boudier et al, C&F, 155:196-214, 2008.
[4] M. Boileau et al., C&F, 154(1-2):2-22, 2008.
[5] G. Staffelbach et al., 32nd Symp., 2008.
[6] E. Riber et al, JCP, 228(2):539-564, 2009.
[7] F. Jaegle, PhD dissertation, INPT, 2009.

I] Recent contributions of LES to Combustor design:



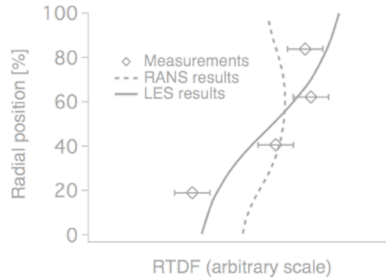
=> Massively parallel context - brief overview of 2000-2010

=> LES modeling and code validations

=> Real scale applications

-> comparison against RANS predictions

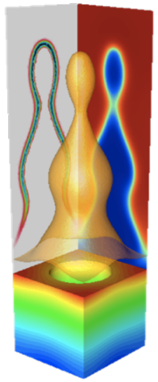
-> thermo-acoustic instability prediction

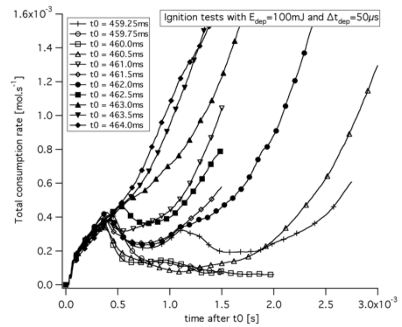


II] LES perspectives and applications:

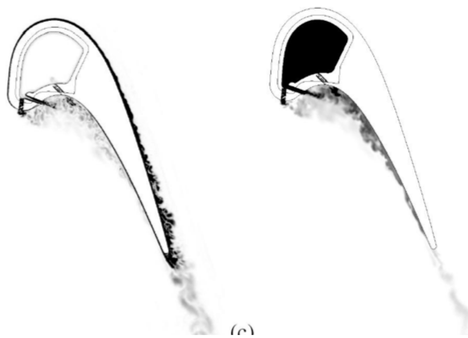
=> Transient reacting flows: ignition process understanding

=> Towards multi-physics CFD based on LES





III] Conclusions and Perspectives



II.2] Towards multi physics CFD based on LES

Improving the temperature field predictions in the burners:

=> on need

if

=> ability)

Need to rely on natural time-scale separations of the different processes as as the different existing dedicated codes

=> LES: here to better predict mean flow field (stationary cdts)

The approach is only aiming at **reproducing a fixed point iterative** scheme to better predict the **mean** thermal environment of the engine.

1 -11 **100000x**

Radiation