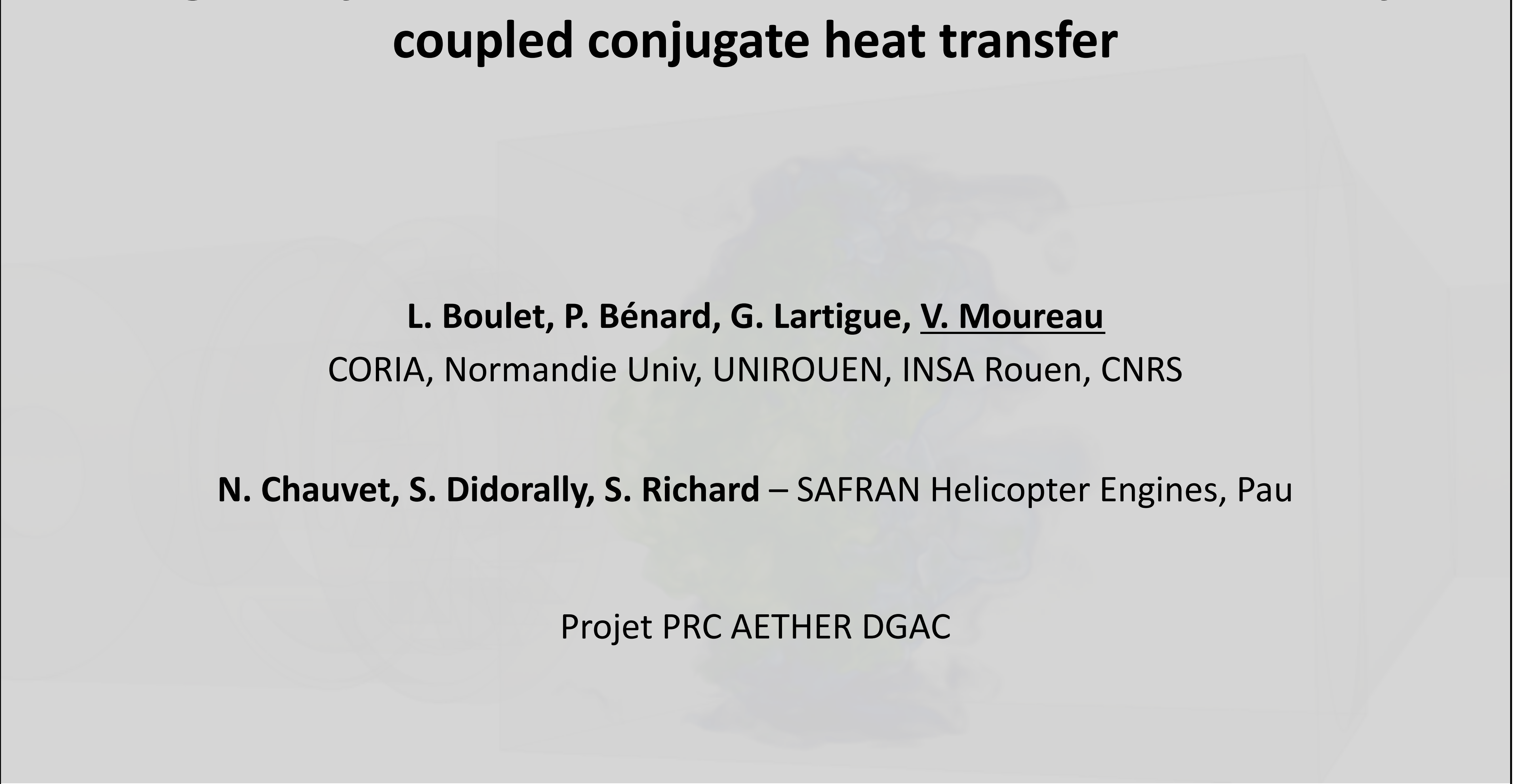
Large-Eddy simulation of a certification burner with fully coupled conjugate heat transfer



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N. Chauvet, S. Didorally, S. Richard – SAFRAN Helicopter Engines, Pau

Projet PRC AETHER DGAC

Journée GdR Feux/GFC, 6/7 décembre 2018

Motivation

- **Context**
  - Manufacturers need to certify equipment in terms of fire resistance (housing, fastening engine, …)
  - Certification: the apparatus needs to be submitted [1]
    - to a kerosene / air burner
    - during a fixed time (5 to 15 minutes)
    - with a standardized flame: 1100°C (≈1300K) and 116 kW/m^2

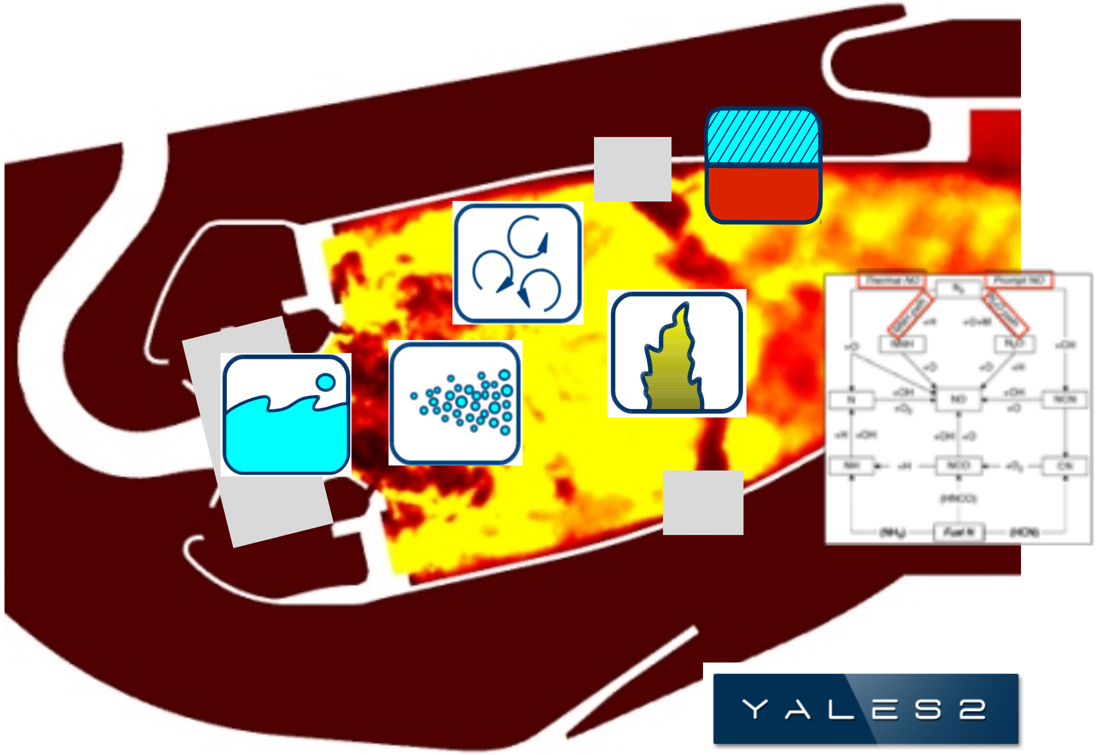
Liquid-fuel burner

- **Objective**
  - Model fire resistance tests with Large-Eddy Simulation
  - Improve comprehension of phenomena involved in tests
  - Try to minimize the risk in the real certification tests
- **Difficulties**
  - Very different time and space scales
  - Multi-physics and complex geometry
  - Very few studies

[1] ISO 2685:1998 (1998). The Int. Organ. for Stand. (ISO)

Large-Eddy Simulation in the aeronautical context

- LES is well suited to the high-fidelity simulation of aeronautical burners
- Challenges
  - Unsteady, multi-scale, multi-physics flows
  - Need to exploit modern super-computers



Aircraft engine chamber

JOLIOT-CURIE, PRACE/GENCI at the
Très Grand Centre de Calcul, CEA
P9 Petaflops, 124 000 cores

The CFD platform: YALES2

- Developed by CORIA and the French Combustion Community
  - +250 researchers/engineers trained at CORIA since 2009
  - +110 articles (Google Scholar)
- A unique network to ease collaboration and transfer of numerics and models to the industry

Academic partners

GIS SUCCESS [1]
CORIA, IMAG, LEGI, EM2C
IMFT, CERFACS, IFP-EN, LMA

ULB, UMONS, UCL, LOMC,
PPRIME, LMB/INRIA,
CORNELL U., SHERBROOK U.
VERMONT U.

HPC centers

CRIHAN, IDRIS, CINES, TGCC
GENCI, PRACE

Industrial partners

SAFRAN
ARIANE GROUP
SOLVAY
AIR LIQUIDE
SIEMENS
…

YALES2

www.coria-cfd.fr

SMEs

GDTech

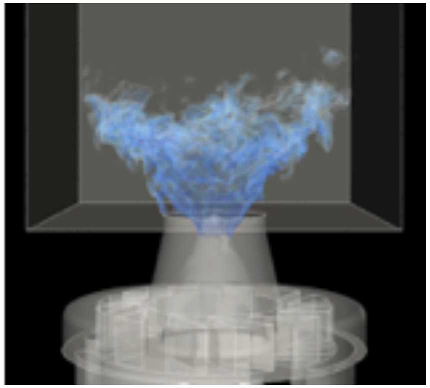
HPC experts

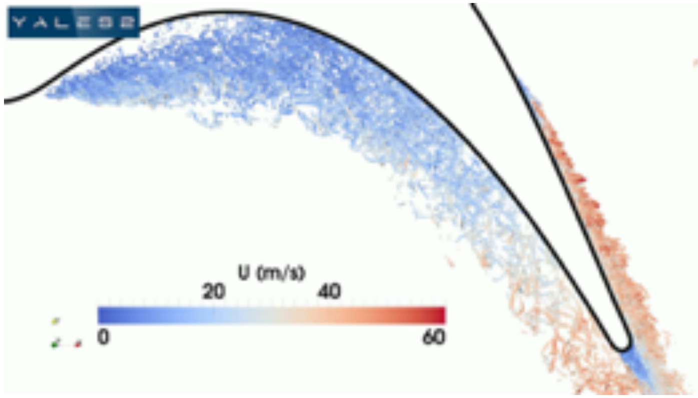
ECR lab
INTEL/CEA/GENCI/UVSQ
IBM/ROMEO

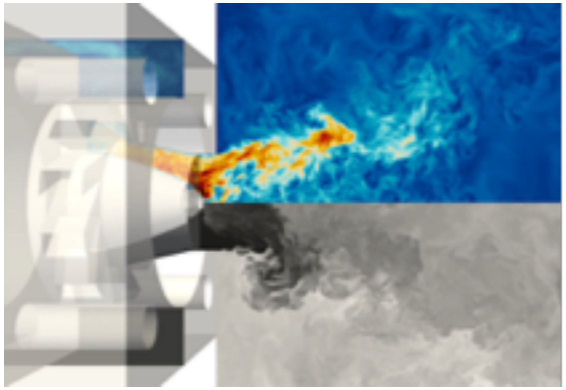
[1] http://success.coria-cfd.fr

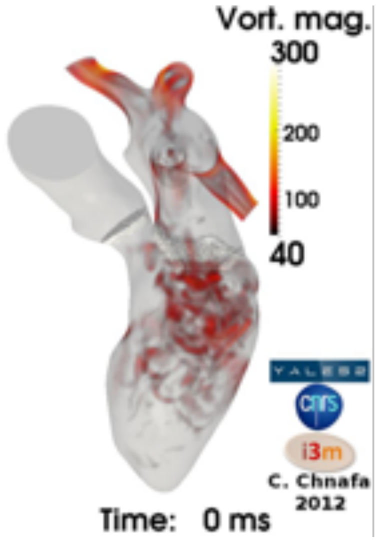
The CFD platform: YALES2

- Features
  - **Unstructured meshes** (complex geometries) and **adaptive grid refinement**
  - **Low-Mach number Navier-Stokes equations** (incompressible and variable density) solved with a projection method
  - Double-domain decomposition [3]
  - Highly efficient solvers for linear system inversion (PCG, DPCG)
  - **4th-order** central finite-volume method and **4th-order** time integration
  - Two-phase flows (Lagrangian particles)
  - Spray and atomization (Levelset)
  - Combustion modeling (Tabulated or complex chemistry, NOx prediction model…)
  - **Suited for massively parallel computing** (>32 000 procs)







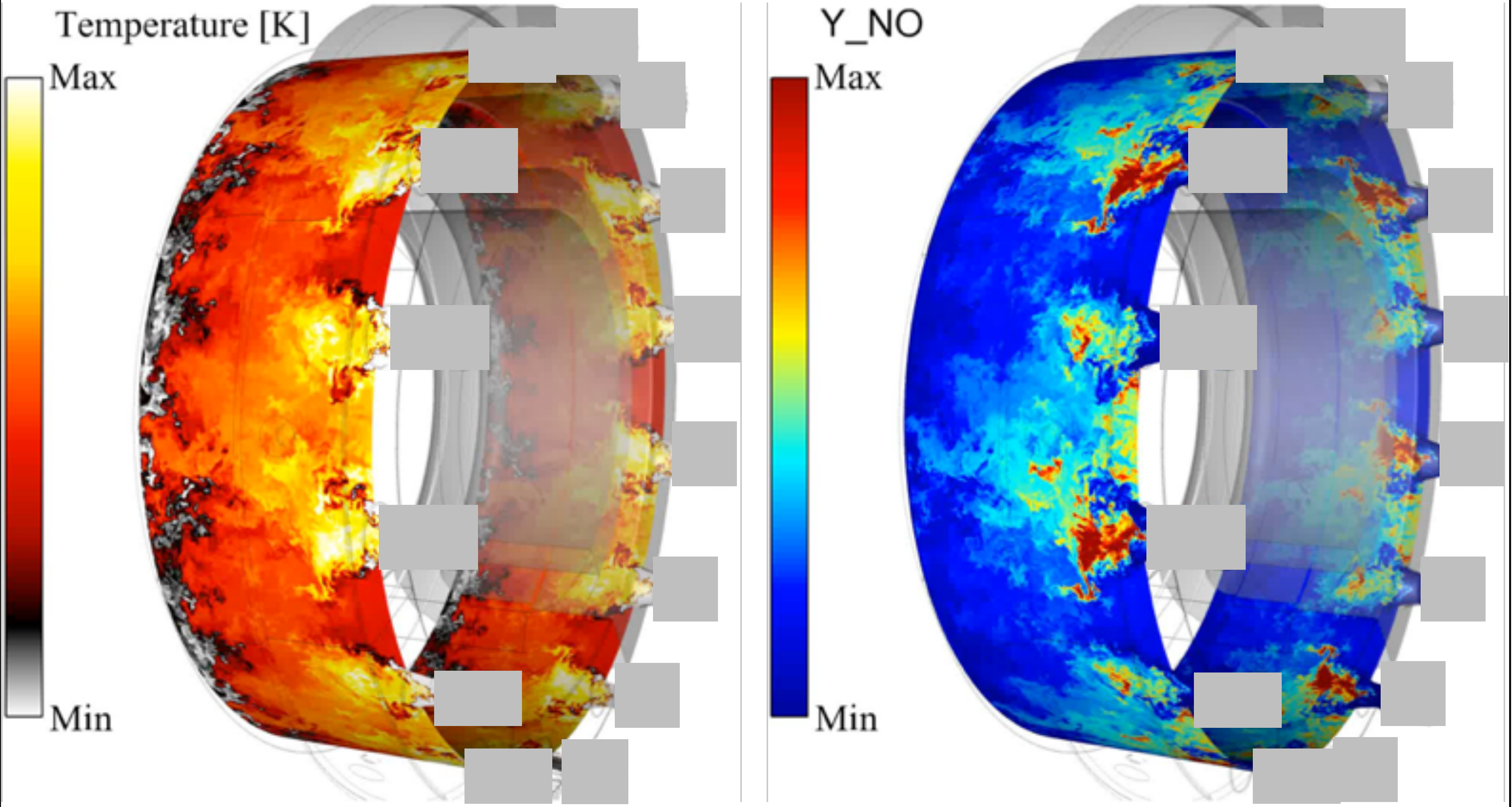


[1] YALES2 web site, http://www.coria-cfd.fr
[2] SUCCESS web site, http://success.coria-cfd.fr

[3] Moureau et. al., CR Mecanique, 2011

Prediction of pollutant emissions in realistic burners: Application to a low-NOx helicopter engine

- LES from J. Lamouroux, SAFRAN Helicopter Engines, in 2015
- 376M elements for 2 injectors, tabulated chemistry, dedicated NOx model [1]



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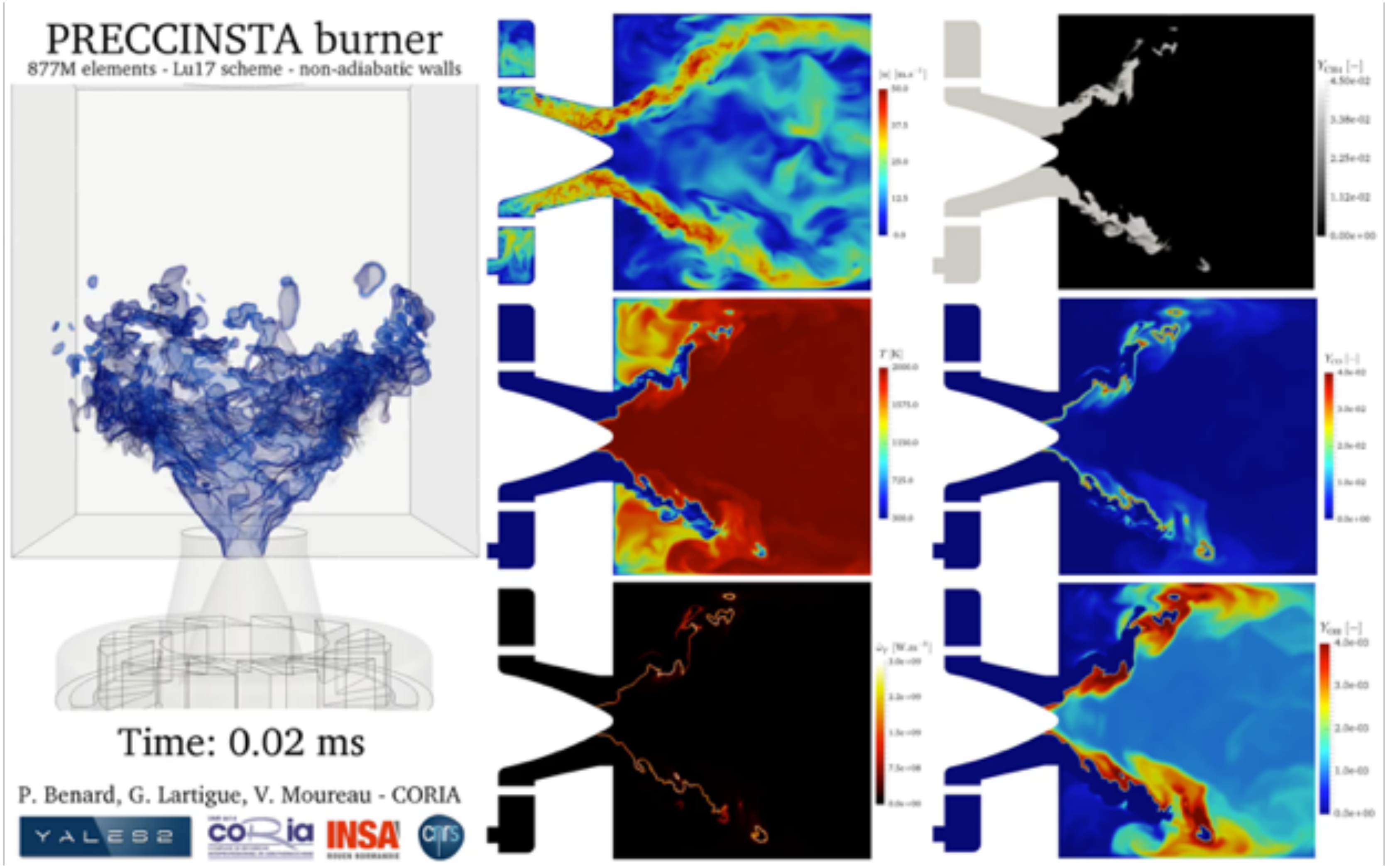
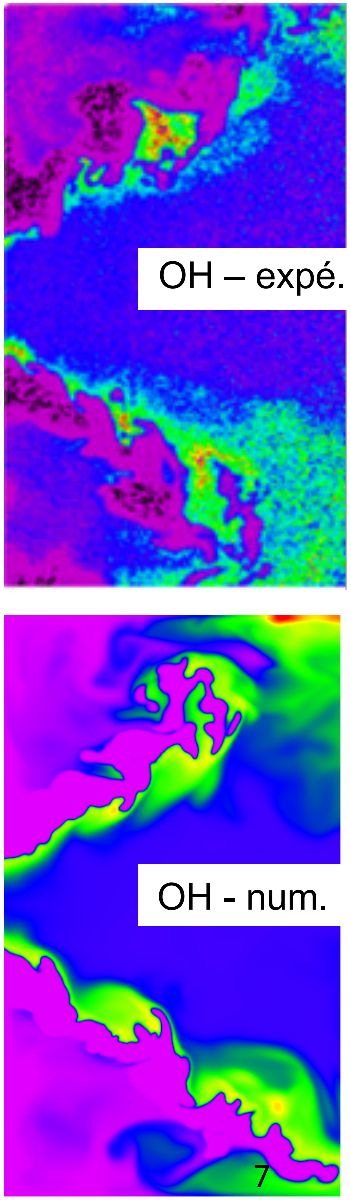
[1] Pecquery et al. (2014) Comb. Flame 161(2)

Prediction of pollutant emissions in realistic burners: Investigation of CO prediction

- PRACE project « FIRELES » (2018): LES of the lean-premixed PRECCINSTA burner with finite-rate chemistry (17 species, 73 reactions) and heat loss [1]





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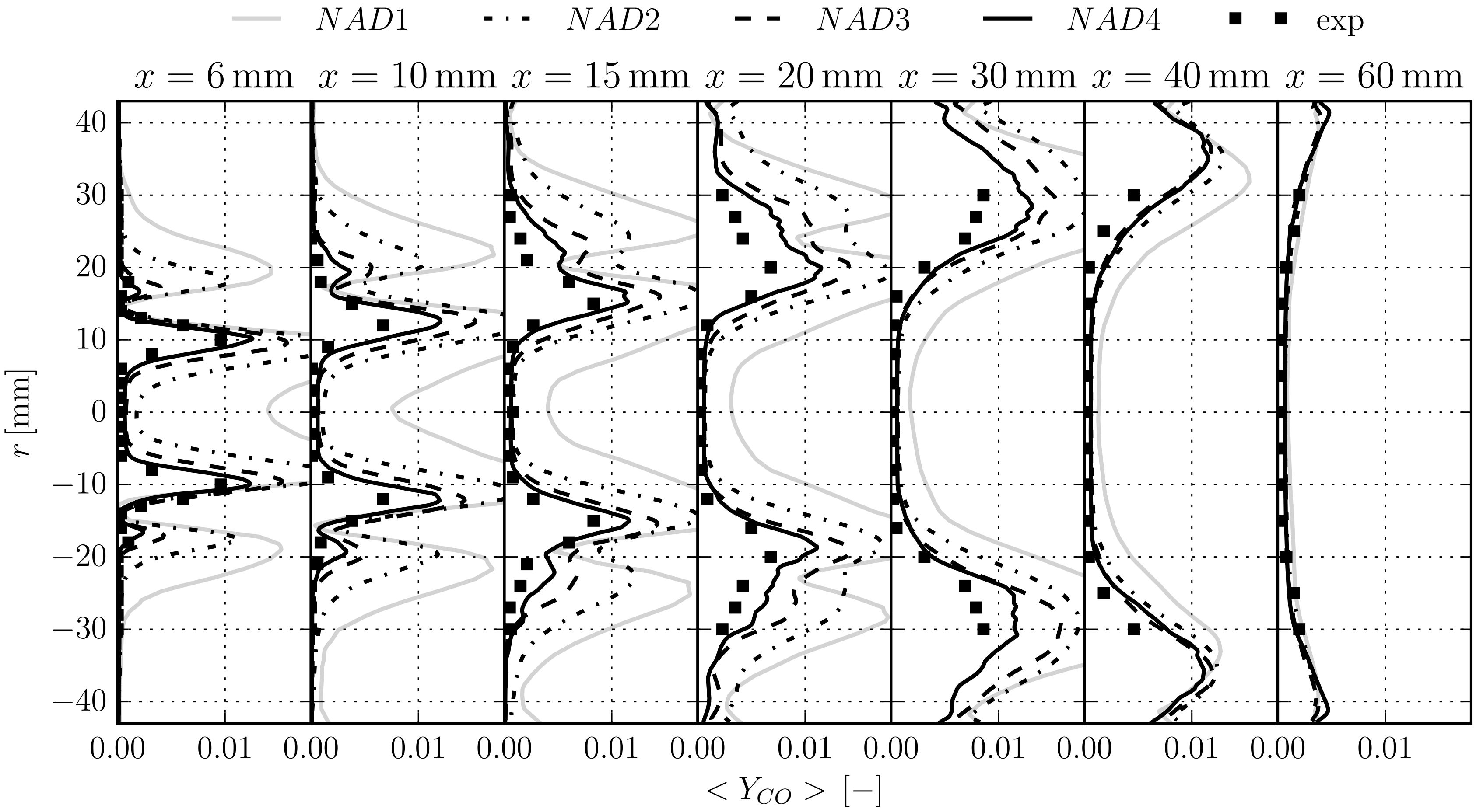
[1] P. Bénard et al. (2018) Int. Comb. Symp., Dublin

Prediction of pollutant emissions in realistic burners: Investigation of CO prediction

- PRACE project « FIRELES » (2018): LES of the lean-premixed PRECCINSTA burner with finite-rate chemistry (17 species, 73 reactions) and heat loss [1]
- Strong sensitivity of the CO prediction to mesh resolution

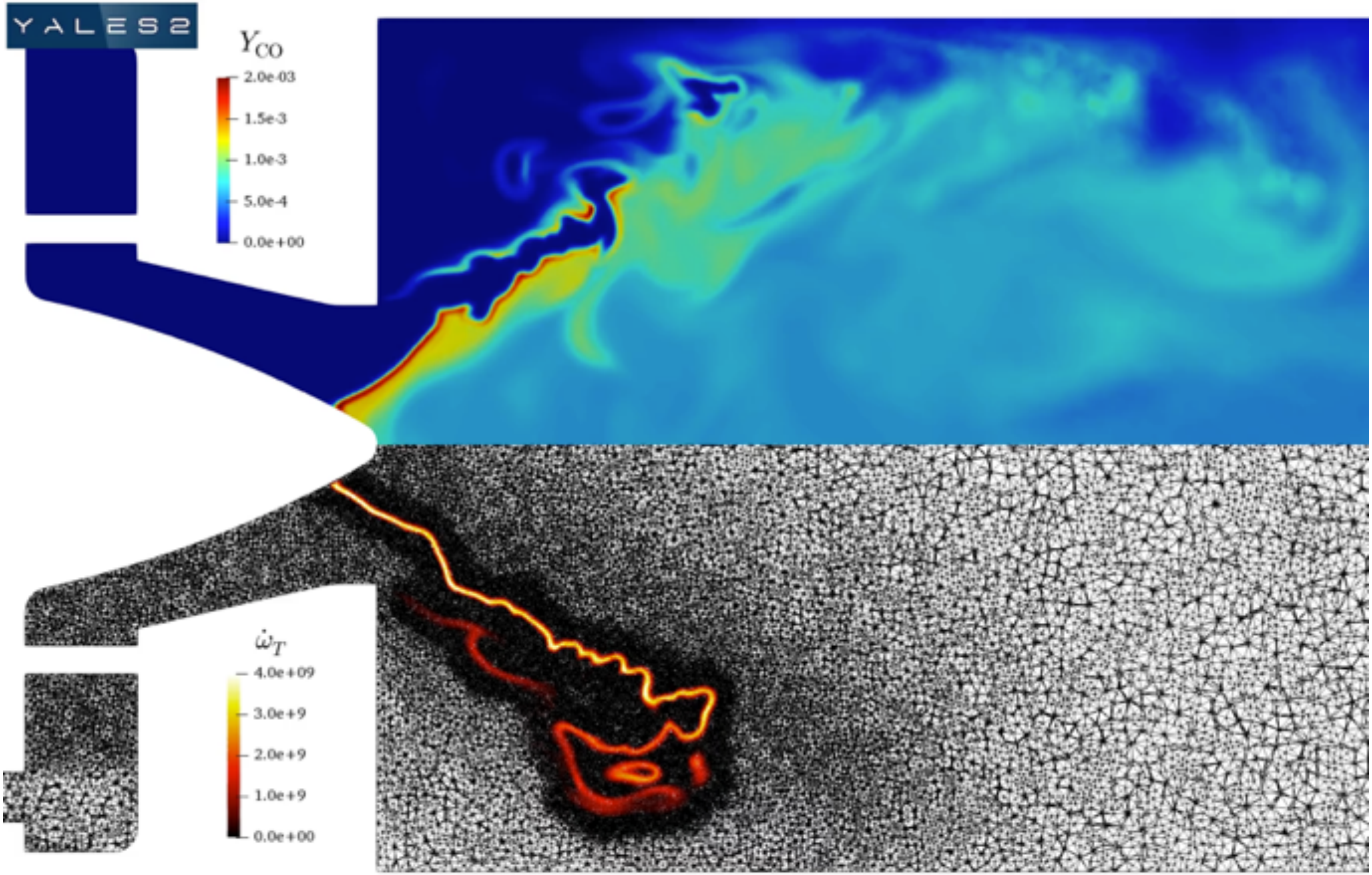


Mesh	NAD1	NAD2	NAD3	NAD4
Cell count [millions]	1.7	14	110	877
Cell size [mm]	1.2	0.6	0.3	0.15

[1] P. Bénard et al. (2018) Int. Comb. Symp., Dublin

The next step: towards dynamic mesh adaptation of massive meshes for front/interface capturing

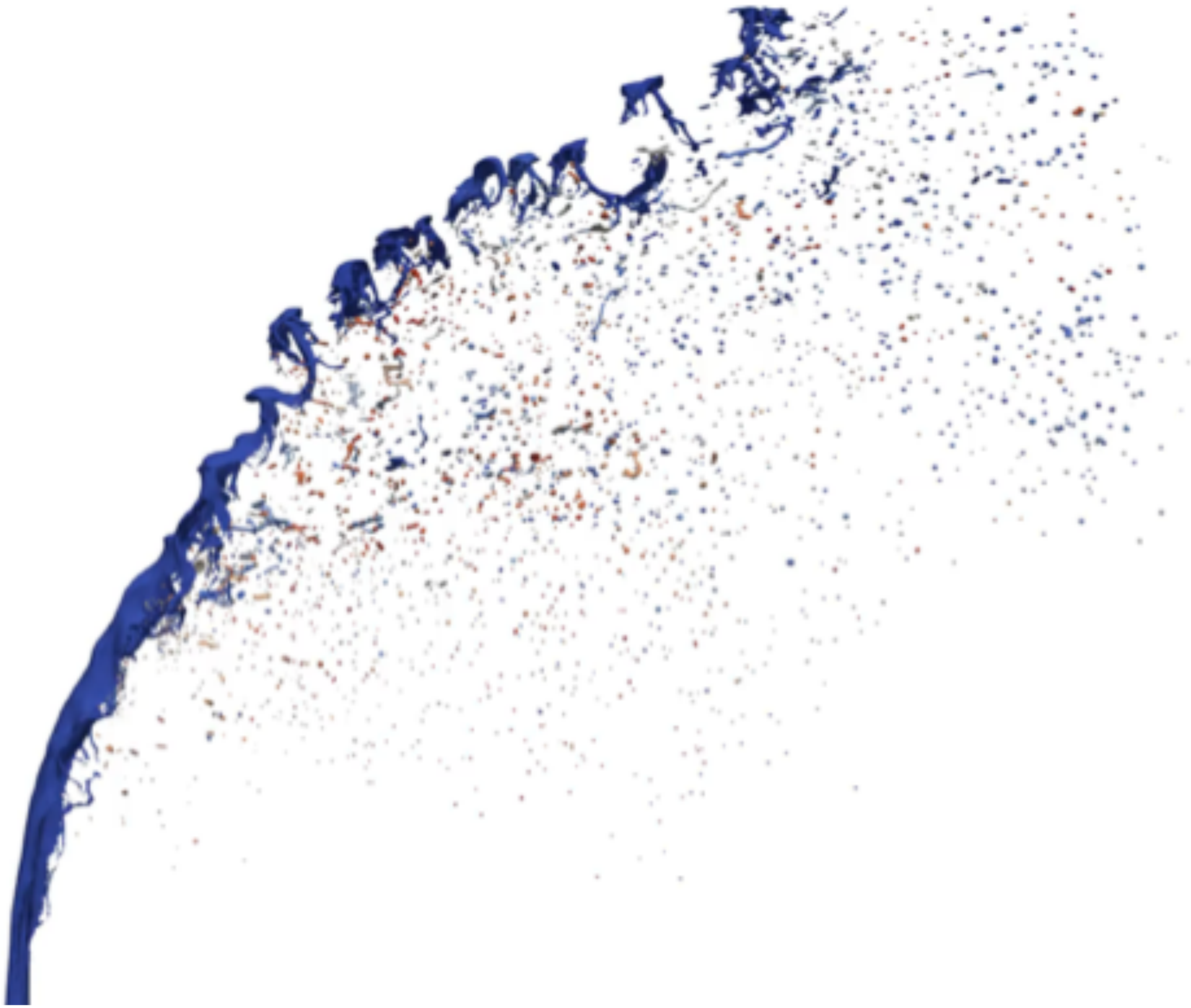
- Collaboration of CORIA/INRIA/SAFRAN awarded at the TERATEC 2018 forum
- Objectives: reduction of CPU cost and modeling errors



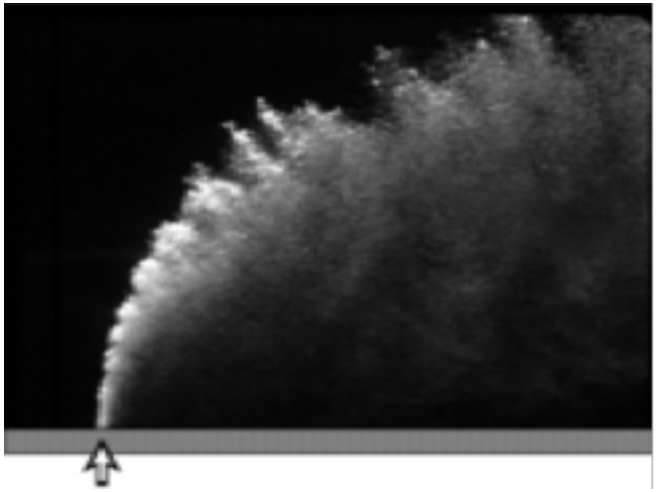
[1] P. Bénard et al. (2016) Int. J. Num. Methods Fluids 81(12)
[2] C. Dobrzynski, P. Frey, (2018) 17th international Meshing Roundtable, USA.

The next step: towards dynamic mesh adaptation of massive meshes for front/interface capturing

- Collaboration with R. Mercier, J. Leparoux, H. Musaefendic, SAFRAN
- Strategy: conservative interface capturing [1] and mesh adaptation
- Objective: reproduce the jet penetration and granulometry



Kerosene jet-in-cross-flow at 10 bar [2]



$$We_{aero} = \frac{\rho_g V_g^2 D_{inj}}{\sigma} = 406.2$$

$$q = \frac{\rho_l . V_l^2}{\rho_g . V_g^2} = 49.6$$

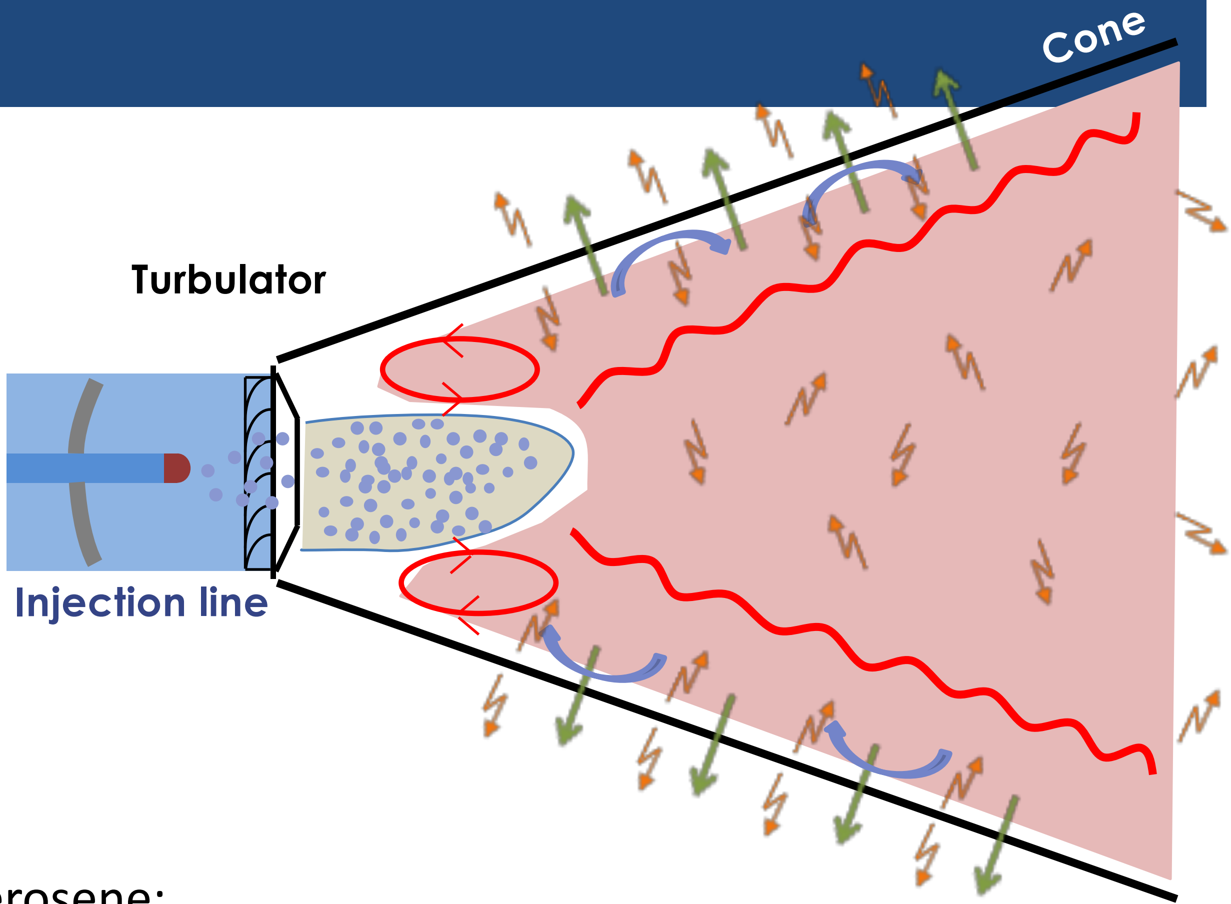
Resolution of 10 microns at interface
Up to 600 million cells
Up to 10 000 cores (Xeon Broadwell)

[1] O. Desjardins et al. (2008) J. Comp. Phys. 227(18)
[2] R. Ragucci et al. (2007) Atomization & Sprays

Torch modeling strategy

- Multi-physics
  - Spray
  - Evaporation
  - Flame

- Heat transfers
  - Convection
  - Conduction
  - Radiation



- Numerical parameters
  - Finite-rate **chemistry** for kerosene:
    - **2-steps scheme** (BFER) [1]
  - Liquid & gas **injection**:
    - Lagrangian spray model
    - **adjusted** thanks to exp. Data
  - No soot model (noticeable limitation)
  - Characteristic numbers
    - Phi = 0.77, Reynolds = 30 700

[1] B. Franzelli (2010). Combust. Flame

Torch modeling strategy: couplings

- Coupling of different solvers

Solid

- Heat transfer in the solid
  - Solving of the unsteady heat equation with an implicit FV method

Fluid
(Gas + Droplets)

- Aero-Thermo-Chemistry in the fluid
  - Low-Mach number / variable density FV solver

Radiation

- Radiative heat transfer
  - Discrete Ordinate Method on the fluid grid with FS-SNB-CK model

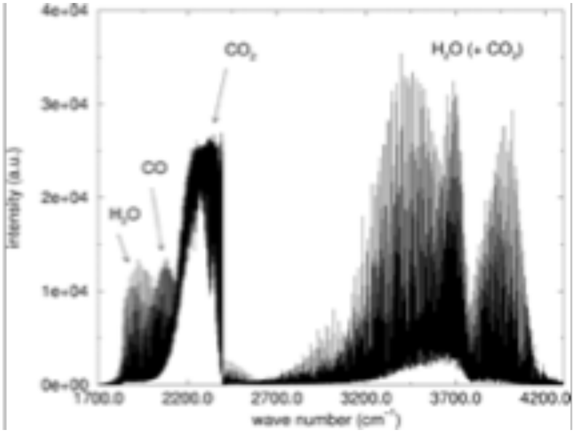
Radiative heat transfer solver

- Discrete Ordinate Method

- Full spectrum SNB-CK model with EM2C database [1,2,3,4]
- Includes CO2, H2O, CO & CH4

- No SGS Turbulent-Radiation Interaction

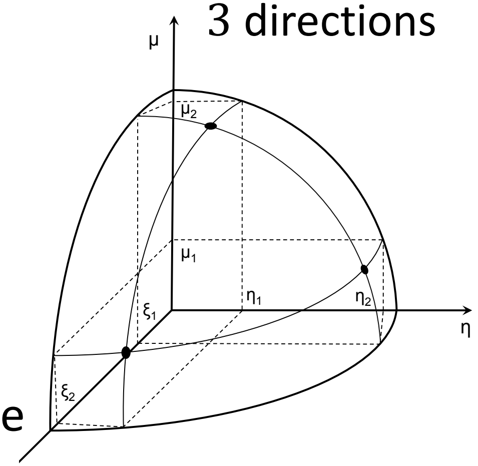
- Quadrature methods
  - **Gauss-Lobato** (**7pts** and 20pts)
  - Gauss-Legendre (2pts, 4pts and 7pts)
  - Gauss-Radau [5] (7pts)



Emission spectrum (CH4/air flame, 2160K)

- In 2D: **S4 (2 directions/quadrant)** to S32 (16 directions/quadrant)
- In 3D: **S4 (3 directions/octant)** to S8 (6 directions/octant)
- 4th-order central FV scheme with 10% upwind for the RTE [6]

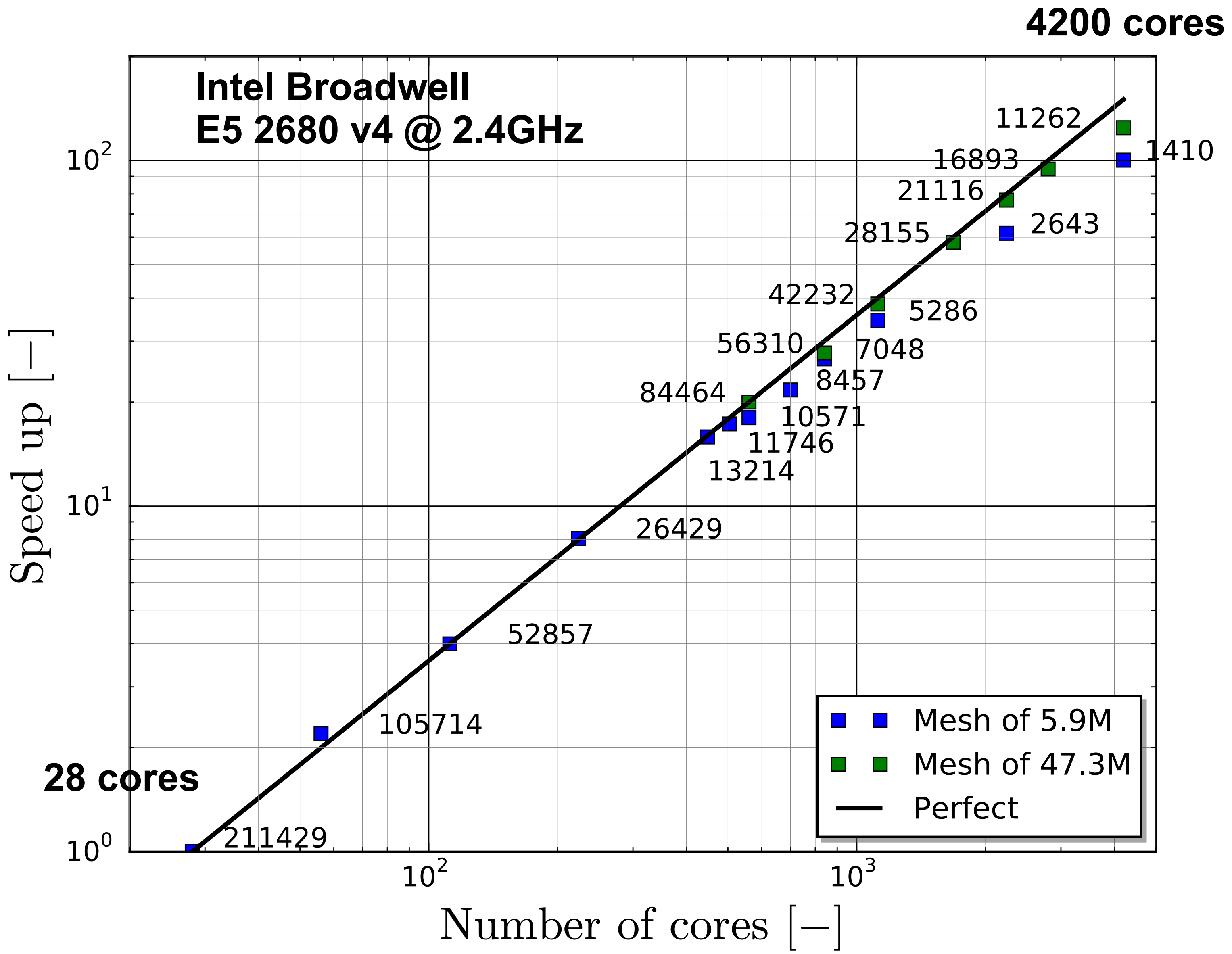
1/8 of space
3 directions



- High-Performance Computing
  - Simultaneous solving of all equations (BiCGStab(2) solver)
  - Optimized Brent Method to solve for k* for each spectral quadrature point
  - Fully vectorized

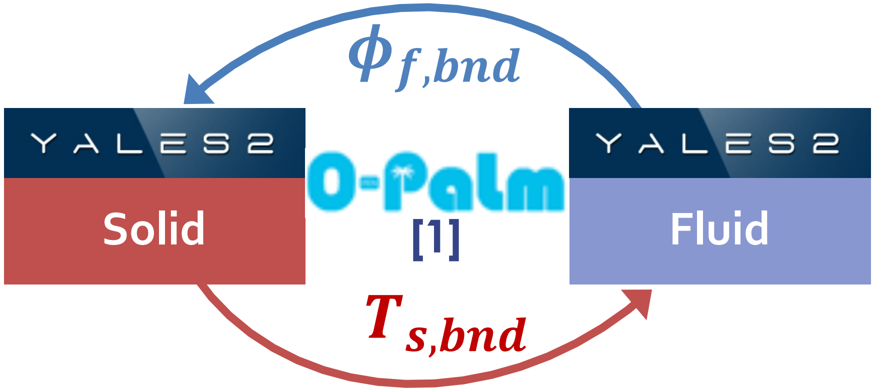
[1] Goody (1989). J. Quant. Spectro. & Radiative Transfer
[2] Lacis & Oinas (1991). J. Geophysical Research
[3] Liu (2000). Int. J. Heat Mass Transfer
[4] Rivière & Soufiani (2012). Int. J. Heat Mass Transfer
[5] Rivière (1992). J. Quant. Spectro. & Radiative Transfer
[6] Nguyen (2010). ECCOMAS CFD2010

Performances of radiative solver

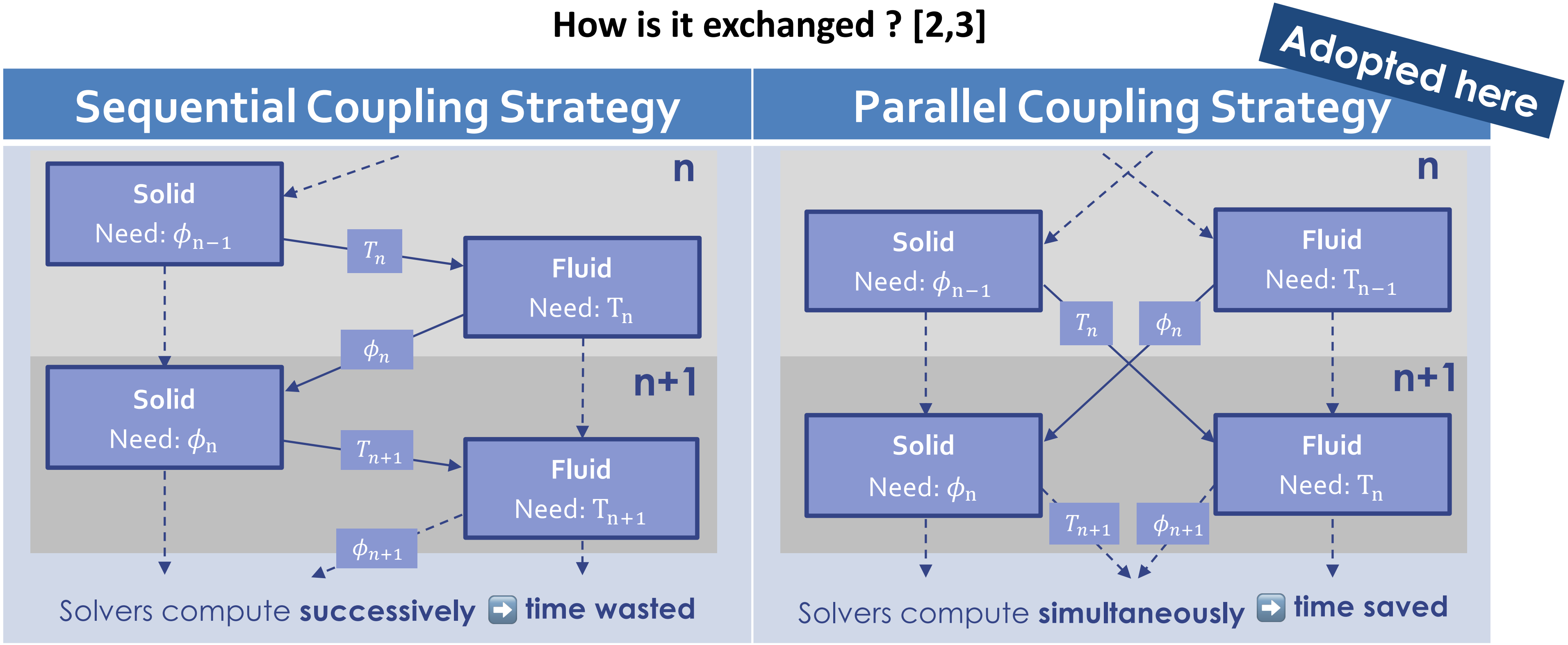


CHT strategy: variables & solver interactions

- CHT coupling must be performed on a parallel super-computer
- 2 strategies
  - Sequential coupling
  - Asynchronous coupling



How is it exchanged ? [2,3]



Solvers compute **successively** ➡ **time wasted**

Solvers compute **simultaneously** ➡ **time saved**

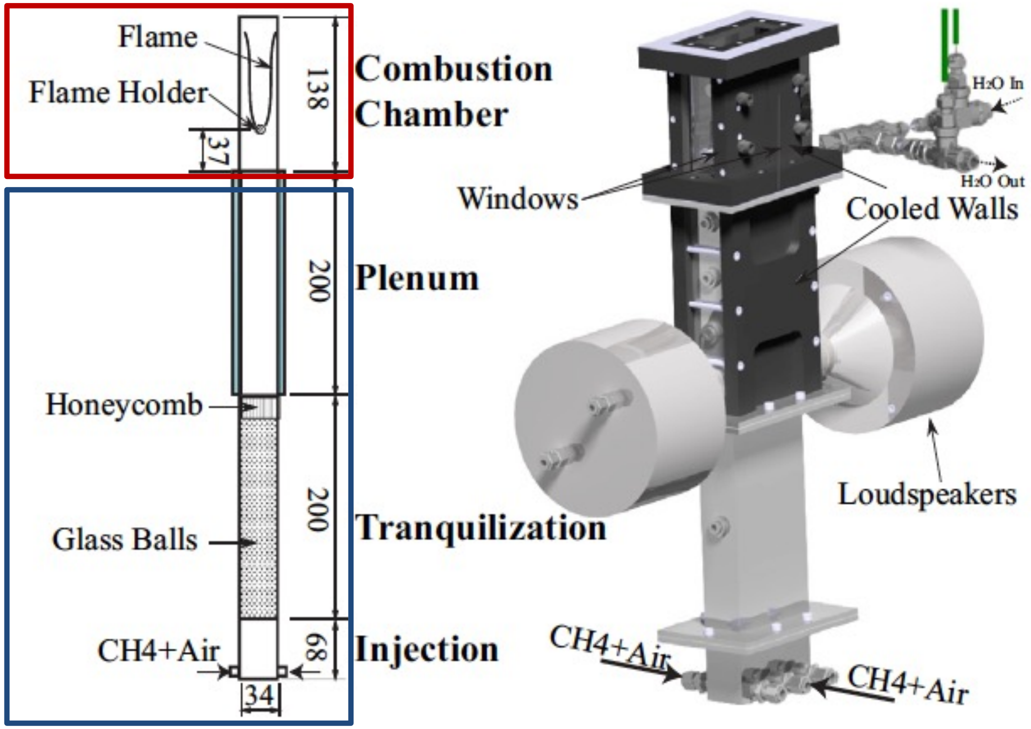
[1] http://www.cerfacs.fr/globc/PALM_WEB/
[2] F. Duchaine (2009). Int Journal of Heat & Fluid Flow
[3] A. Felippa (2001). Comput. methods in appl mech & eng

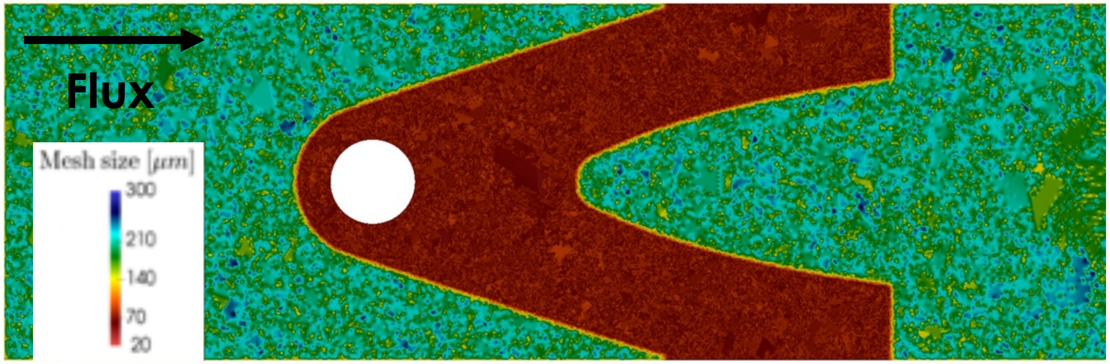
Validation: INTRIG burner

[1] Miguel-Brebion (2016). Comb & Flame
[2] Xavier (2017). JFM
[3] Meija (2017). Proceedings Comb Inst
[4] Meija (2018). Comb & Flame

- INTRIG burner [1,2,3,4]
  - Laminar premixed flame anchored to a steel cylinder
  - Mixture: CH$_4$ and Air
- Heat transfer
  - Fully coupled CHT/RTE with participative medium
- Numerical parameters
  - Fluid: air at $u \approx 1\, m/s$
    - $Re = 584$
  - Von-Karman streets at $40Hz$
  - 2D Mesh: 630 000 tetrahedrons
    - $70\mu m$ in flame and solid
    - Prisms of $20\mu m$ at interface

Part to simulate

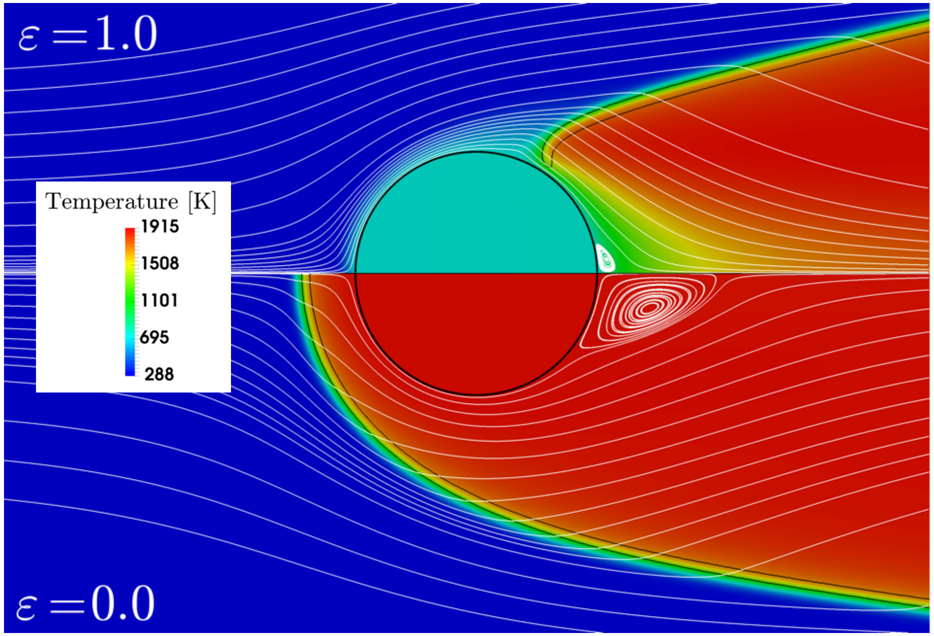


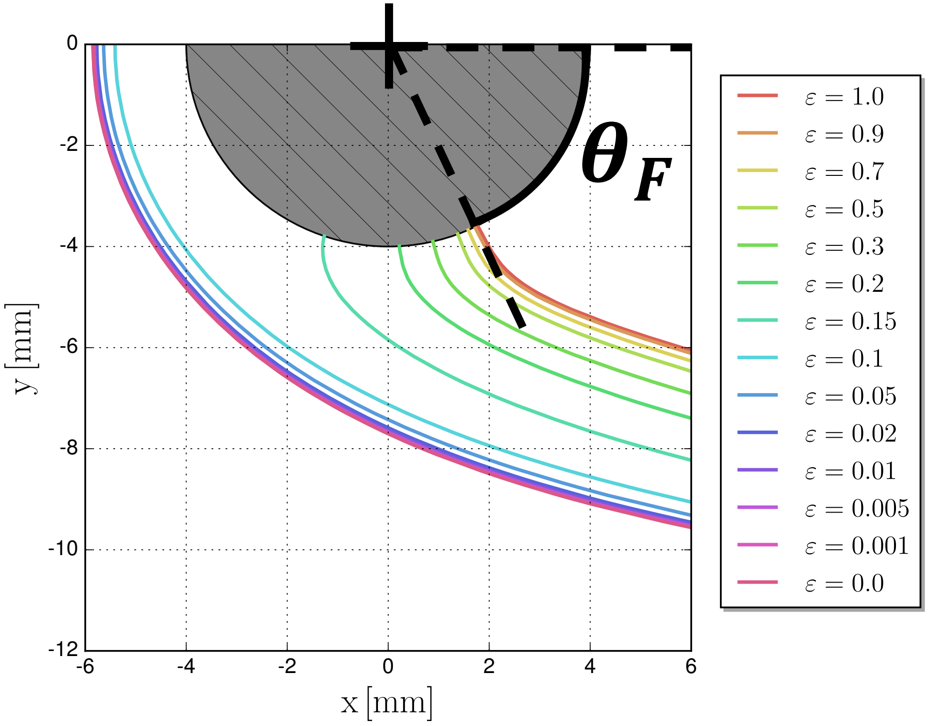


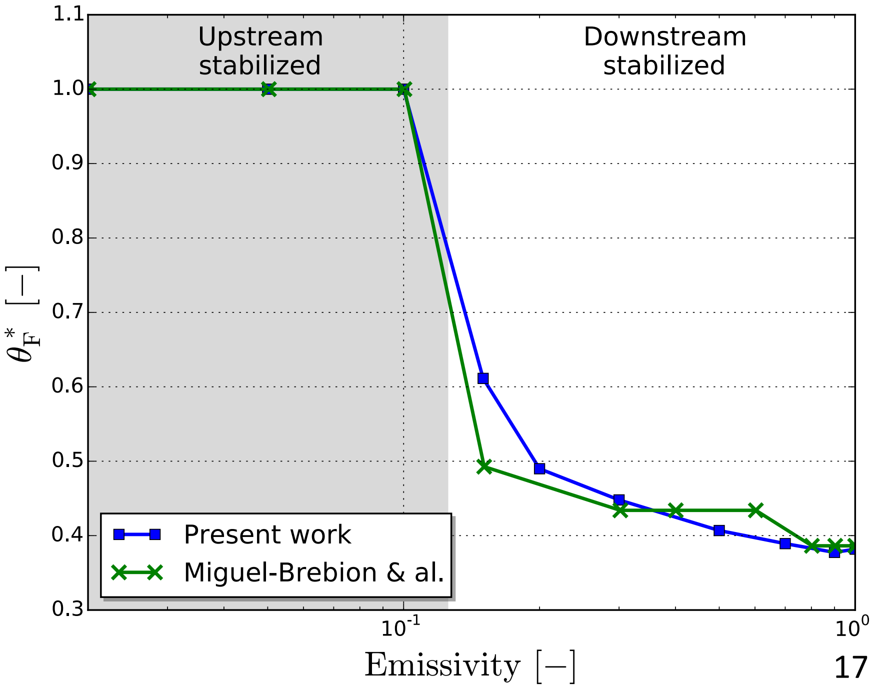
Validation: INTRIG burner

- 2 types of flame stabilisation
  - $\varepsilon = 1.0$: downstream stabilized
    - Low T & little recirculation zone
  - $\varepsilon = 0.0$: upstream stabilized
    - High T & large recirculation zone

- Angle profile
  - Gap between $\varepsilon = 0.15$ and $\varepsilon = 0.1$
  - Good comparison with Miguel-Brebion (2016). Comb & Flame

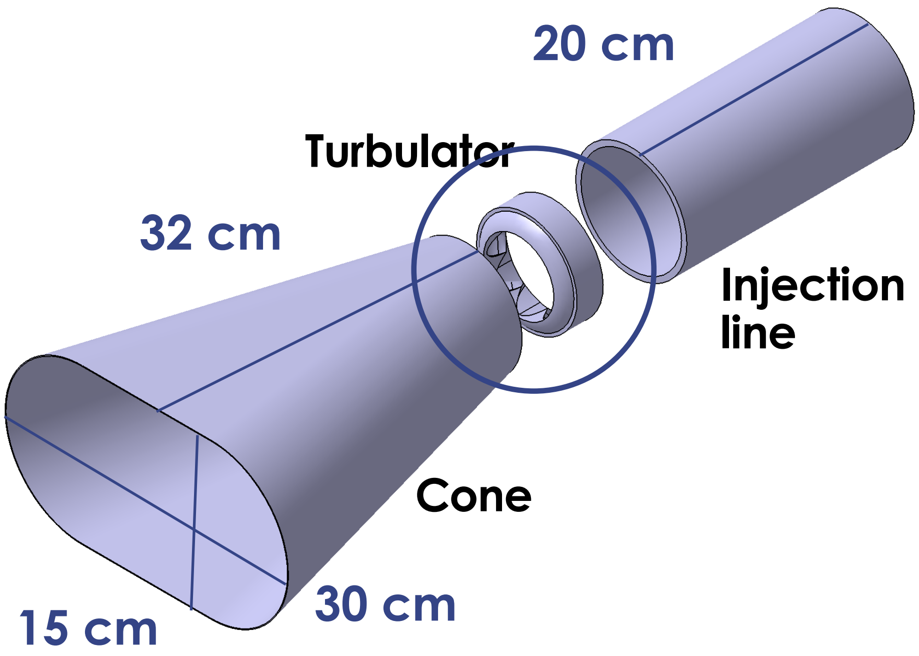




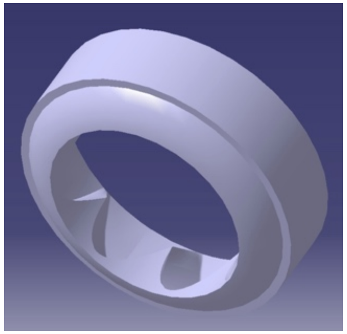


Certification torch: Numerical setup

Domain & mesh



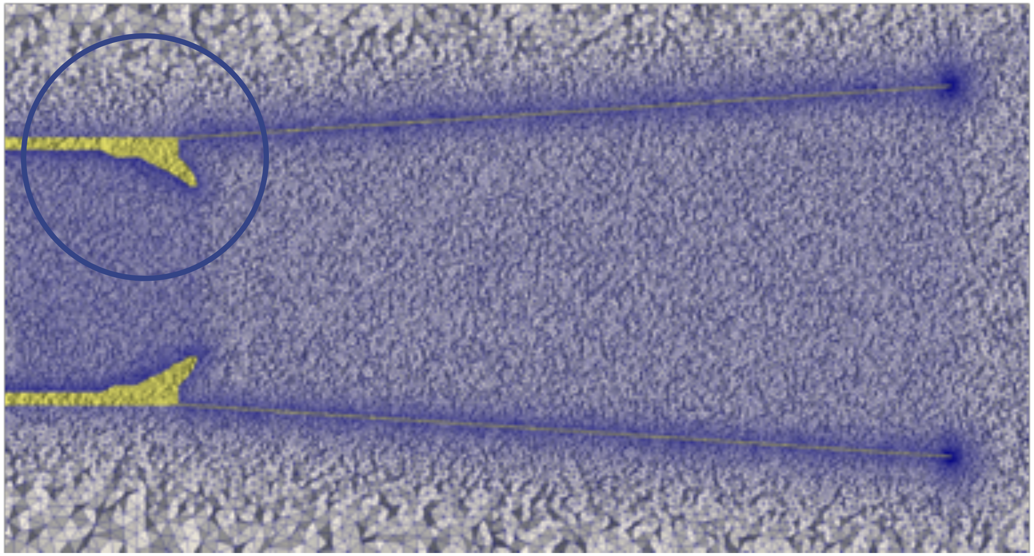
Turbulator:

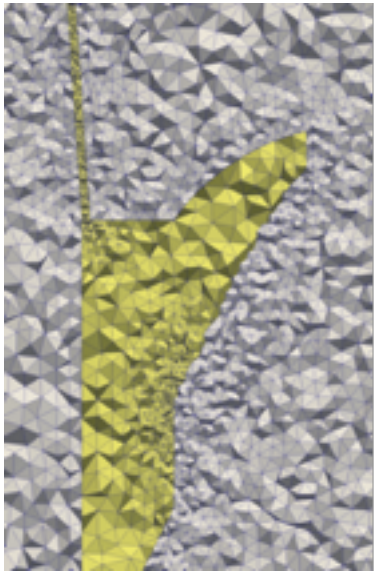


Front

Rear

Simulation domain ≈ $3m^3$

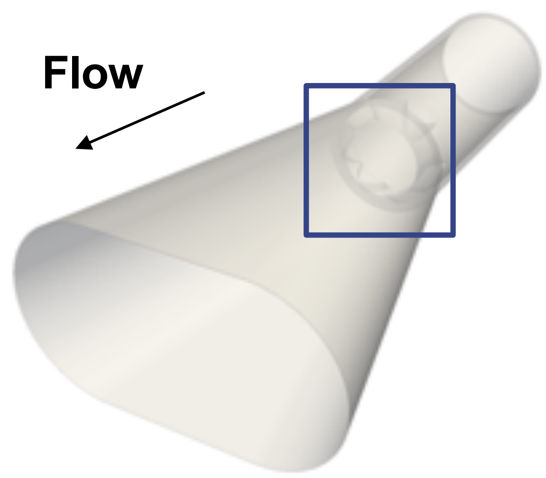


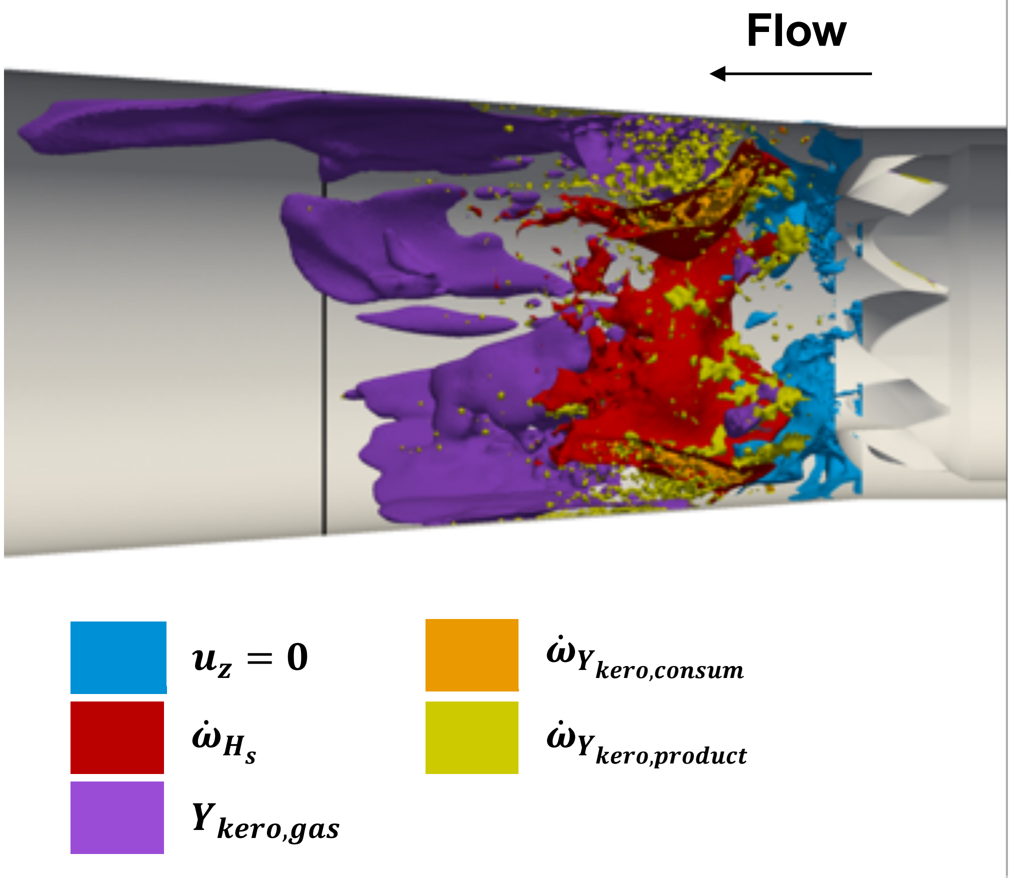


- Fluid:
  - From 0.4 to 2 mm
  - Cell count: **40M tets**
  - Max y+ around **4** inside
- Solid:
  - From 0.2 to 1 mm
  - Cell count: **140M tets**
    ➡ thinness of the cone

Topology of the flame: adiabatic case

- Corner recirculation zone
- High values of fuel consumption where the flame is the strongest
- Large-scale flame wrinkling due to the turbulator
- Individual droplet evaporation at the wall and group droplet evaporation in the center
- Gaseous kerosene found at the wall due to large droplets crossing the flame





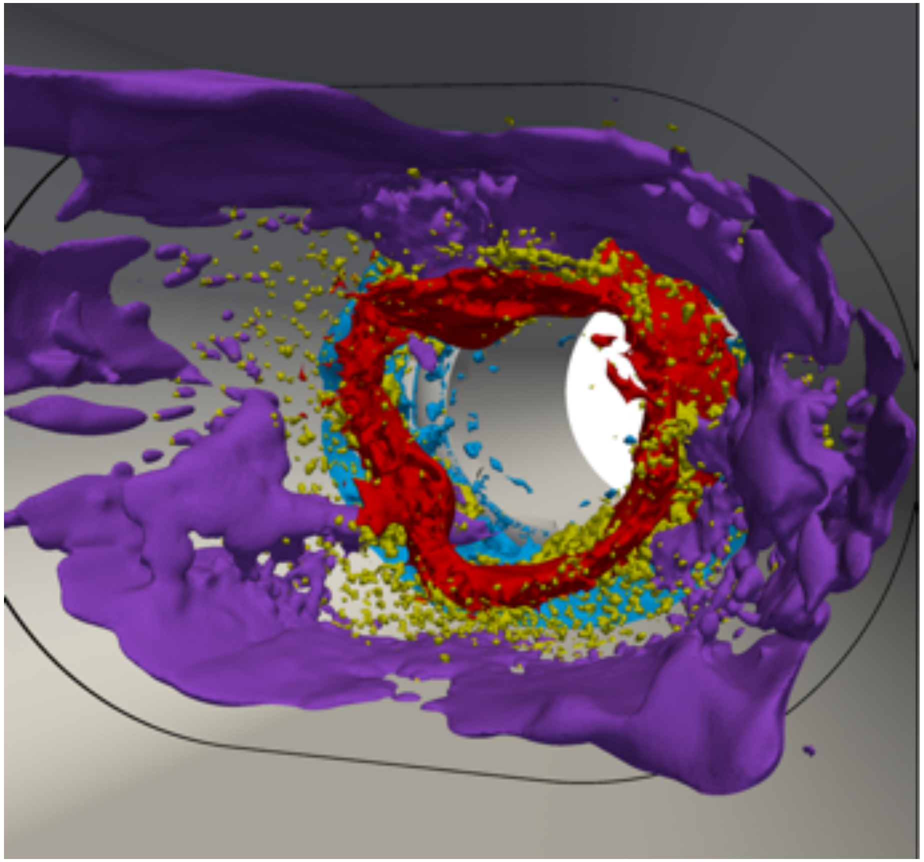
🟦 $u_z = 0$

🟥 $\dot{\omega}_{H_s}$

🟪 $Y_{kero,gas}$

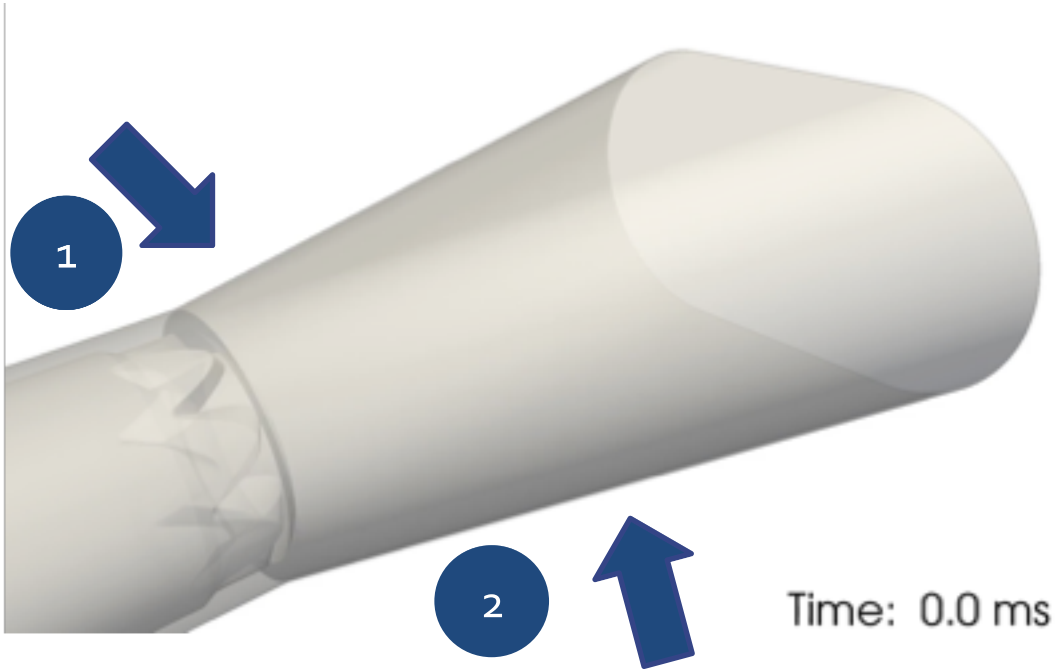
🟧 $\dot{\omega}_{Y_{kero,consum}}$

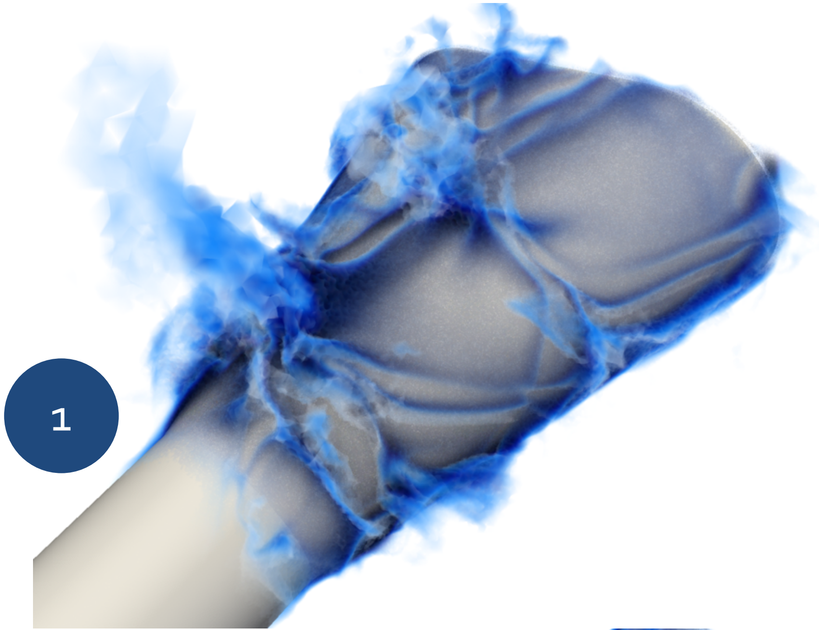
🟨 $\dot{\omega}_{Y_{kero,product}}$



Topology of the flow inside and outside

- Rendering of high values of $\dot{\boldsymbol{\omega}}_T$ during 20ms
  - Wrinkling due to the turbulator
  - Isolated hot spots: combustion of droplets





Rendering of T in the air

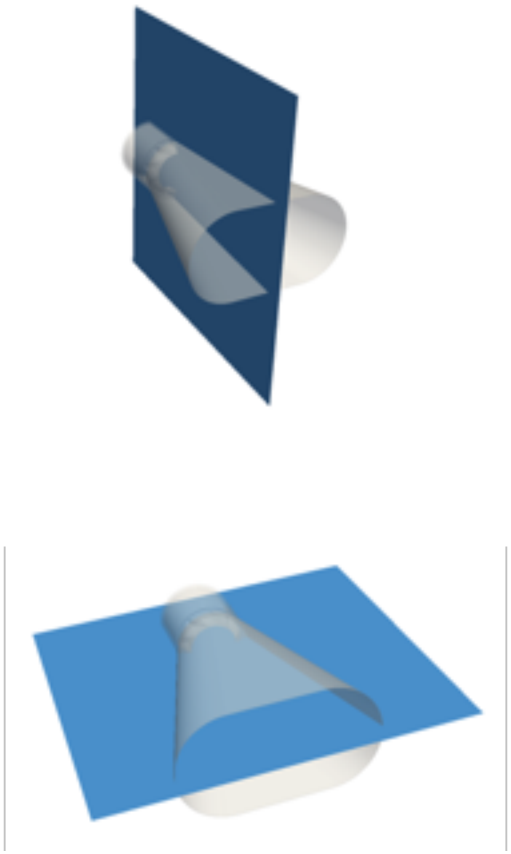
- CHT + RTE in participative medium
- Fluid: 1024 cores / Solid: 60 cores
- 6h on Occigen, CINES
- Upper side: buoyancy driven flow ($R_a = 6.10^6$)
- Lower side: stable stratification

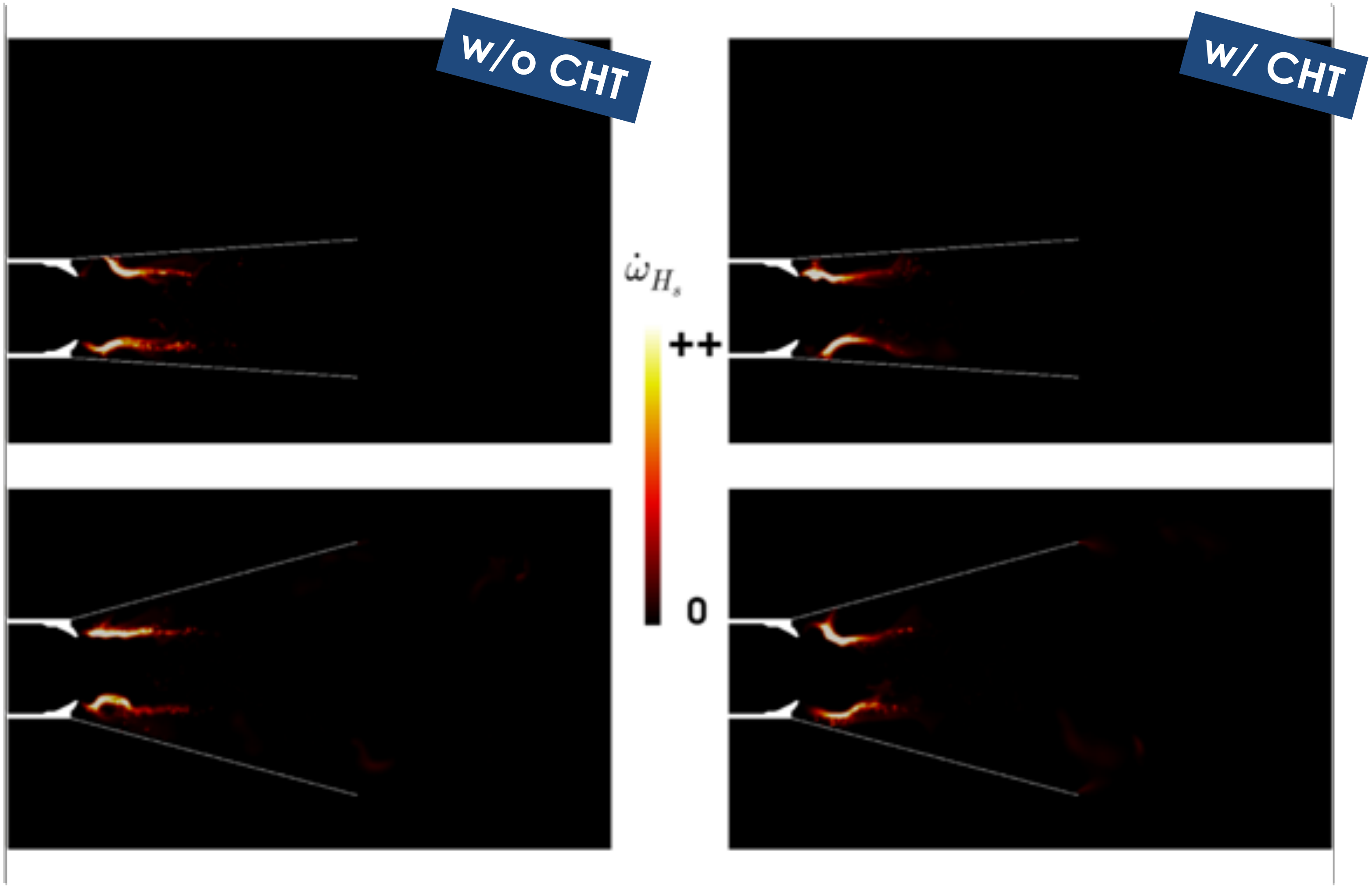
Topology of the flame: adiabatic vs CHT

- Droplet evaporation starts upstream of the flame
- w/ CHT: consumption at the wall & the outlet

- w/ CHT: presence of gaseous kerosene on the walls
- Flame lift-off more important w/o CHT: Hotter recirculation zones

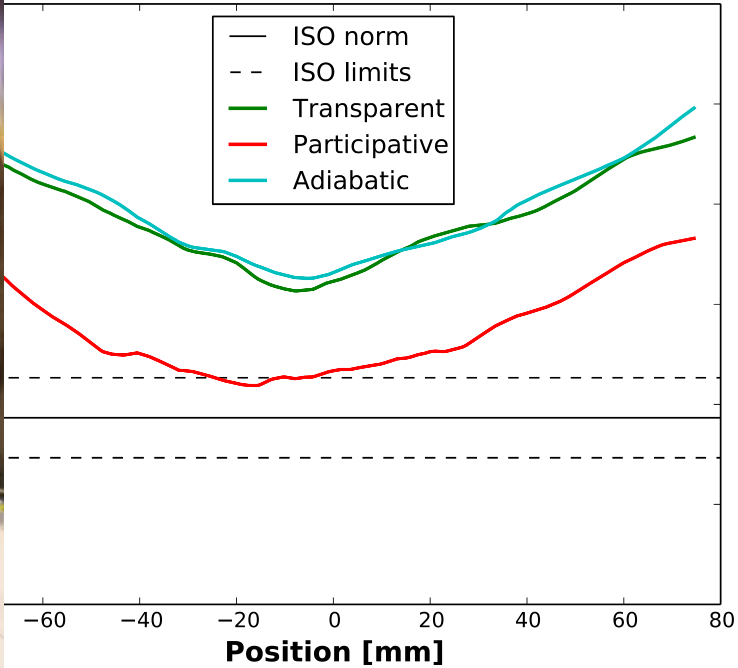
- Large-scale flame wrinkling unaffected by CHT
- Hot air plume above the cone



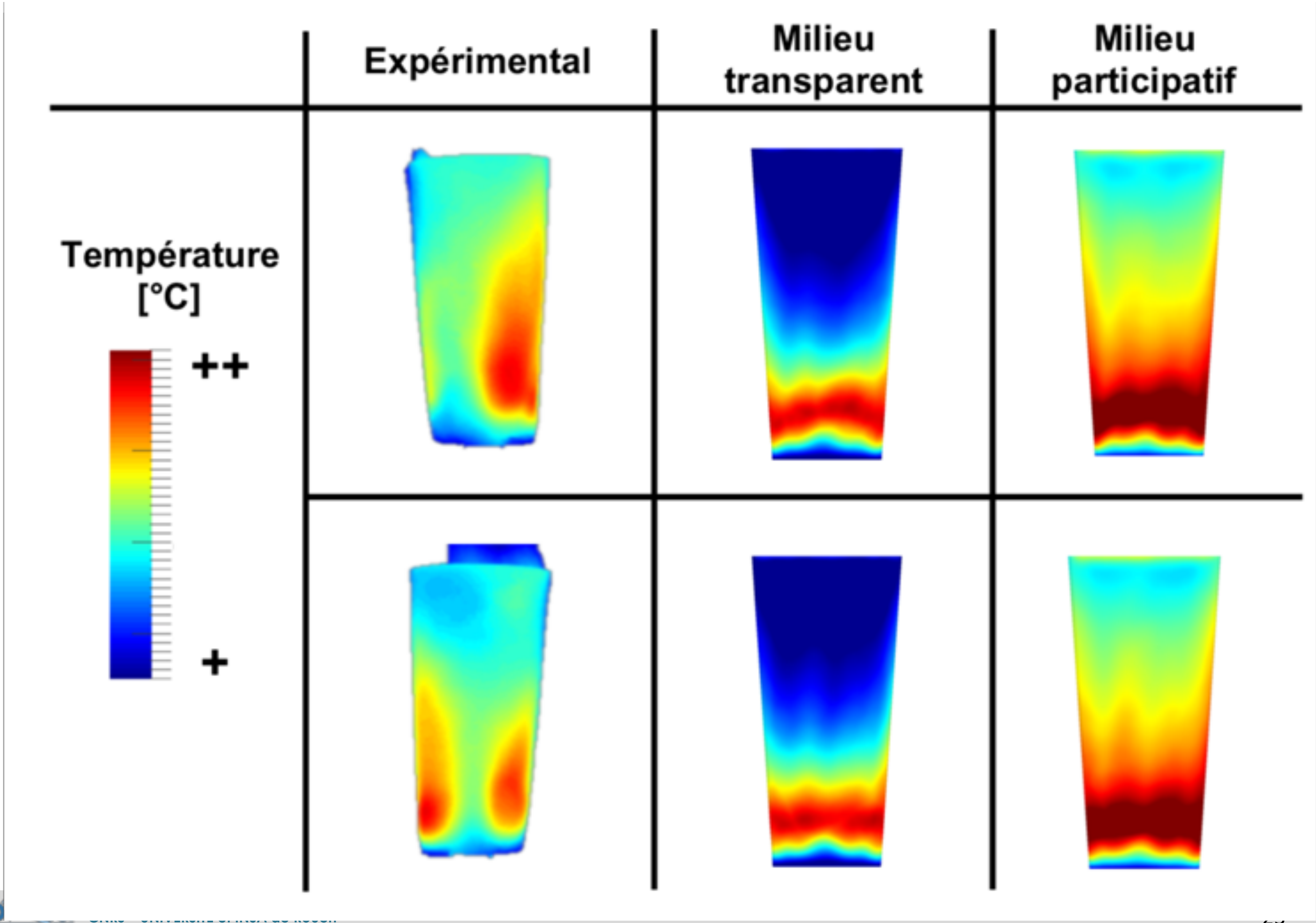


Temperature profiles

- Instantaneous temperature fields
  - Seems to be lower with participative gases
- Mean temperature at the outlet
  - Adiabatic: too high values
  - Transparent: same level as adiab. case
  - Participative: $\approx 200\ K$ lower -> almost at ISO values
  - Limitations
    - Simple chemistry (2 reactions)
    - No model for soot formation/radiation



External wall temperatures



Conclusion & perspectives

- LES of certification burners is challenging but feasible
  - Long integration time / large domain volume
  - Multi-physics

- Many models and sub-models are still required in this work
  - Soot formation/radiation models
  - More detailed chemistry for kerosene

- Perspectives
  - Comparison of T & ϕ on plane plate with exp. results
  - Simulation of a real certification test with engine envelope