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

GRT ACCORT – Centrale Supelec
22/11/2018

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Collaboration: **SAFRAN Helicopter Engines**
(N. CHAUVET, S. DIDORALLY)

CORIA – COMPLEXE DE RECHERCHE INTERPROFESSIONNEL EN AEROTHERMOCHIMIE
INSA – INSTITUT NATIONAL DES SCIENCES APPLIQUÉES ROUEN NORMANDIE
SAFRAN

Motivation

❖ Context

- ➢ Manufacturers need to certify equipments 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
  - This can be **VERY** expensive…

Liquid-fuel burner

❖ Purpose

- ➢ Model fire resistance tests with Large-Eddy Simulation (LES)
- ➢ Improve comprehension of phenomena involved in tests
  - Characterize inhomogeneities inside the torch (burnt gases, droplets)
- ➢ Perform many **NUMERICAL** certification tests
- ➢ Try to minimize the number of **REAL** certification tests

❖ Difficulties

- ➢ Very different time and space scales
- ➢ Multi-physics and complex geometry
- ➢ Very few studies

Large-Eddy Simulation

[1] T. Poinsot, D. Veynante (2005). RT Edwards
[2] B. Abramzon, W.A. Sirignano (1989). Int J Heat Mass Transfer
[3] P. Dagaut, M. Cathonnet (2006). Progress Energy & Comb Sci
[4] L. Guedot (2014). ERCOFTAC ETMM 10

❖ Large-Eddy Simulation [1]

- ➢ Filter Navier-Stokes equations
- ➢ Transport of large scales
- ➢ Modelling of small scales
- ➢ Well adapted to unsteady phenomena

❖ Models for combustion in aero engines

- ➢ Two phase flow (liquid fuel) [2]
- ➢ Detailed chemistry (a lot of reactions) [3]
- ➢ Crude models for heat transfer
  - Few studies with Conjugate Heat Transfer (CHT)
  - No Radiative Heat Transfer

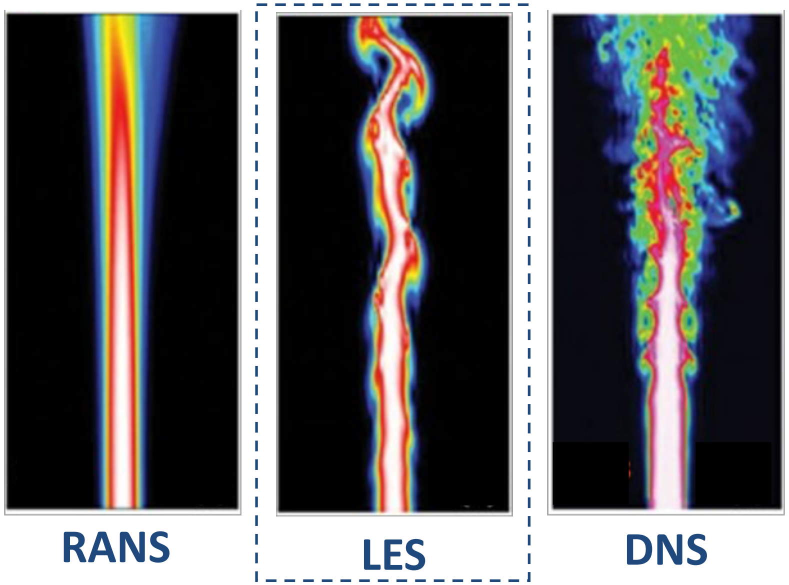
❖ Objectives of the present study

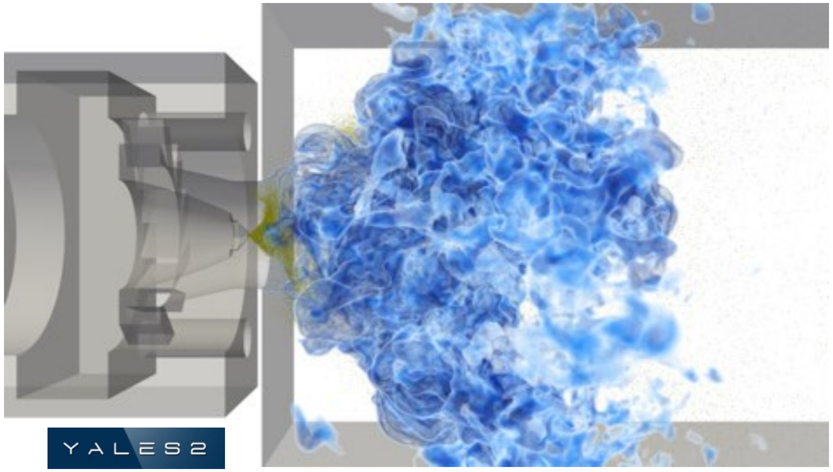
- ➢ Progress on HT modelling
  - Convection
  - Conduction
  - Radiation

Conjugate Heat Transfer

CHT + radiation

- ➢ Validate the models
- ➢ Investigate their impact in an industrial system





MERCATO combustion chamber [4]

I. Model and coupling strategies

II. Academic validation

III. Torch flame results

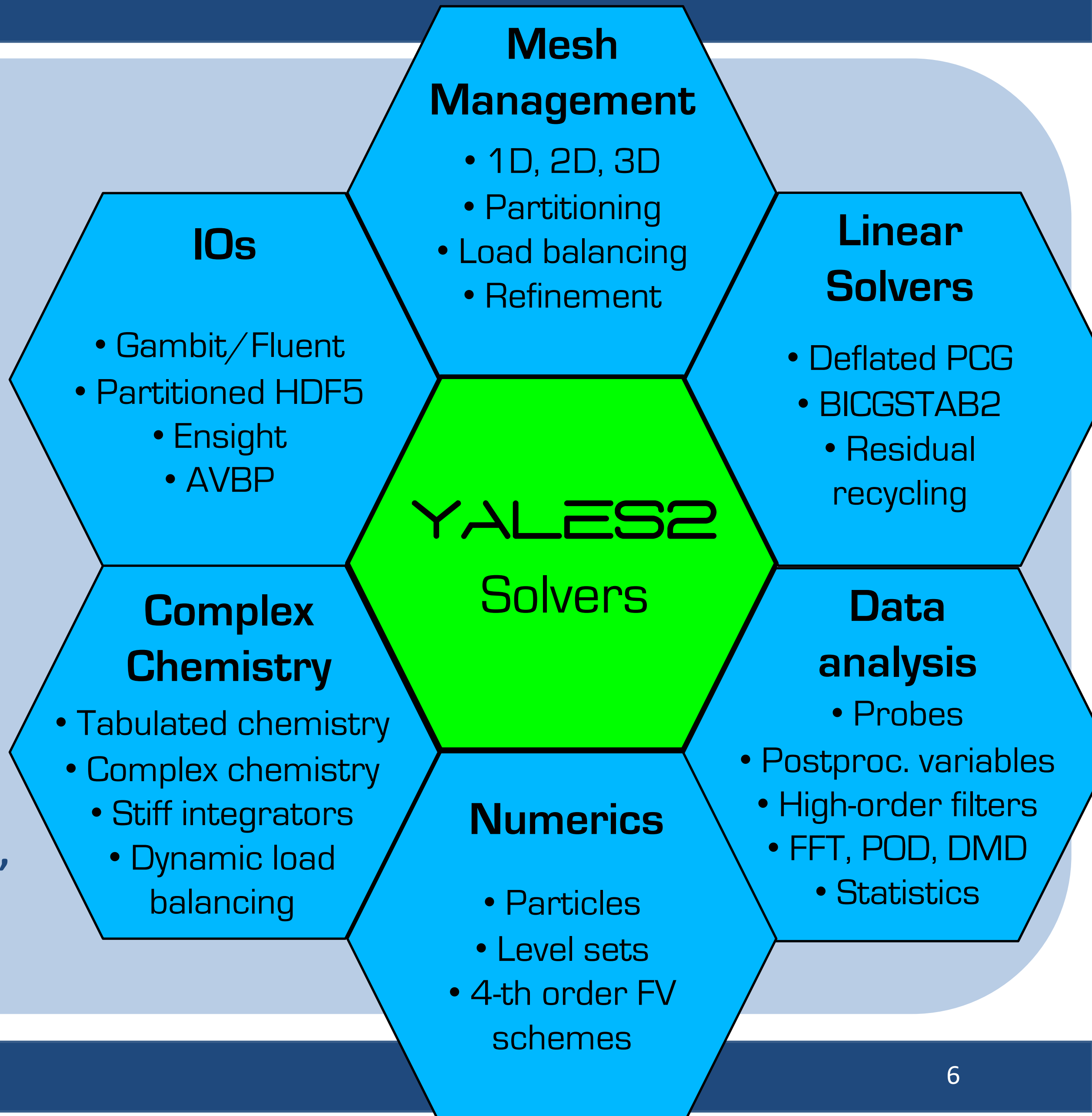
Fluid solver: YALES2 [1]

[1] V. Moureau (2011). Combustion & Flame
[2] M. Malandain(2013). Journal of Computational Physics

- Low-Mach Number Navier-Stokes equations
- Finite Volumes on unstructured meshes
- Dedicated to DNS & LES of Multiphysics Flows
  - Turbulence
  - Combustion
  - Two-phase flows (droplets, bubbles, liquid sheets, …)
- High-order schemes (centred 4th) ➔ low dissipation and dispersion
- In house linear solver: Deflated PCG [2] for symmetric systems
- Designed for HPC: scale-up to 10^{10} cells and 10^5 cores
- More than 200 users across Europe, both industry and academic
- More than 80 publications related to YALES2 (Google Scholar)
- 2011 IBM Faculty award

Fluid solver: YALES2

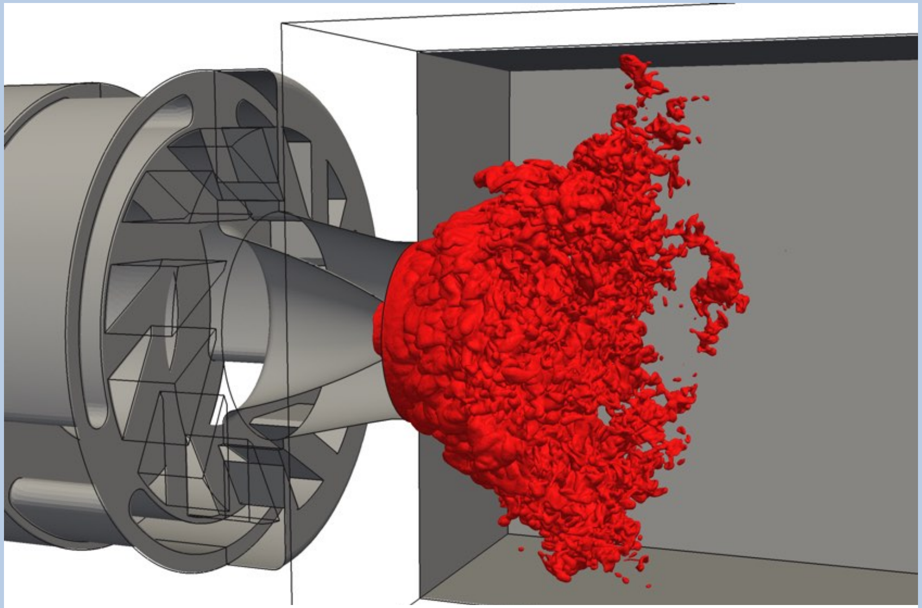
- **3 main maintainers**
  - V. Moureau
  - G. Lartigue
  - P. Bénard
- **430 000 lines of object-oriented f90**
- **Python interface**
- **Git**
- **Portable on all the major platforms + ARM, Xeon Phi, …**



Fluid solver: YALES2

❖ Solvers list

- Scalar solver (SCS)
- Level set solver (LSS)
- Lagrangian solver (LGS)
- Incompressible solver (ICS)
- Variable density solver (VDS)
- Spray solver (SPS)
- Magneto-Hydrodynamic solver (MHD)
- Heat transfer solver (HTS)
- Chemical reactor solver (CRS)
- Linear acoustics solver (ACS)
- Mesh movement solver (MMS)
- ALE solver (ALE)
- Radiative HT solver (RDS)
- Explicit compressible solver (ECS)
- Implicit compressible solver (CPS)
- Immersed boundary solver (IBS)
- Darcy solver (DCY)
- Granular flow solver (GFS)
- …

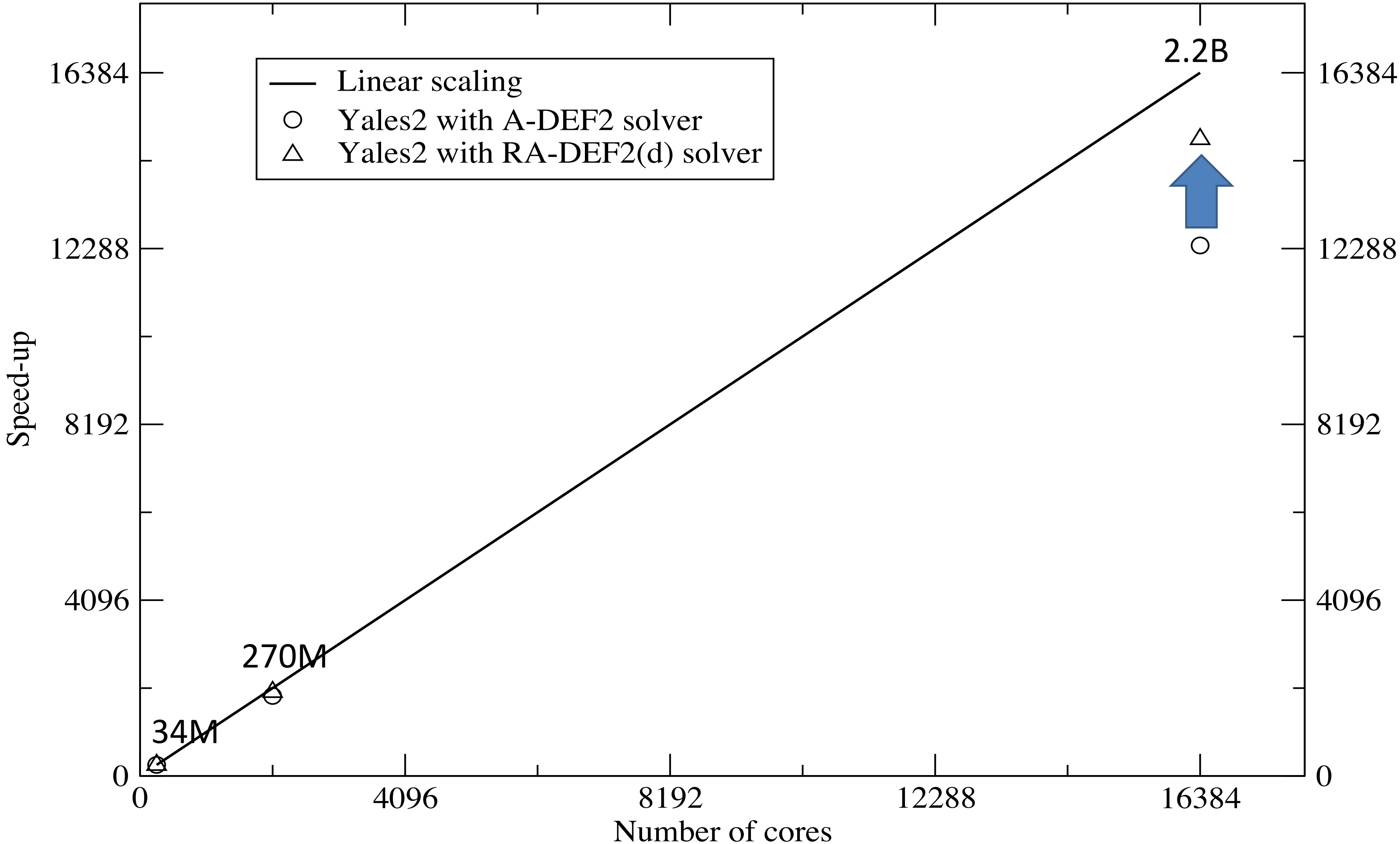


PRECCINSTA Burner
2.6 billion cells, 16384 cores of BG/P

More details:
- www.coria-cfd.fr
- www.youtube.com/user/CoriaCFD

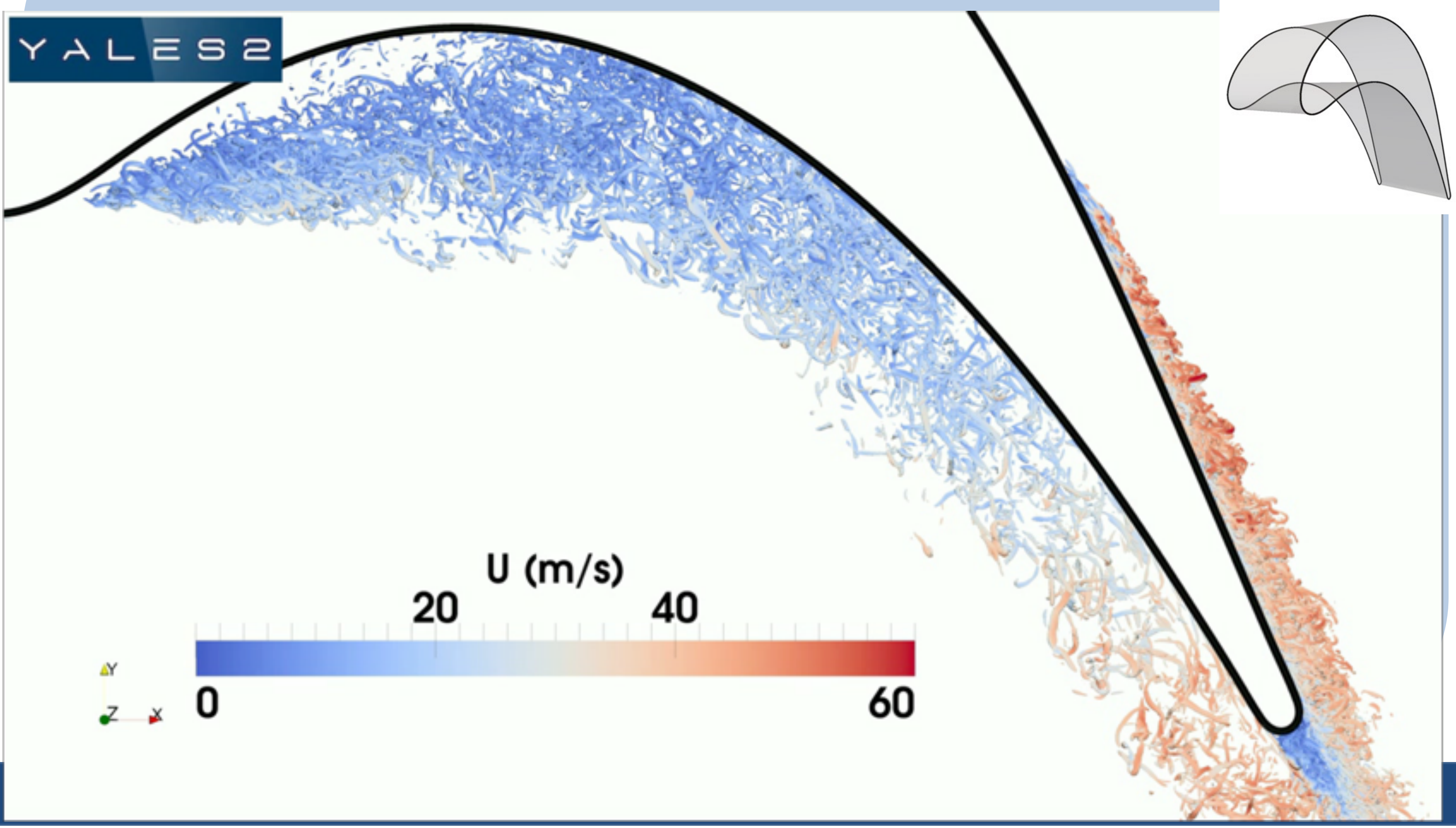
Fluid solver: YALES2

❖ **Speed-up of the YALES2 incompressible solver on Curie (TGCC-CEA)**



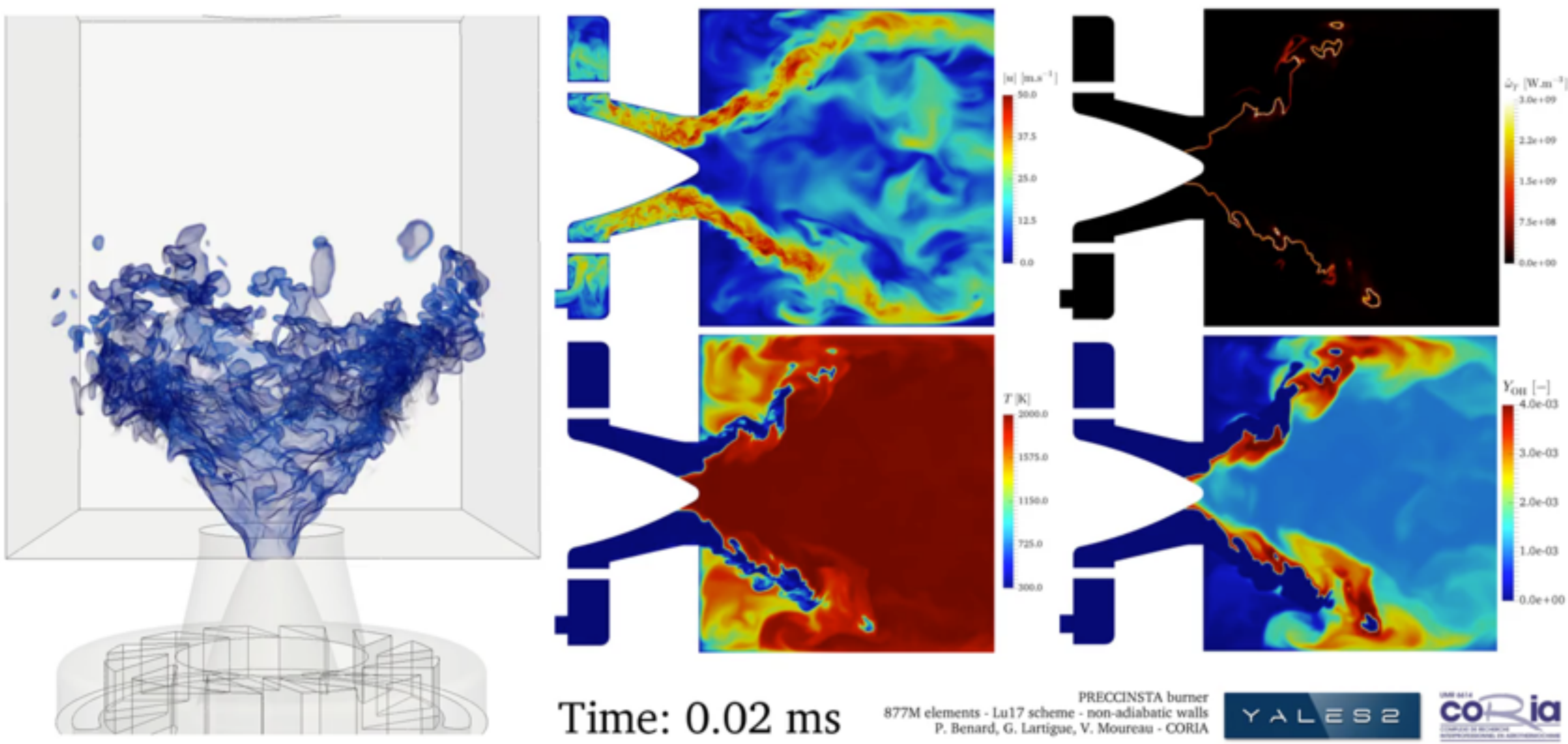
Fluid solver: YALES2

- Visualisation of the vortices cores by iso Q-criterion colored by velocity
- 2.2B cells on 16'384 cores

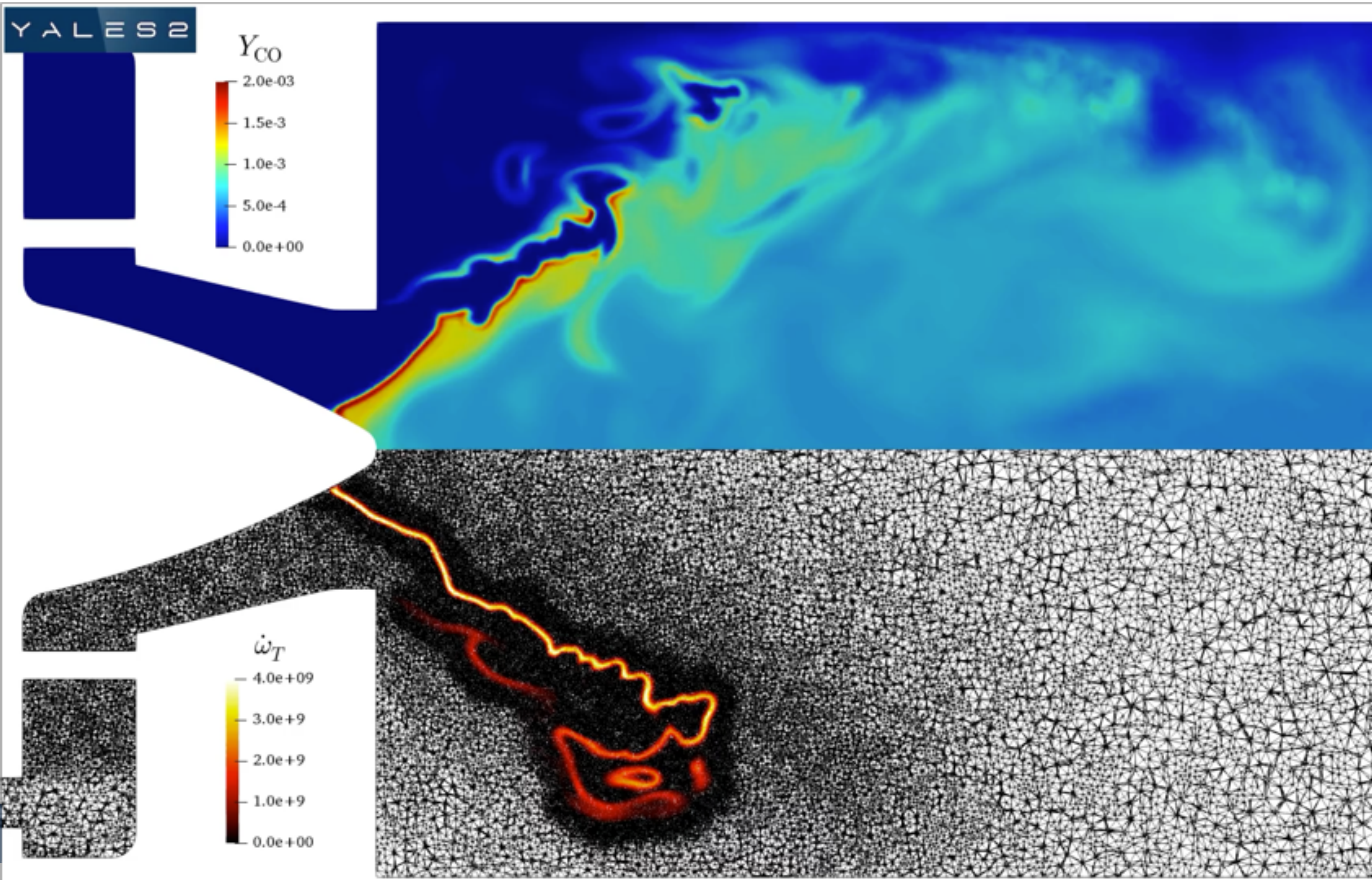


Fluid solver: YALES2

- Computation of the PRECCINSTA semi-industrial burner with YALES2
- Quasi-DNS (Δx = 50µm in the flame) with complex chemistry (Lu17 scheme)
- Including Wall Heat Losses
- 877M cells / 10’000 processors

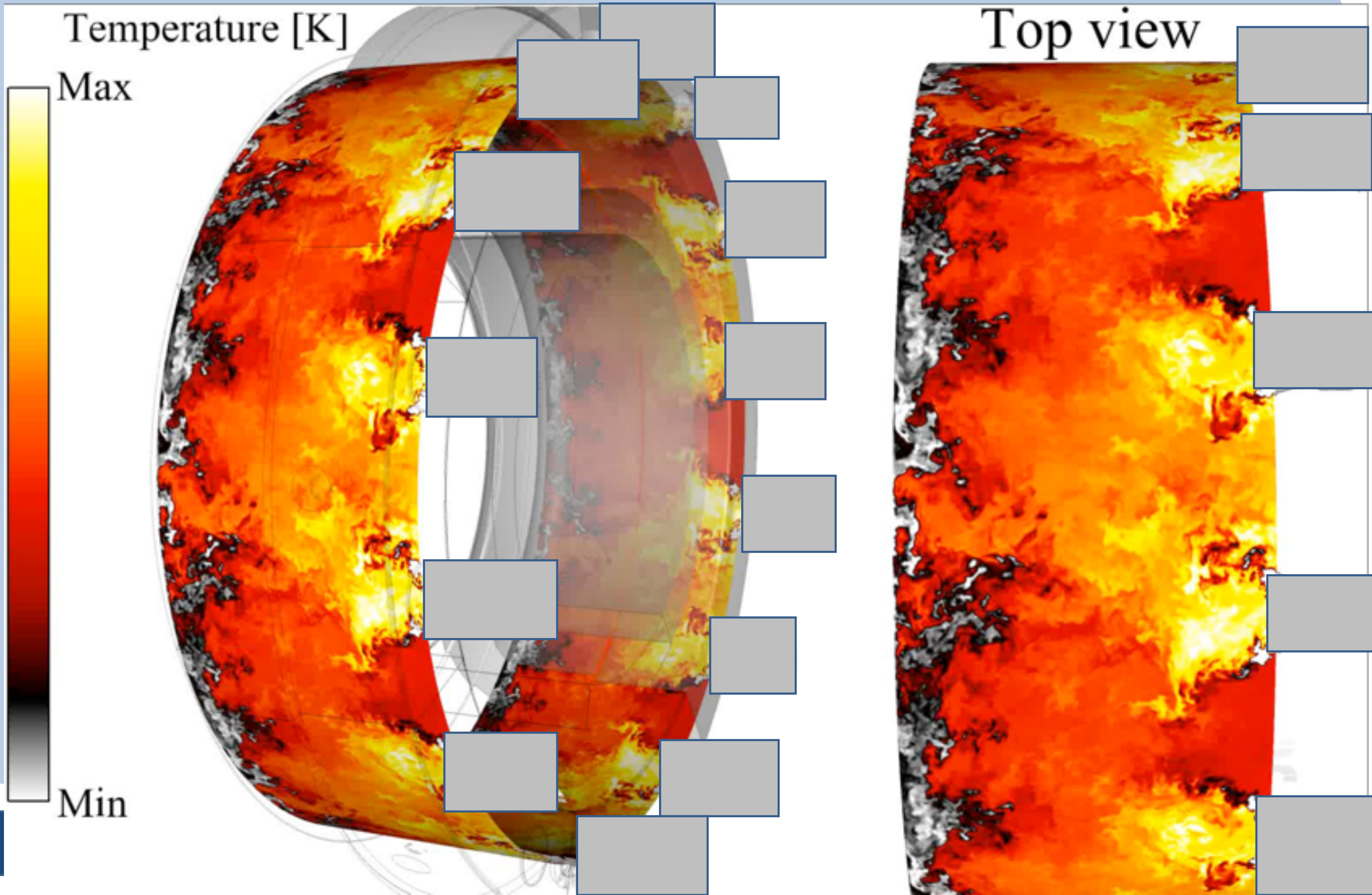


Fluid solver: YALES2



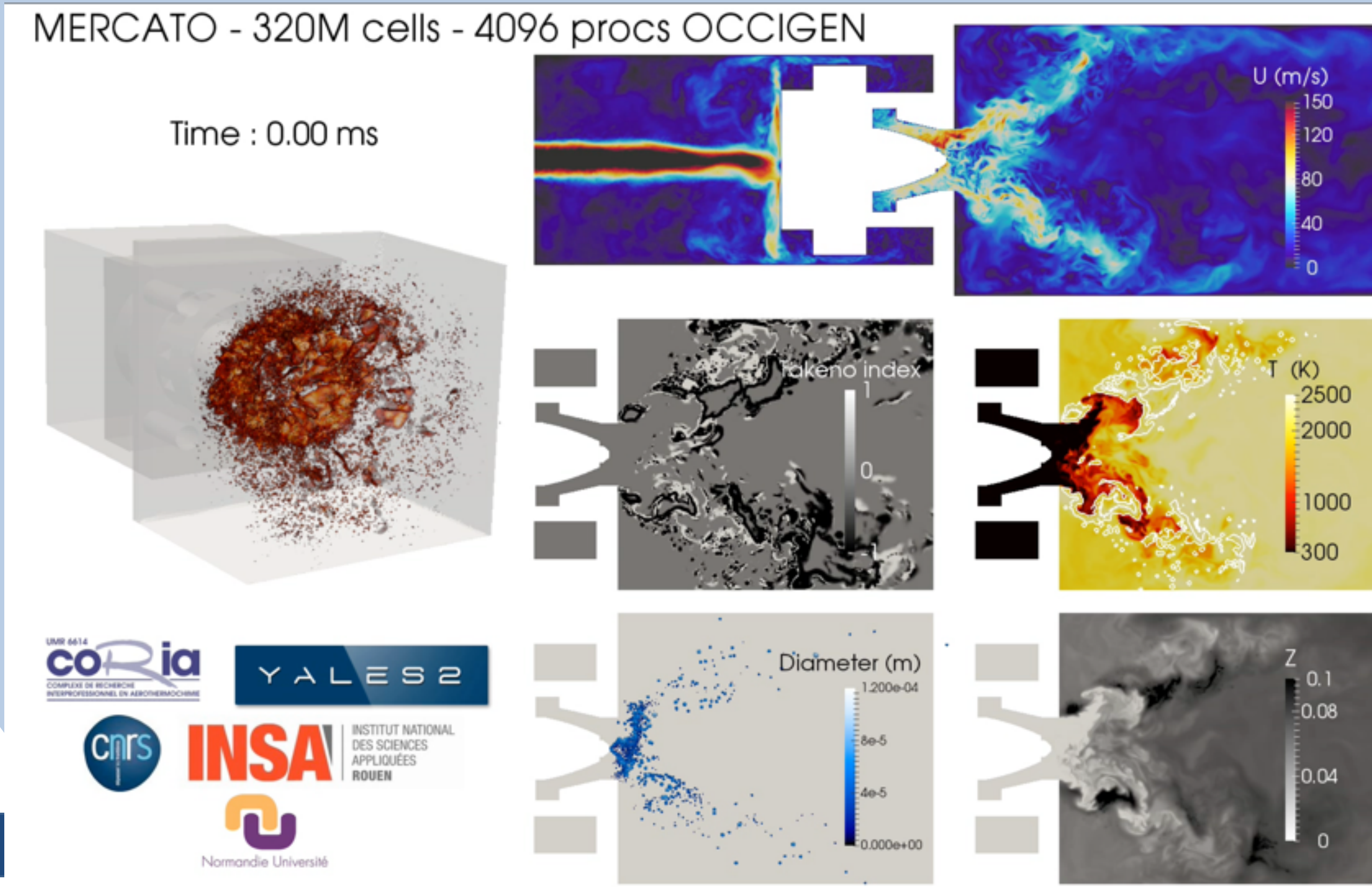
Fluid solver: YALES2

❖ **LES of a Low-NOx combustor (courtesy Safran HE) with 376M cells**



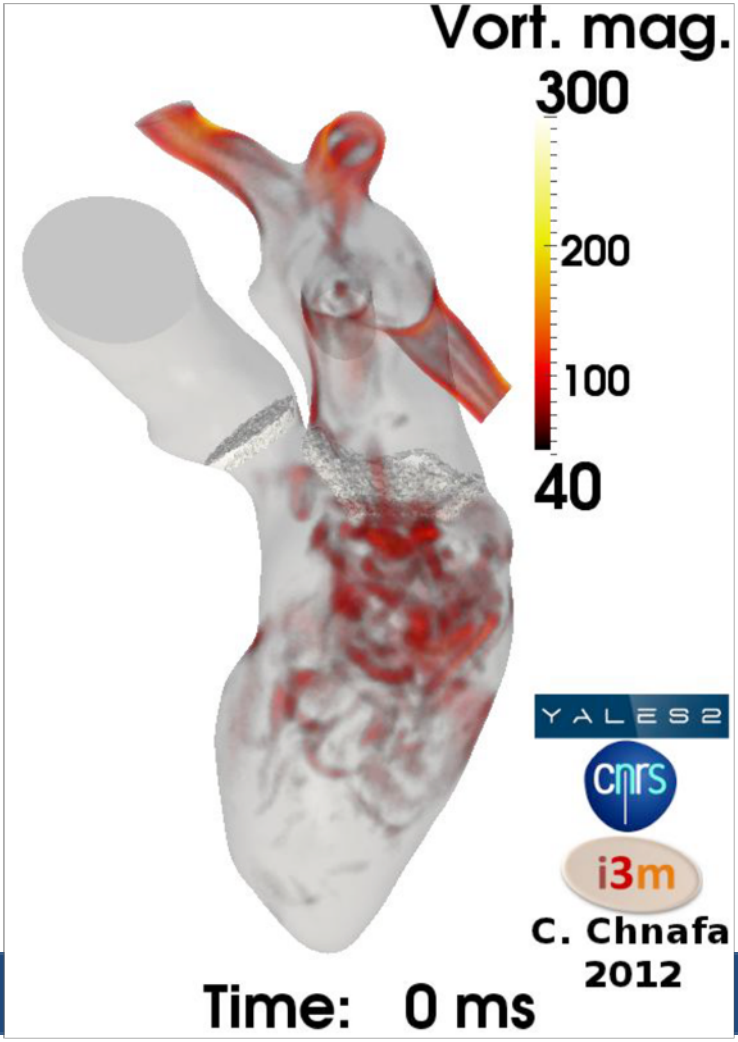
Fluid solver: YALES2

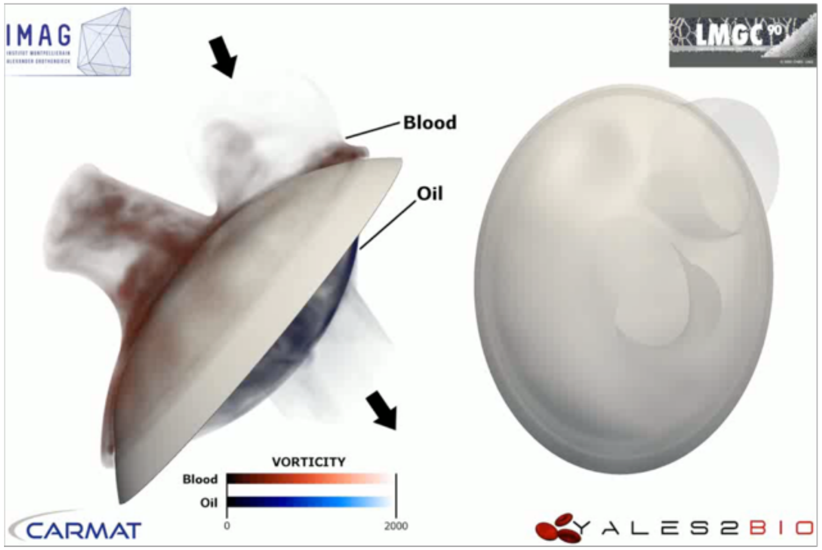
❖ **LES of the atomization and combustion of a kerosene injector with 320M cells**

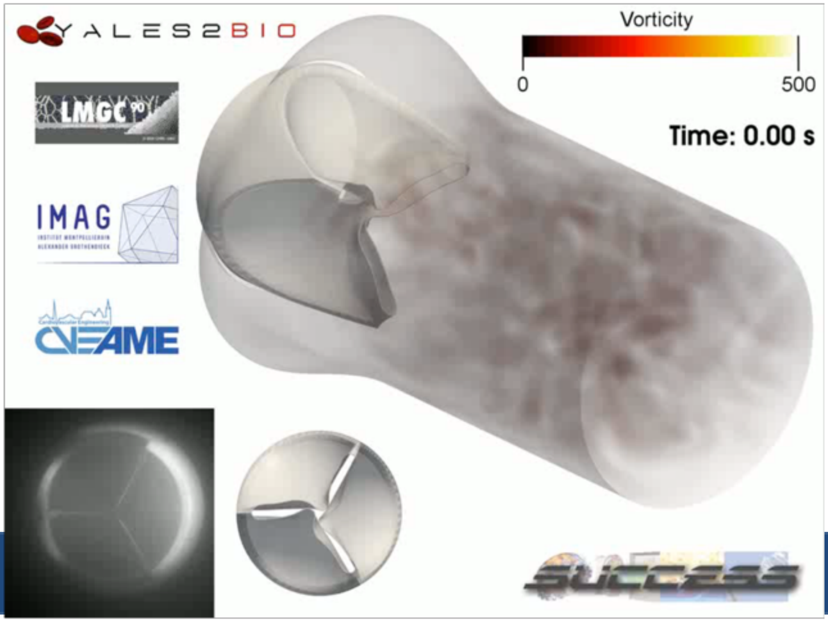


Some studies with YALES2BIO

❖ **Project led by S. Mendez and F. Nicoud at IMAG, Montpellier**







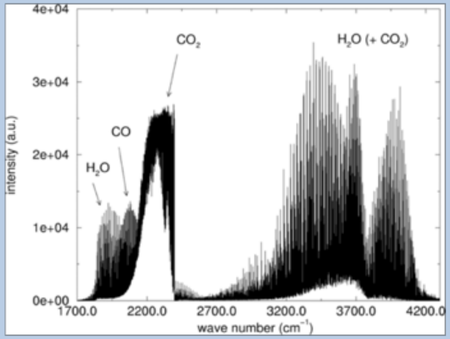
The YALES2 Team

Coupling strategy: solver interactions

[1] V. Moureau (2011). Combustion & Flame
[2] http://www.cerfacs.fr/globc/PALM_WEB/
[3] M.B. Giles (1997). Int. journal for num methods in fluids
[4] F. Duchaine (2009). Int Journal of Heat & Fluid Flow
[5] A. Felippa (2001). Comput. methods in appl mech & eng
[6] M.F. Modest (2013). Academic Press

CHT

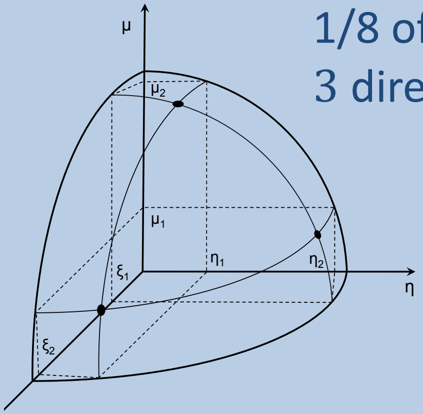
- **Fluid** and **Solid** have to **communicate**
  - Solver: **YALES2 [1]**
  - Coupling: **OpenPALM [2]**
- **What is exchanged? [3,4]**
  - **Fluid** side: **Flux** is sent
  - **Solid** side: **T** is sent
- **How? Parallel Asynchronous Coupling Strategy [4,5]**



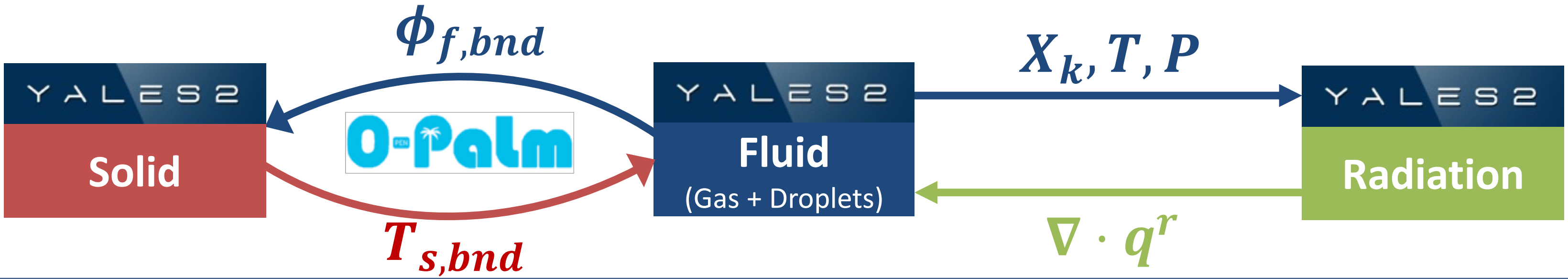
Emission spectrum (CH4/air flame, 2160K)

Radiation

- **Importance of radiation in combustion**
  - High temperatures
  - Burnt gases: high absorption power
- **Solve Radiative Heat Transfer Equation [6]**
  - Spectral quadrature
  - **Angular quadrature (DOM)**
  - Spatial discretization **SAME MESH as Fluid**



1/8 of space
3 directions



Radiative solver: gas properties

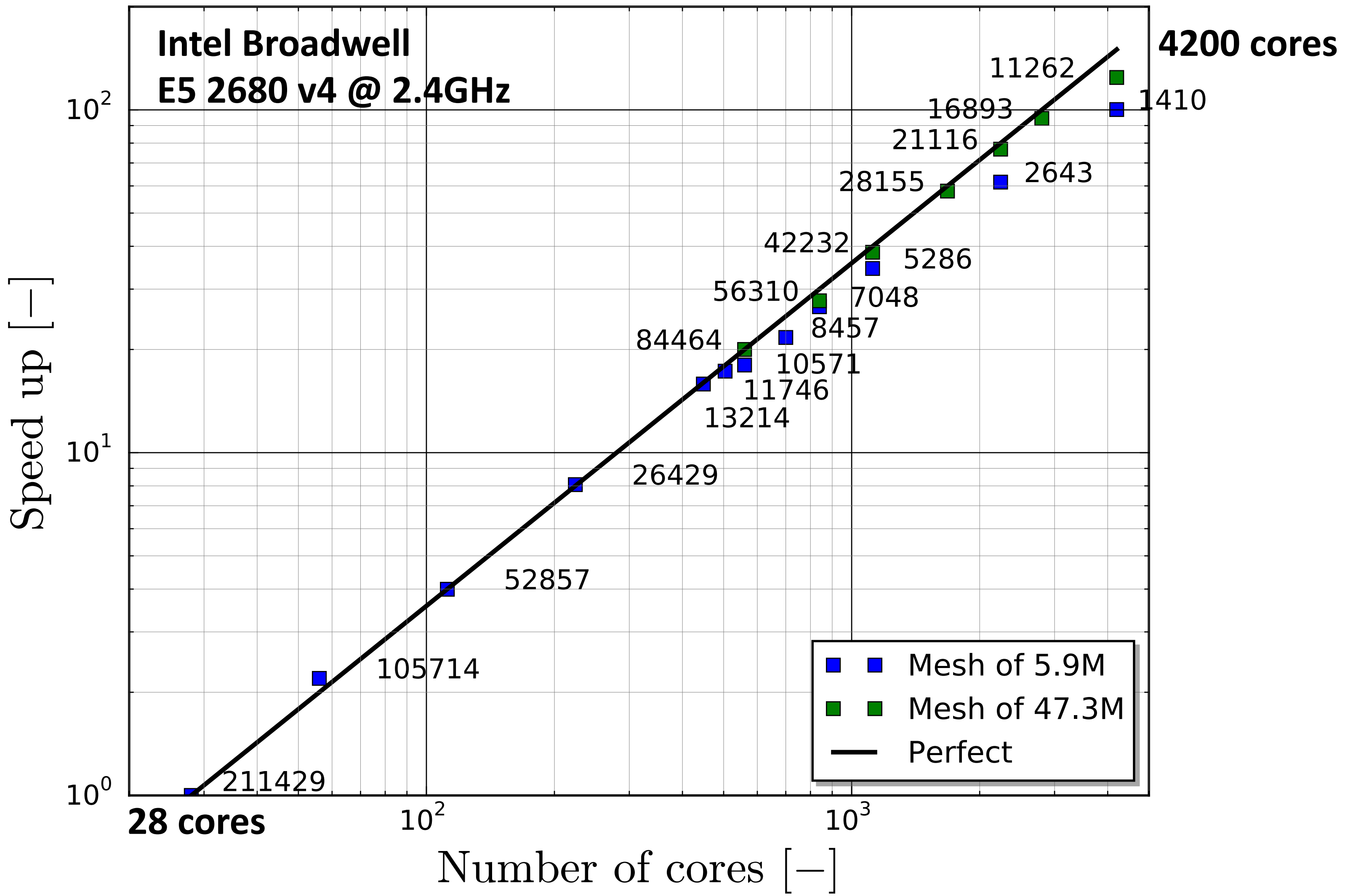
[1] Goody (1989). J. Quant. Spectro. & Radiative Transfer
[2] Lacis & Oinas (1991). J. Geophysical Research
[3] Liu (2000). Int. J. Heat Mass Transfer
[4] Rivière & Soufiani (2012). Int. J. Heat Mass Transfer
[5] Rivière (1992). J. Quant. Spectro. & Radiative Transfer

- YALES2 solves the RTE:
  - For a transparent media (surface to surface)
  - For a participating media in reordered k-space
- SNB-CK model based on EM2C latest 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)
- Optimized Brent Method to solve for k* for each spectral quadrature point
- Vectorized instructions to accelerate computations
- Low impact on CPU consumption

Radiative solver: DOM

- YALES2 solves the RTE with a DOM method
- In 2D: S4 (2 directions/quadrant) → S32 (16 directions/quadrant)
- In 3D: S4 (3 directions/octant)
- All directions are solved simultaneously:
  - without scattering: directions are decoupled (efficient)
  - with scattering: only minor modifications to the solver
- The RTE is discretised with a 4^{th} order centred method with 10% upwinding
- Linear solver: optimized and fully vectorized parallel BiCG-Stab(2) [1]
- Very efficient: uses the SAME MESH as the fluid (tens of millions of cells)

HPC: performances of YALES2 radiative module



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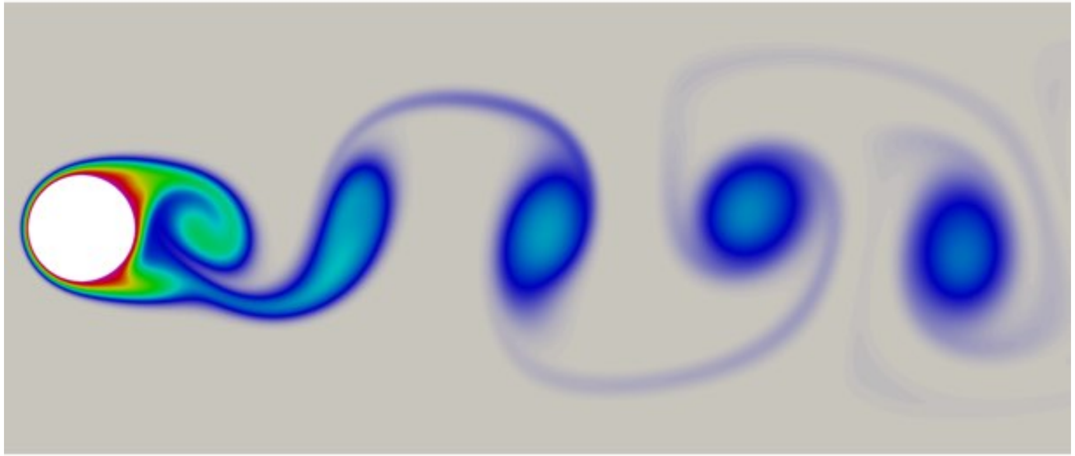
II. Academic validation



III. Torch flame topology

Academic validation test-case: INTRIG

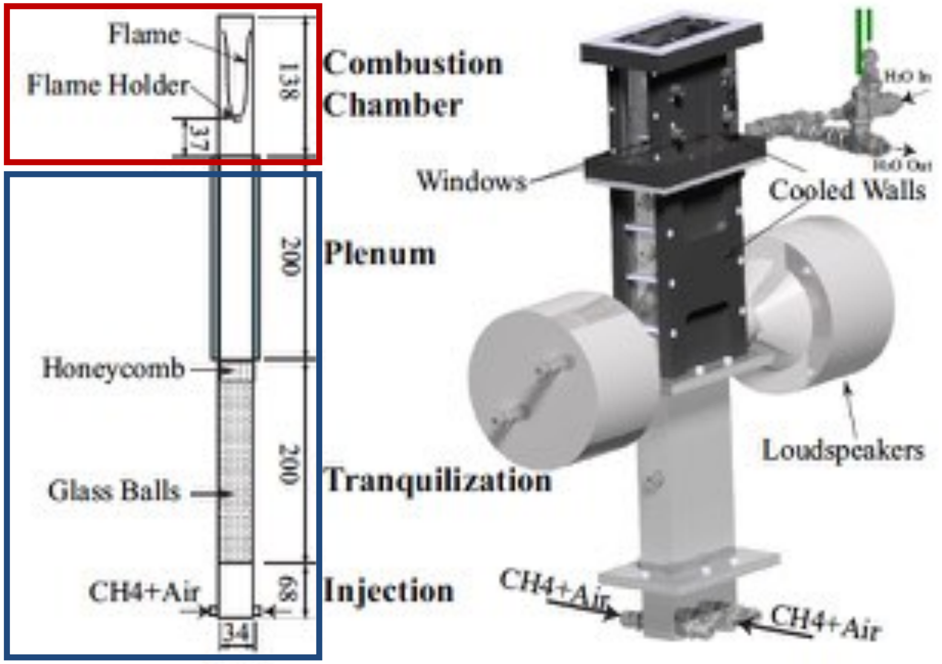
[1] Miguel-Brebion (2016). Comb & Flame
[2] Xavier (2017). JFM
[3] Meija (2017). Proceedings Comb Inst
[4] Meija (2018). Comb & Flame

- **INTRIG: experimental combustion chamber [1,2,3,4]**
  - Mixture: CH_4 and Air
  - Laminarized flow
  - Combustion chamber:
    - owns a cylindrical steel Bluff-body
    - stabilizes a V-flame

- **Numerical parameters**
  - Fluid: air at $u \approx 1m/s$ ($Re = 584$)
  - Flow with Von-Karman streets ($40Hz$)
  - 2D Mesh: 630 000 tetrahedrons
    - $70\mu m$ in the flame and the solid
    - Prism layers of $20\mu m$ at interface

- **Interest**
  - Validate CHT & radiation strategies
  - Use radiation // present studies [1,2]

Part to simulate



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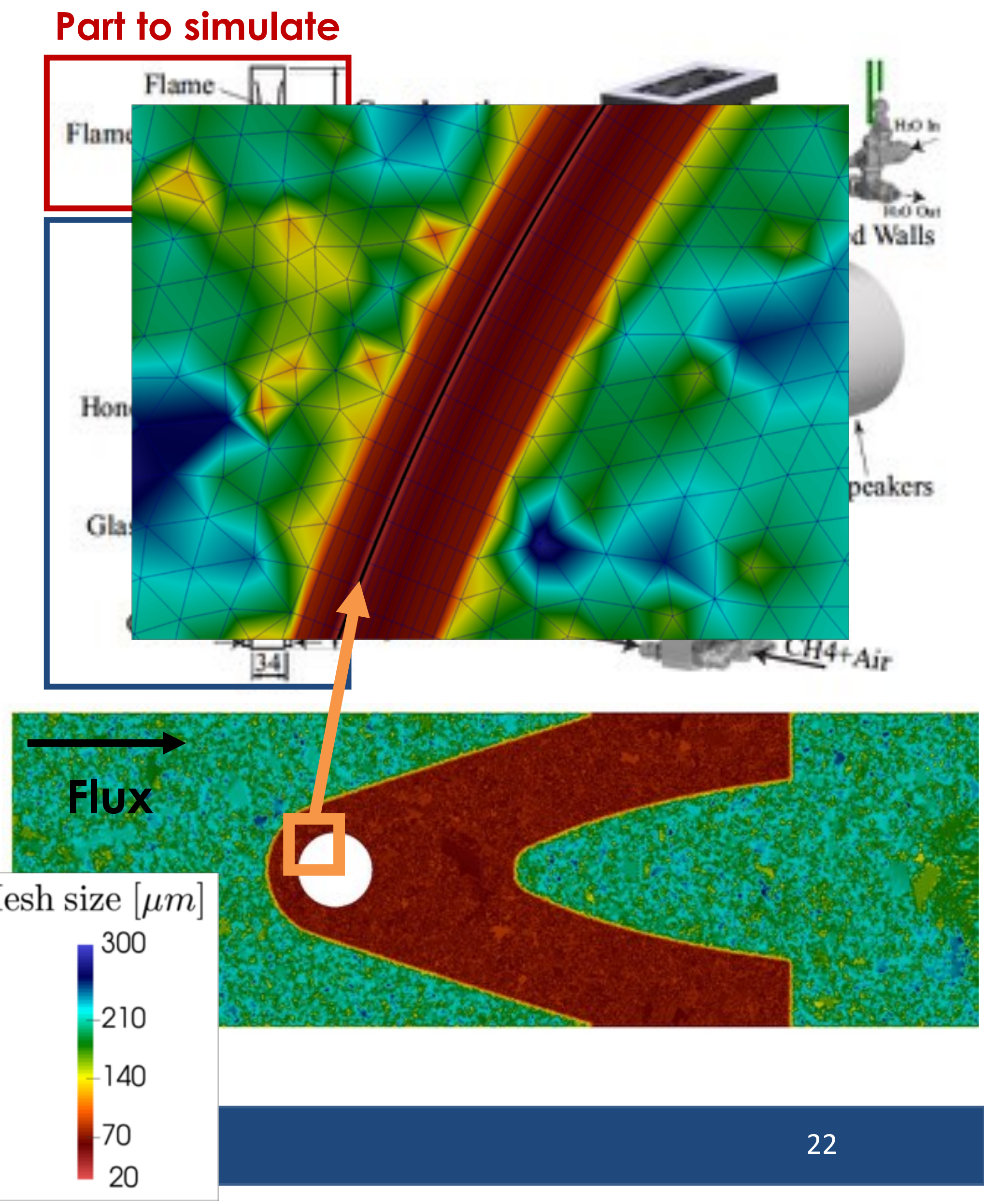
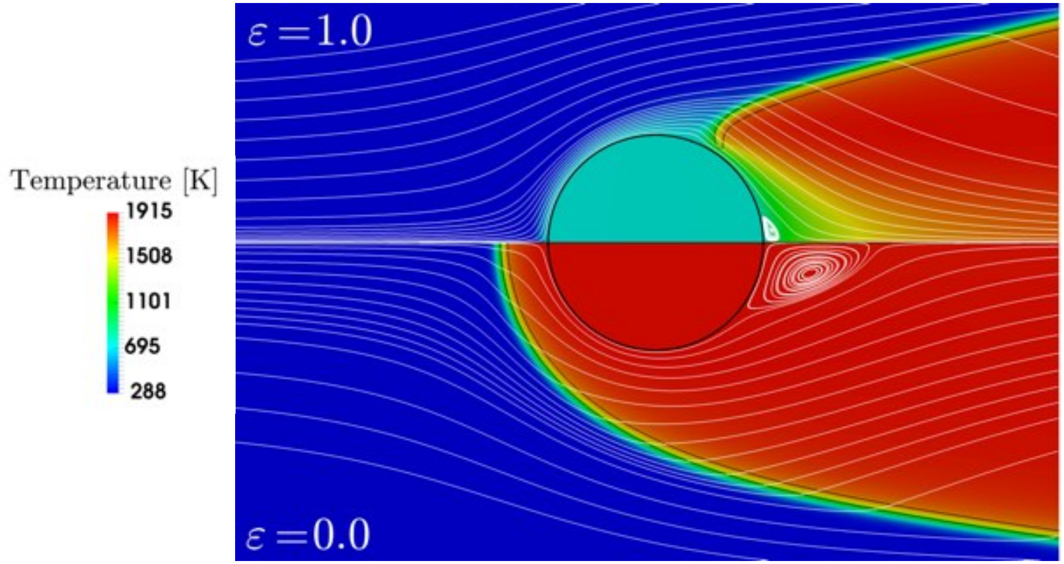


[1] Miguel-Brebion (2016). Comb & Flame

Academic validation test-case: Influence of cylinder emissivity

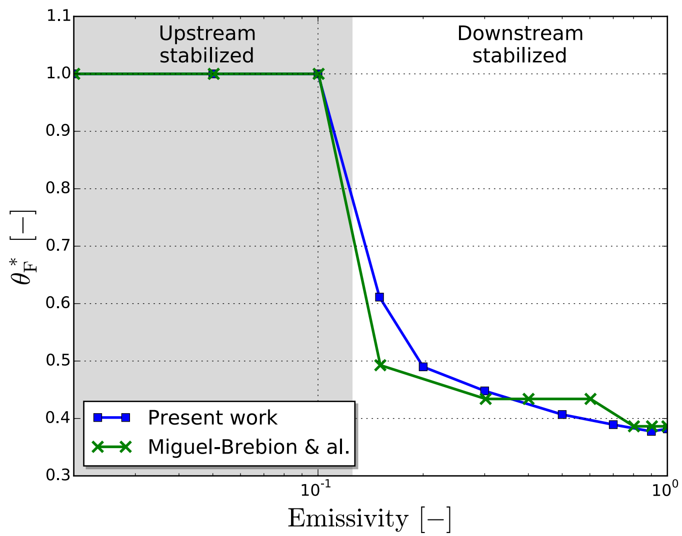
❖ 2 types of flame stabilisation

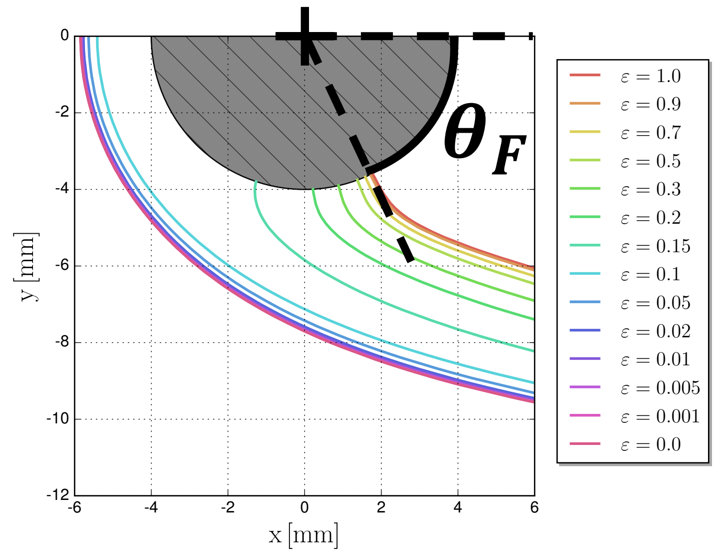
- ➢ $\varepsilon = 1$: downstream stabilized
  - Low T & little recirculation zone
- ➢ $\varepsilon = 0$: upstream stabilized
  - High T & large recirculation zone



❖ Angle profile

- ➢ Gap between $\varepsilon = 0.15$ and $\varepsilon = 0.1$
- ➢ Good comparison with [1]



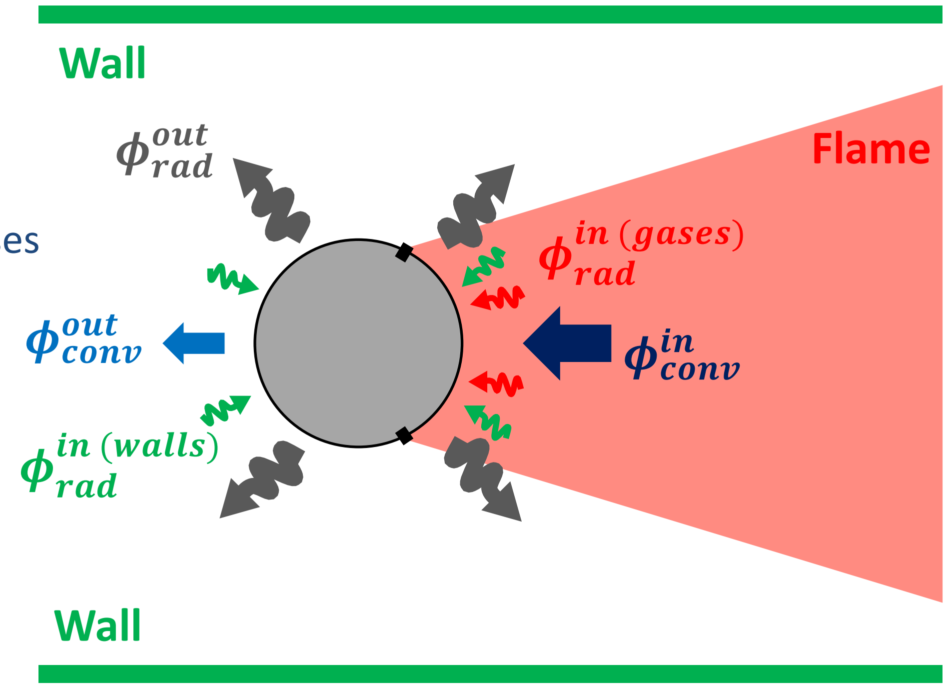


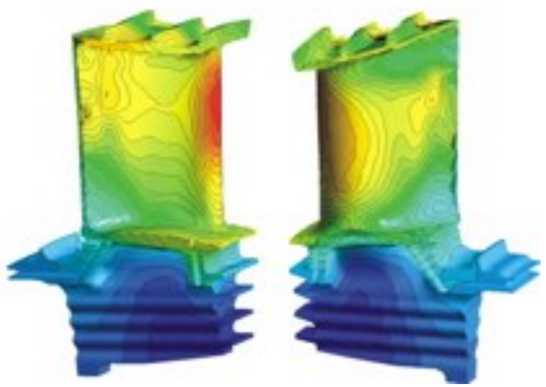
[1] Miguel-Brebion (2016). Comb & Flame
[2] Reyhani (2013). Prop & Pow Research
[3] Gao (2015). Measurm Science & Tech

Academic validation test-case: Influence of transparent & participative medium

- **2 possibilities of interactions for RHT**
  - Transparent medium: walls
    - Like in [1]
  - Participative medium: walls + burnt gases
    - New approach
- **Impact on the cylinder T**
  - Similar behaviour
  - At $\varepsilon = 0$: $T = T_{adiab}$
  - Difference up to $30K$ for high ε
- **Is this T difference really important?**
  - In aeronautic field: **YES**!
  - Prediction of T on turbine blade
    - Range of ε: between 0.6 and 0.9 [3]
  - ↗ T of $30K$ ↘ Time Life by a factor of 9 [2]

High influence of Participative gases at high ε





Temperature profile [2], from 700K (blue) to 1200K (red)

Academic validation test-case: Influence of transparent & participative medium

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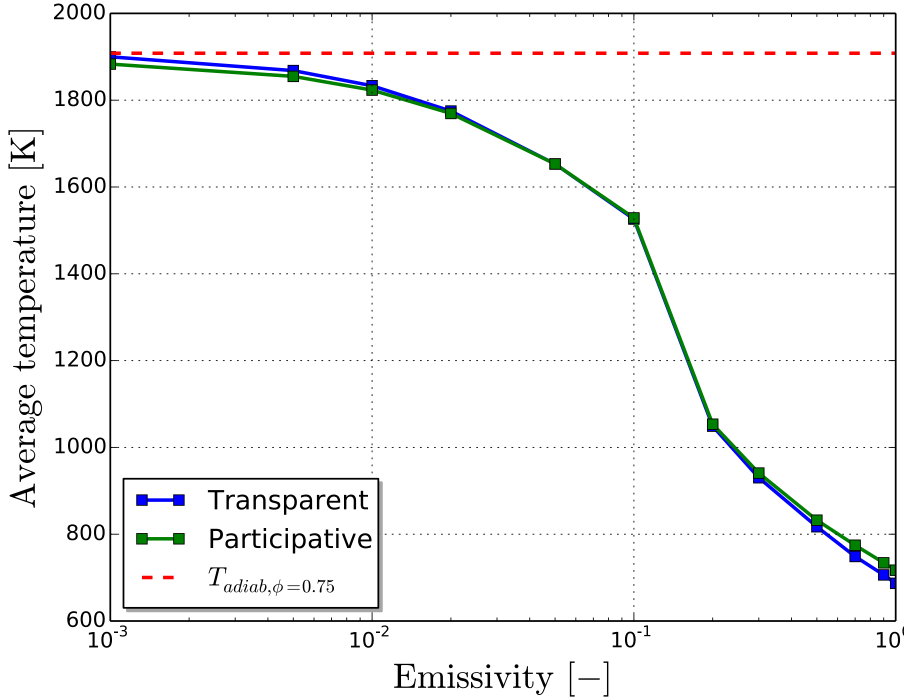

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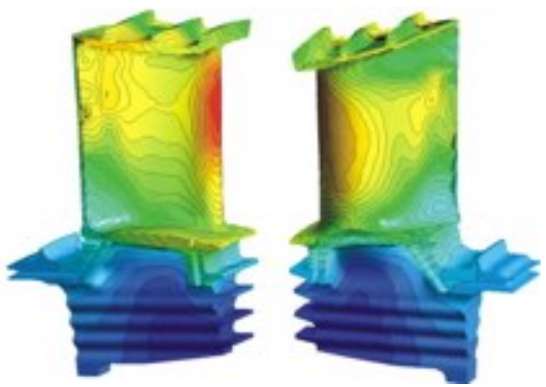

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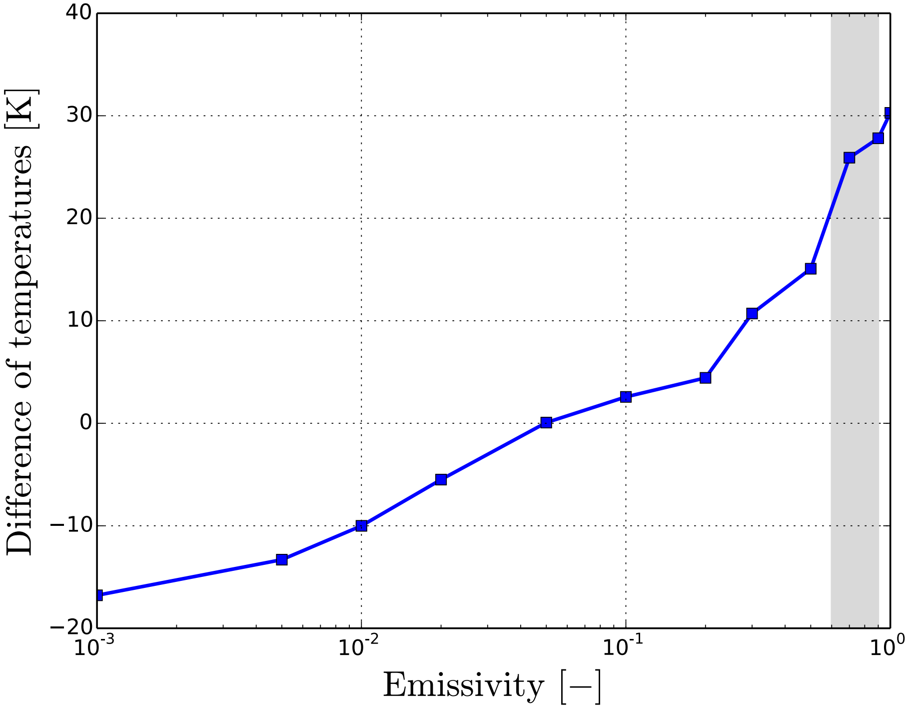

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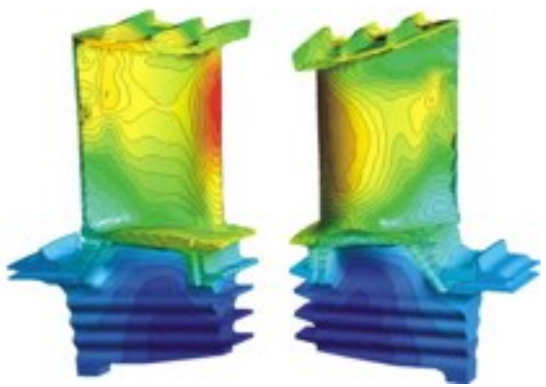

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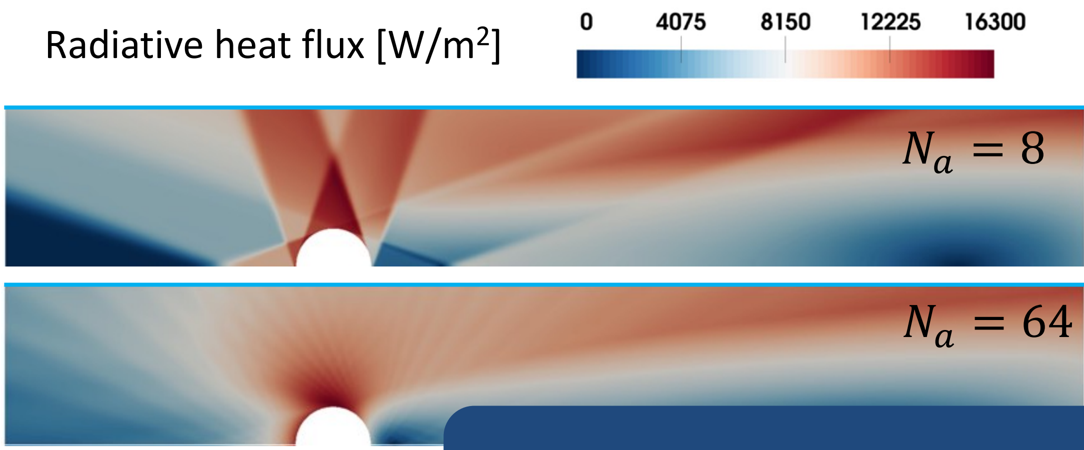
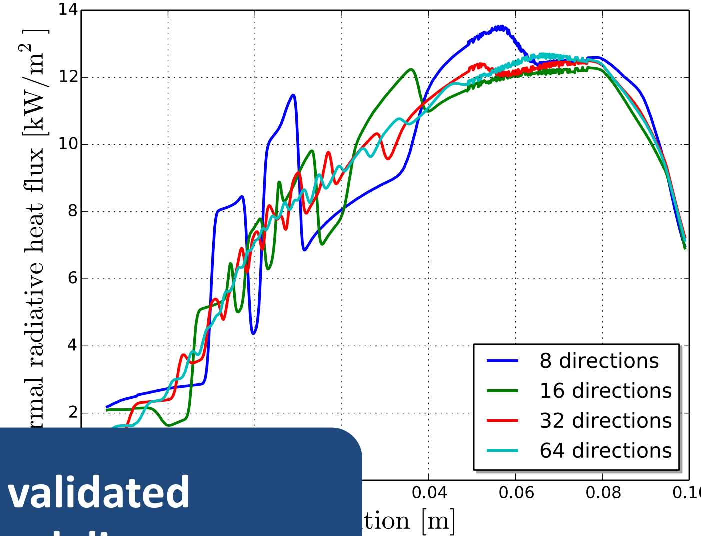
Academic validation test-case: Influence of angular discretisation

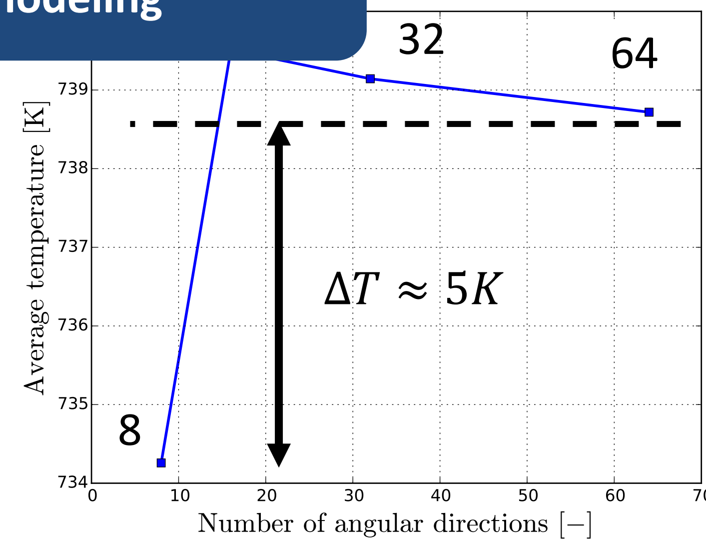




CHT and radiative strategy validated

➢ **Application to torch modeling**

- **Influence on w**
  - ➢ $N_a = 8$ used until here
  - ➢ + discretisation = - ray effects
  - ➢ This can lead to major over/under-shoots on wall heat fluxes
- **Influence on $T_{cylinder}$ ($\varepsilon = 0.9$)**
  - ➢ Convergence toward a stable T
  - ➢ Difference of about $5K$



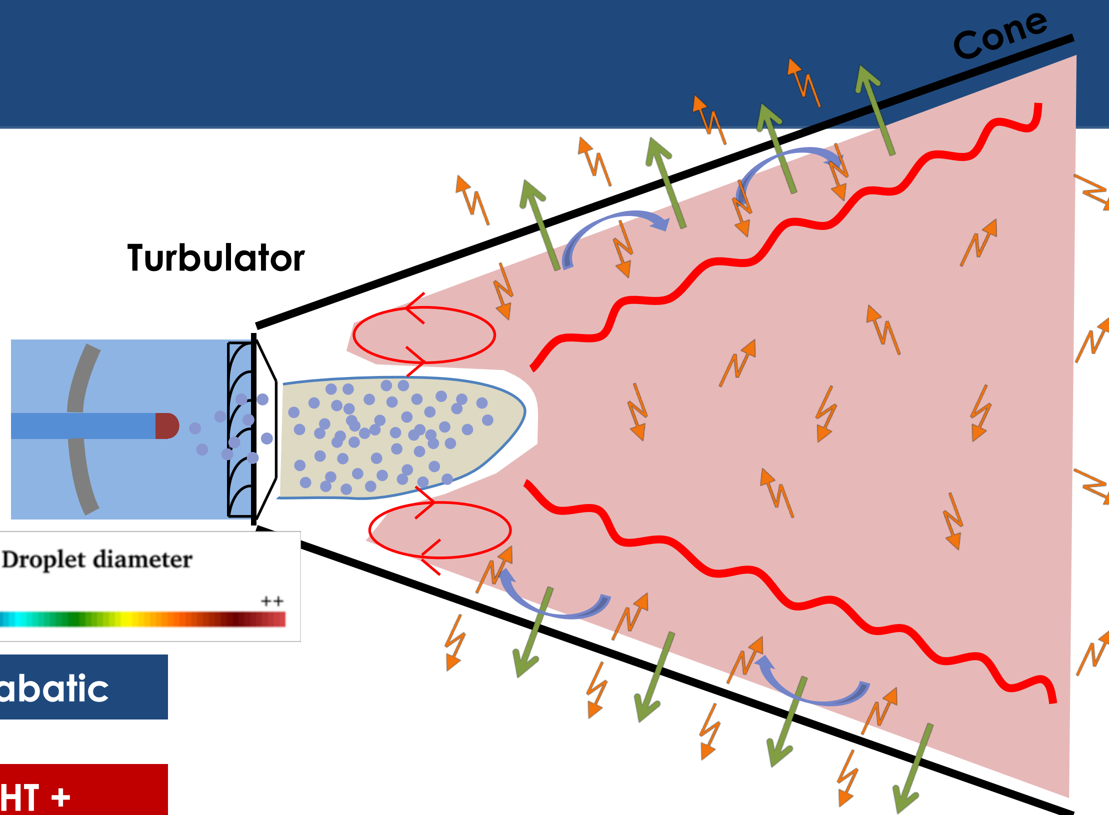
Key role of Angular Discretisation for CHT

I. Model and coupling strategies

II. Academic validation

III. Torch flame analysis

Torch modeling strategy



❖ Multi-physic aspects

- Spray
- Evaporation
- Flame

❖ Heat transfers

- Convection
- Conduction
- Radiation

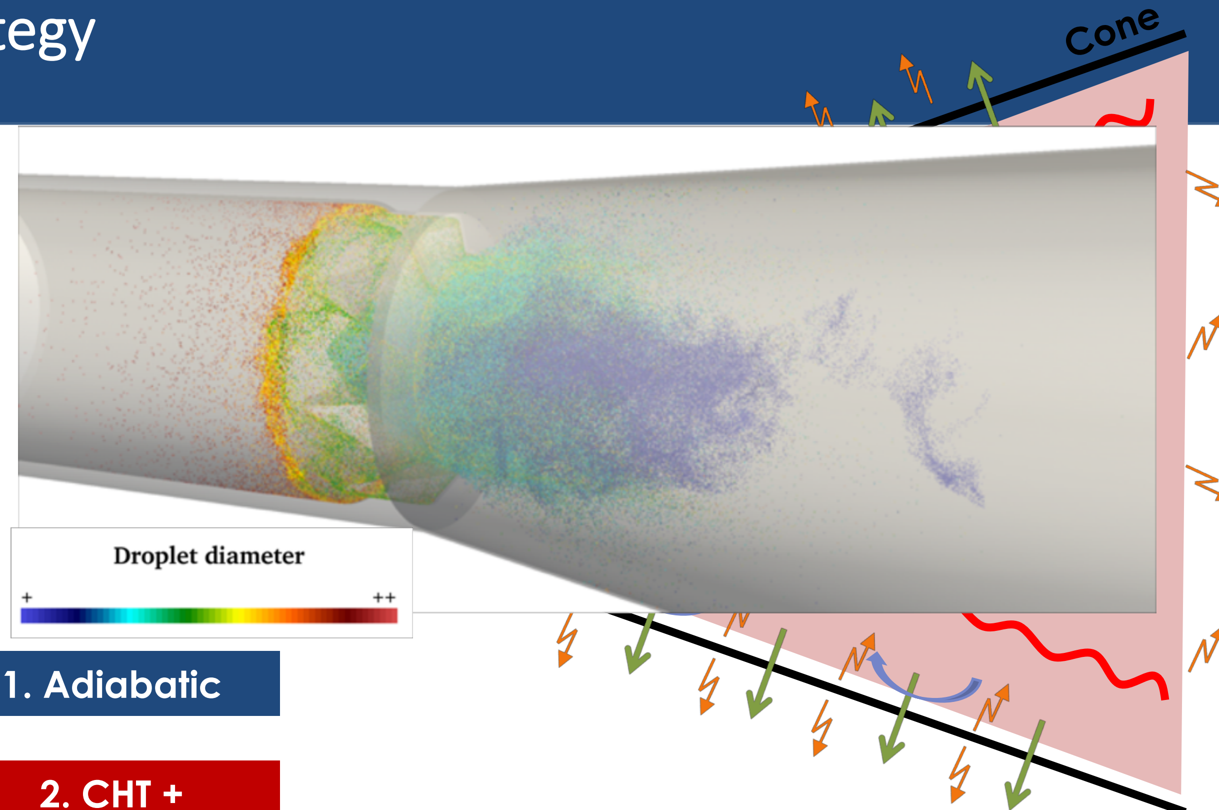
1. Adiabatic

2. CHT + Radiation

❖ Numerical parameters

- DOM: S4 ➔ 24 directions
- Spectral quadrature: Gauss-Lobato with 7 pts
- dt_fluid = 4.5µs   dt_solid = 29.2µs

Torch modeling strategy



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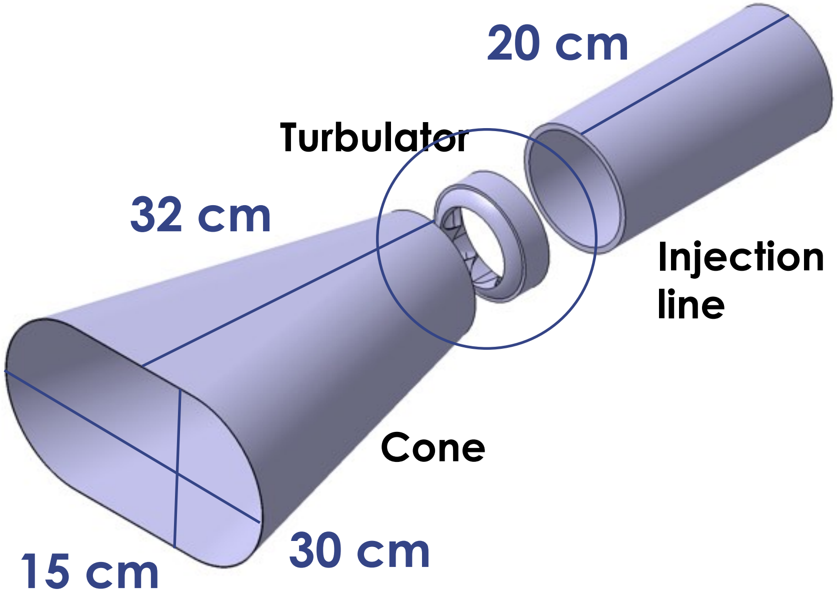
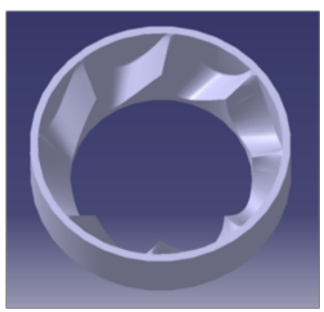
Geometry modeling



Turbulator:

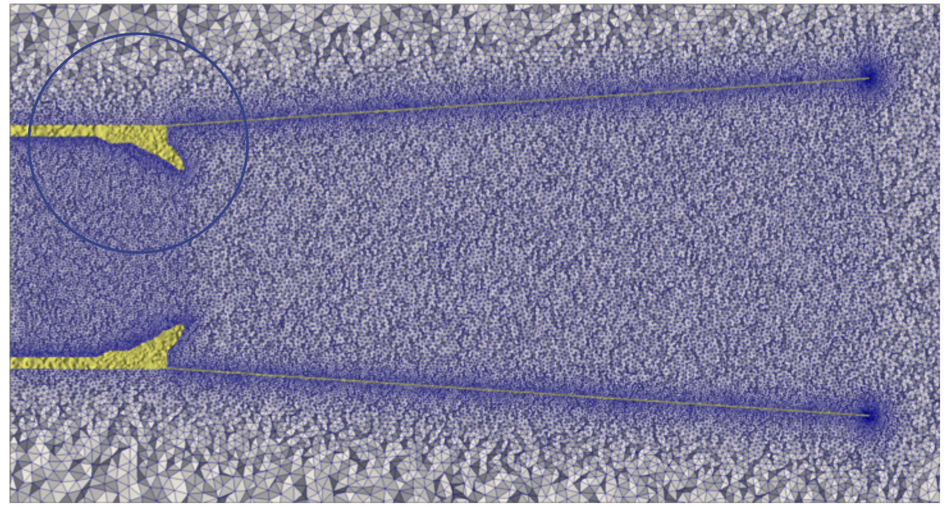
Front



Rear

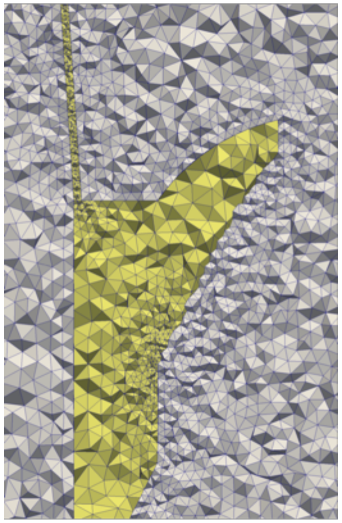
Domain & mesh

Simulation domain $\approx 3m^3$



Fluid:
- From 0.4 to 2 mm
- Cell count: 40 M tets

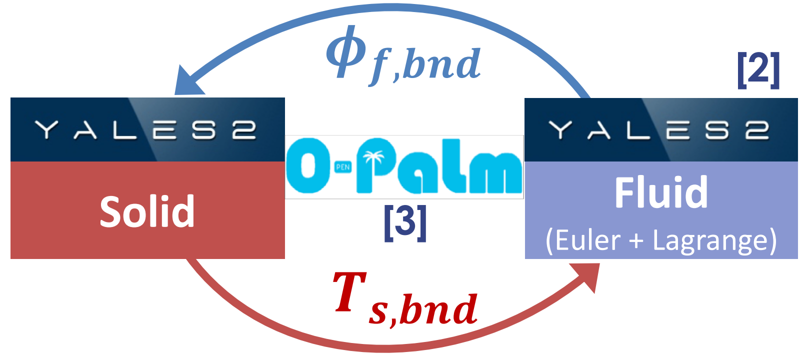
Solid:
- From 0.2 to 1 mm
- Cell count: 140 M tets
  thinness of the cone



CHT strategy: variables & solver interactions

[2] V. Moureau (2011). Combustion & Flame
[3] http://www.cerfacs.fr/globc/PALM_WEB/
[4] M.B. Giles (1997). Int. journal for num methods in fluids
[5] F. Duchaine (2009). Int Journal of Heat & Fluid Flow
[6] A. Felippa (2001). Comput. methods in appl mech & eng

Fluid and **Solid** have to **communicate**
Solvers: YALES2
Coupling: **OpenPALM**



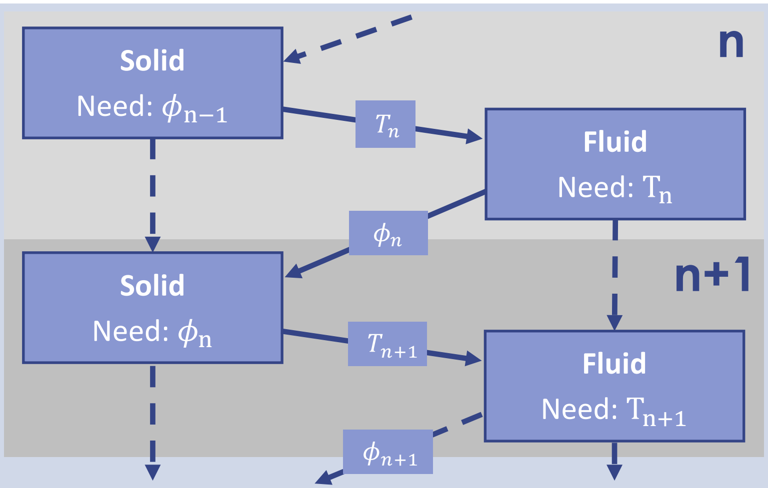
What is exchanged?

Adopted here [4,5]
- **Fluid** side: **Flux** is sent
- **Solid** side: **T** is sent

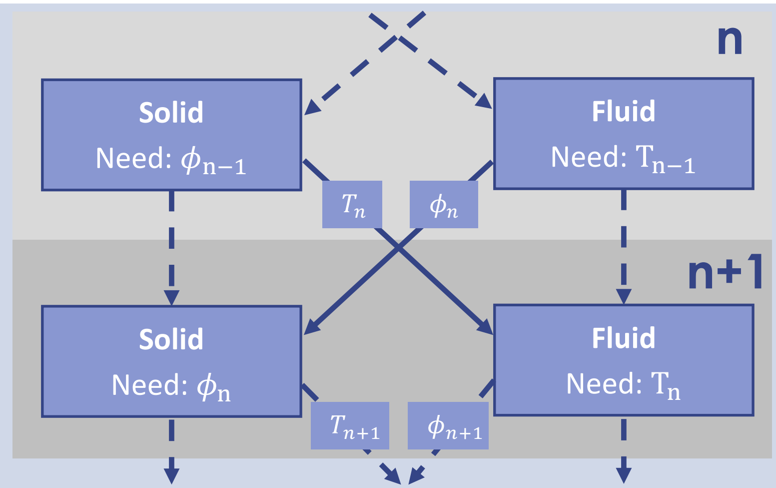
How is it exchanged ? [5,6]

Adopted here

Sequential Coupling Strategy	Parallel Coupling Strategy



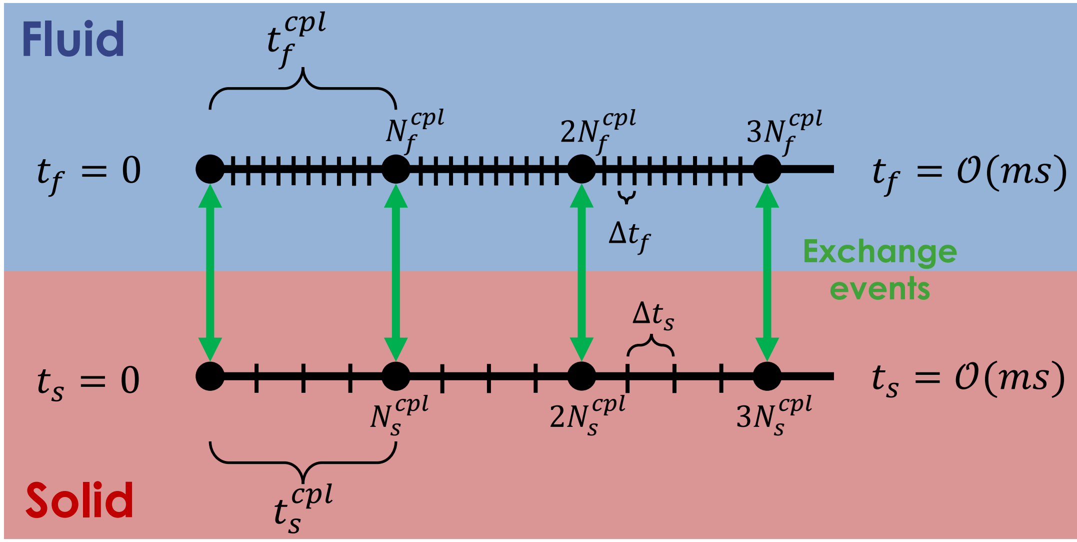
Solvers compute **successively** **time wasted**



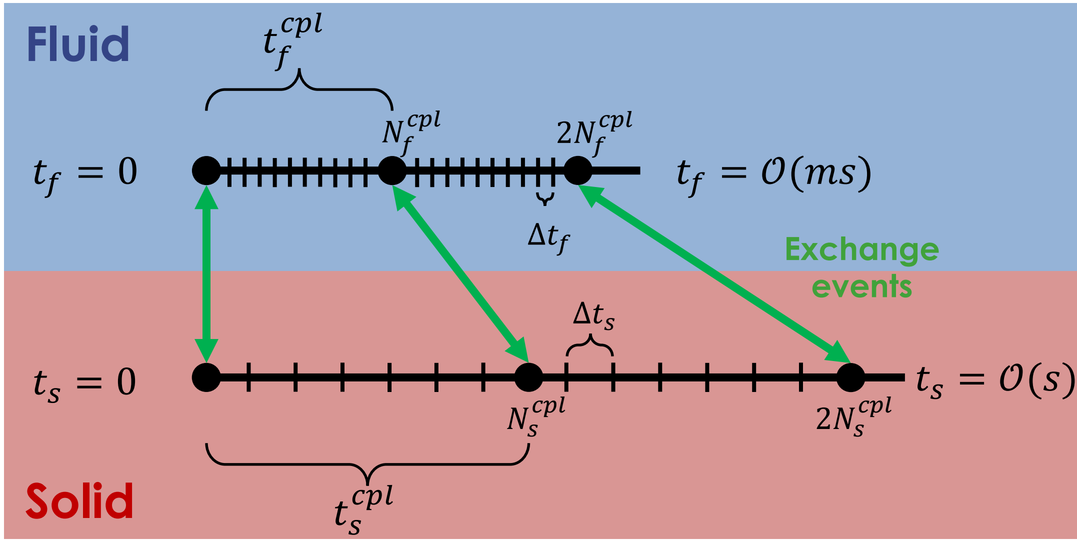
Solvers compute **simultaneously** **time saved**

Coupling strategy: synchronisation time

- **Synchronous coupled simulation:**
  - **Between exchange, the same physical time is computed by each solvers**
  - **Time step of solid larger than time step of fluid**
    - **Waste of CPU time**
    - **Study transient state**



- **Asynchronous coupled simulation:**
  - **Between exchange, different physical times are computed by each solvers**
  - **Bigger physical time can be computed in the solid**
    - **Waiting time reduced**
    - **Study converged state**

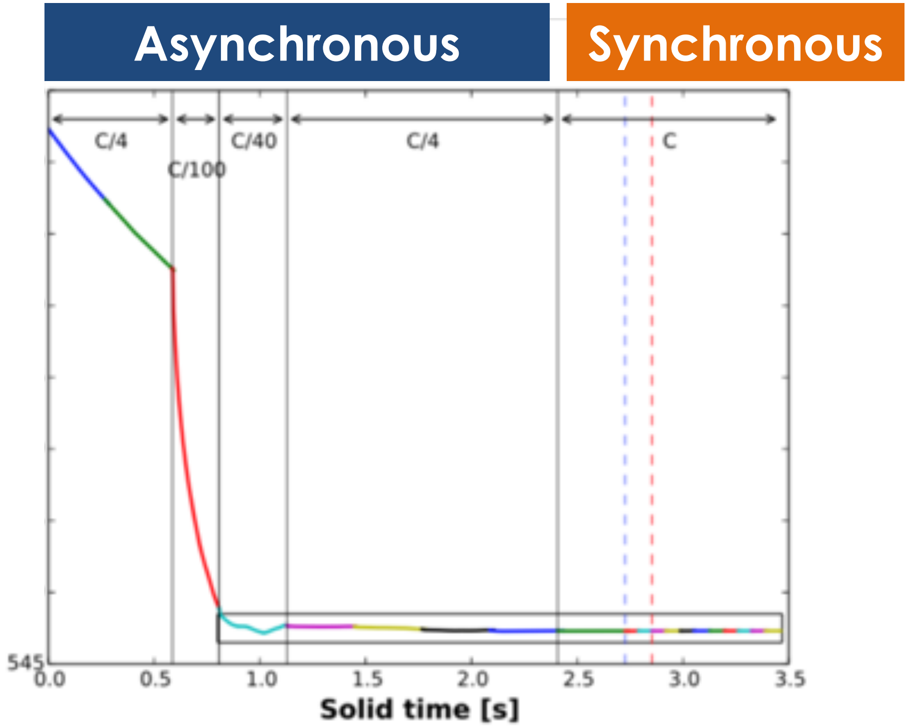


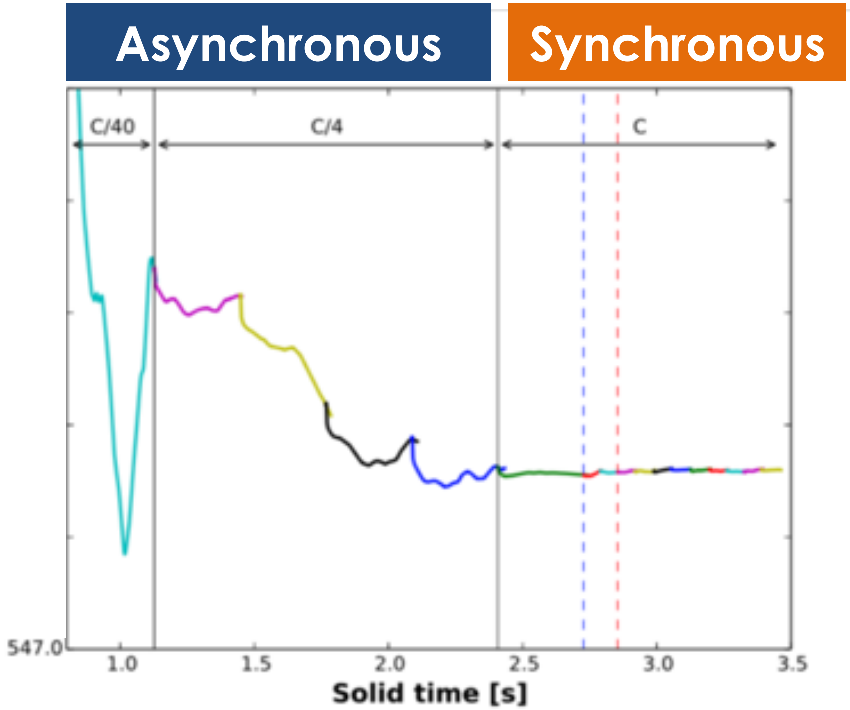
Coupling strategy: improving convergence

- **To reach steady-state**
  - **The heat capacity of the solid is artificially lowered**
  - **And then reset to its real value**

    same steady state

    obtained much faster



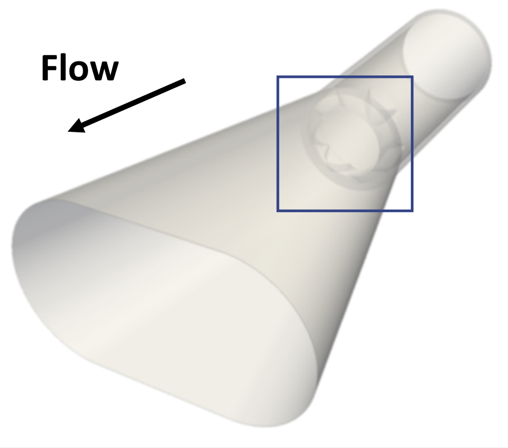


Coupling strategy: including Radiation

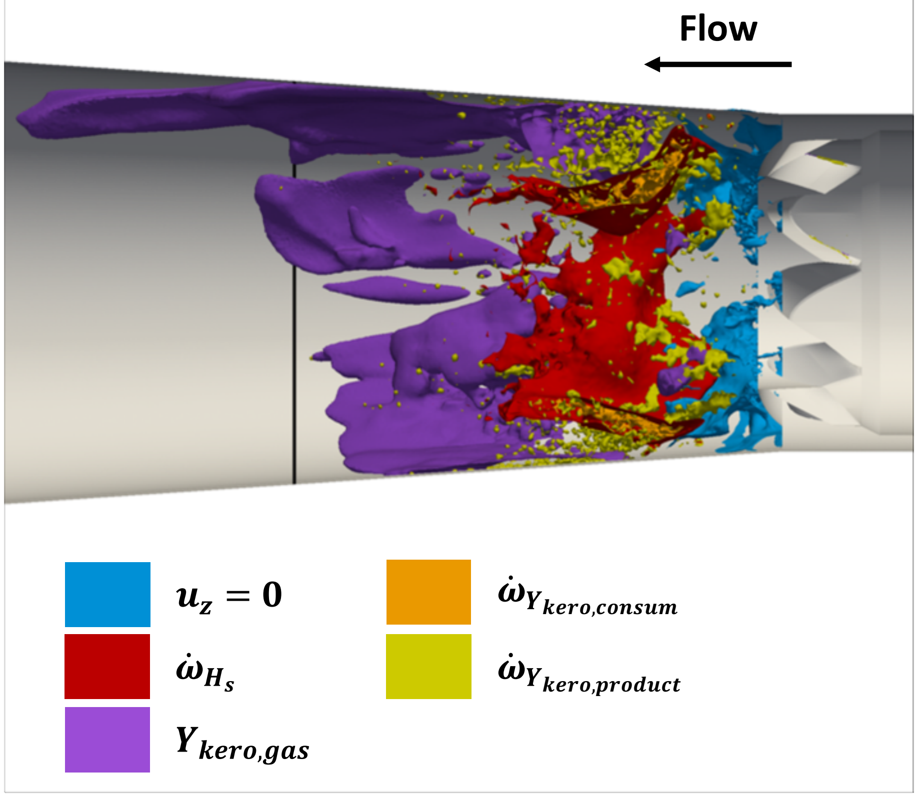
- Radiative solver invoked in the fluid phase before each coupling event
- At each 32 iterations, i.e. each 144µs.
- On a 40M cells mesh, with S4 and 7pts quadrature
- Non-symmetric and ill-conditioned lienar system
- BiCG-Stab(2) with ~1'200M DoF
- On 1024 processors…
- This represents ~40% of total CPU time

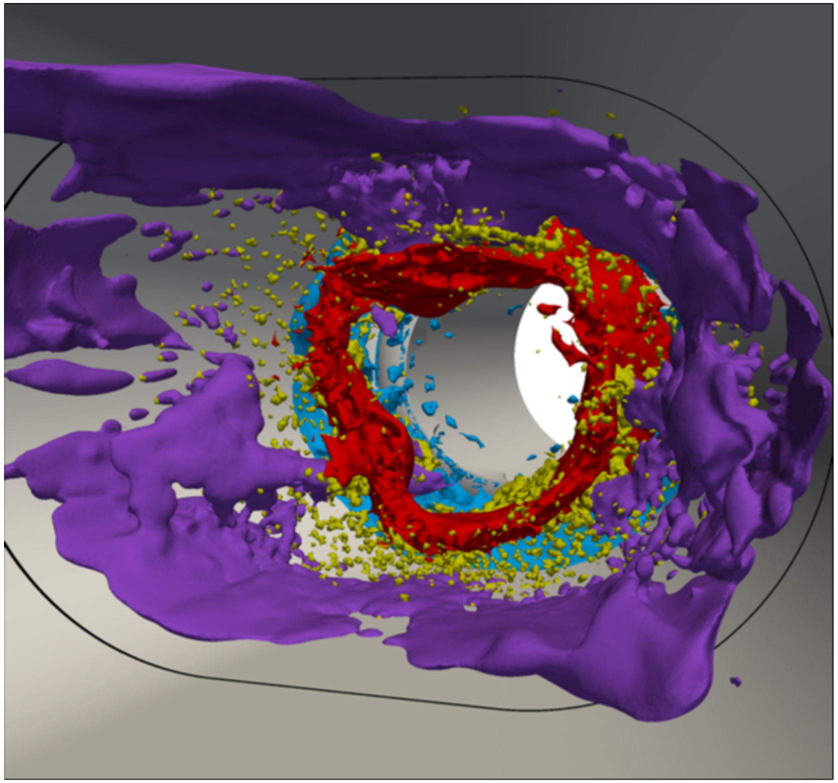
- For simulations of transparent media, radiation = 2% of total CPU time

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

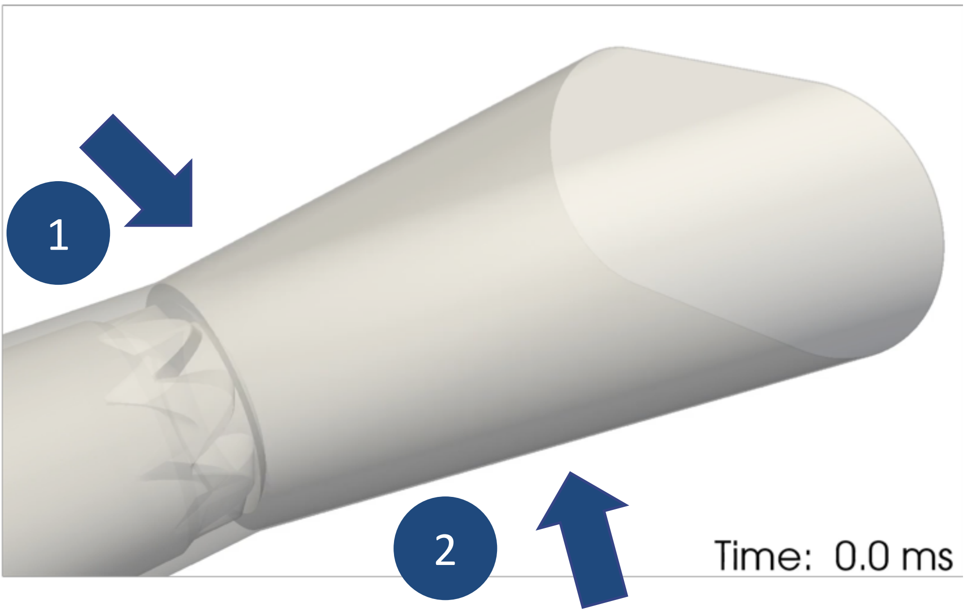




Topology of the flame inside the torch
Analysis of hot air plumes above the cone

❖ Rendering of high values of $\dot{\omega}_T$ during 20ms

- ➢ Wrinkling due to the turbulator
- ➢ Isolated hot spots: combustion of droplets



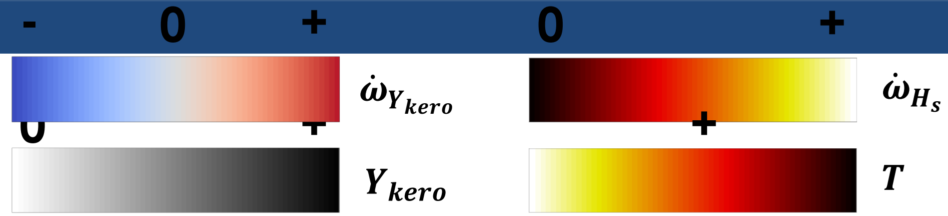
❖ Rendering of T in the air

- ➢ CHT + Radiation in participative medium
- ➢ Upper side: natural convection driven by T gradient at the torch wall ($R_a = 6.10^6$)
- ➢ Lower side: quite stable stratification

Fluid: 1024 procs
Solid: 60 procs

Calculation time: 6h
Computer: Occigen

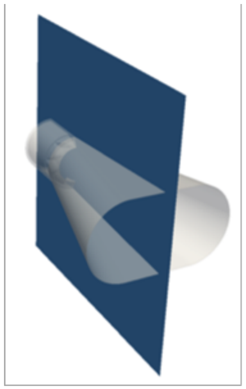
Topology of the flame: adiabatic vs CHT

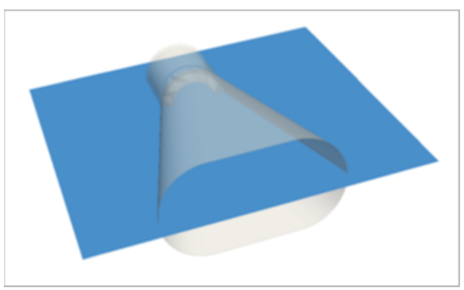


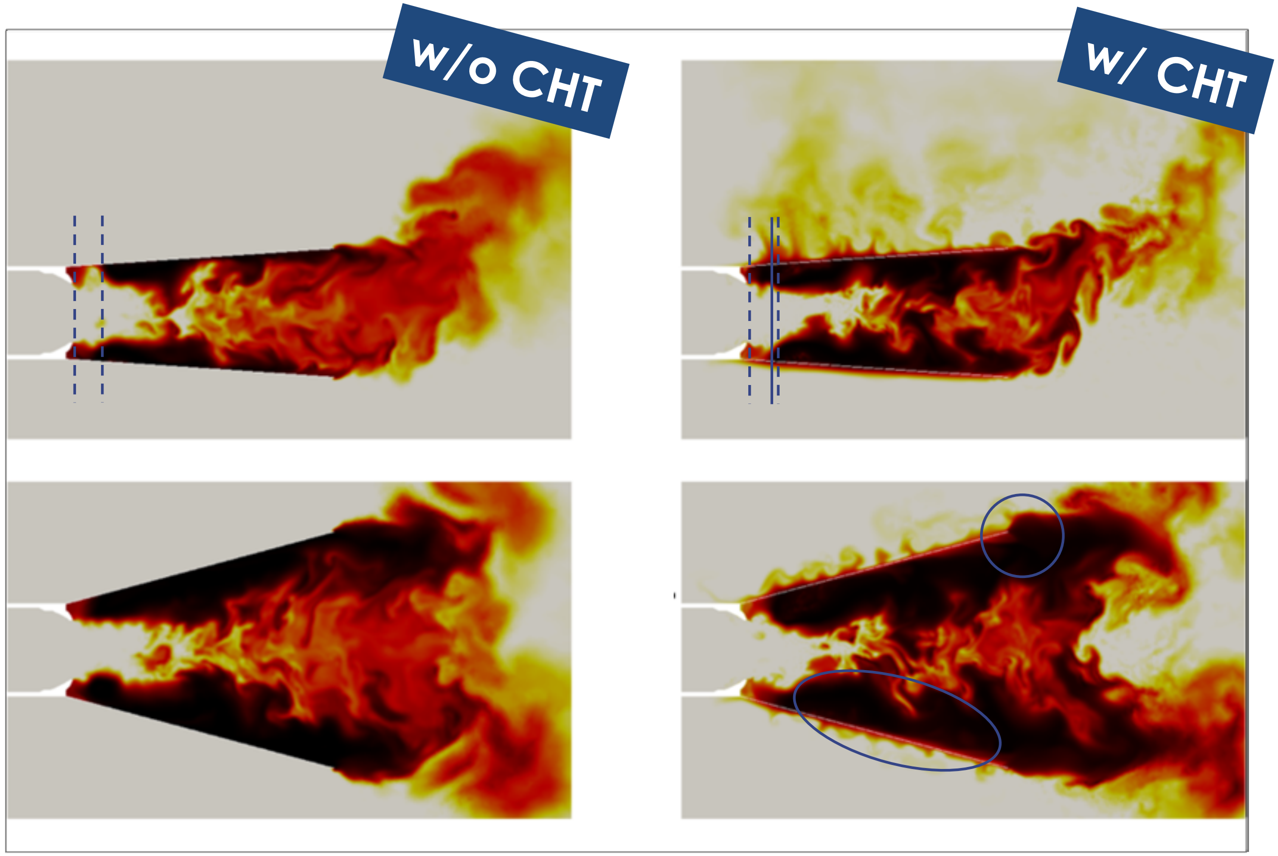
- Droplet evaporation starts upstream of the flame
- w/ CHT: consumption at the wall & the outlet

- 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

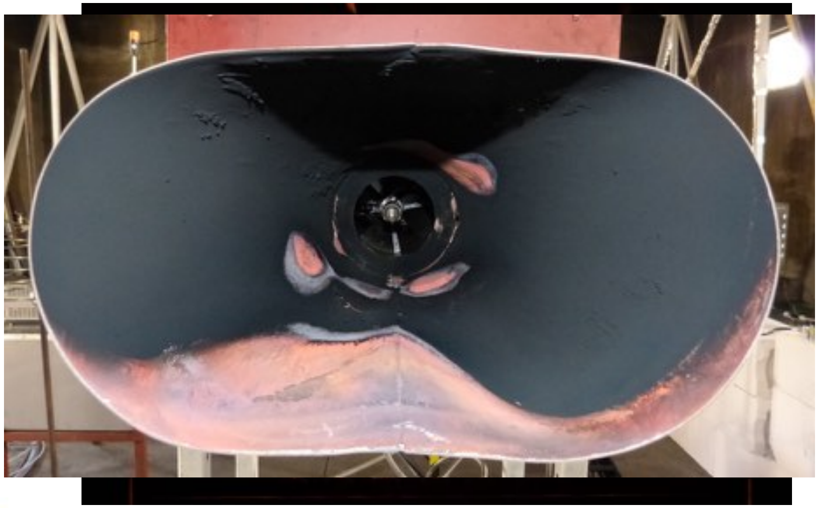


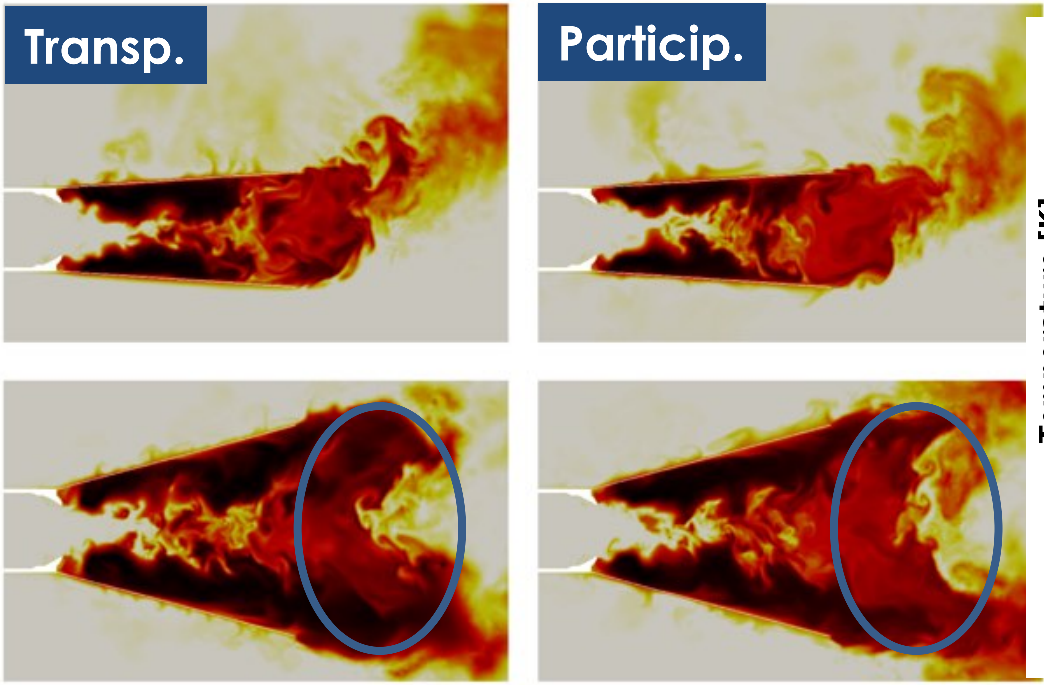


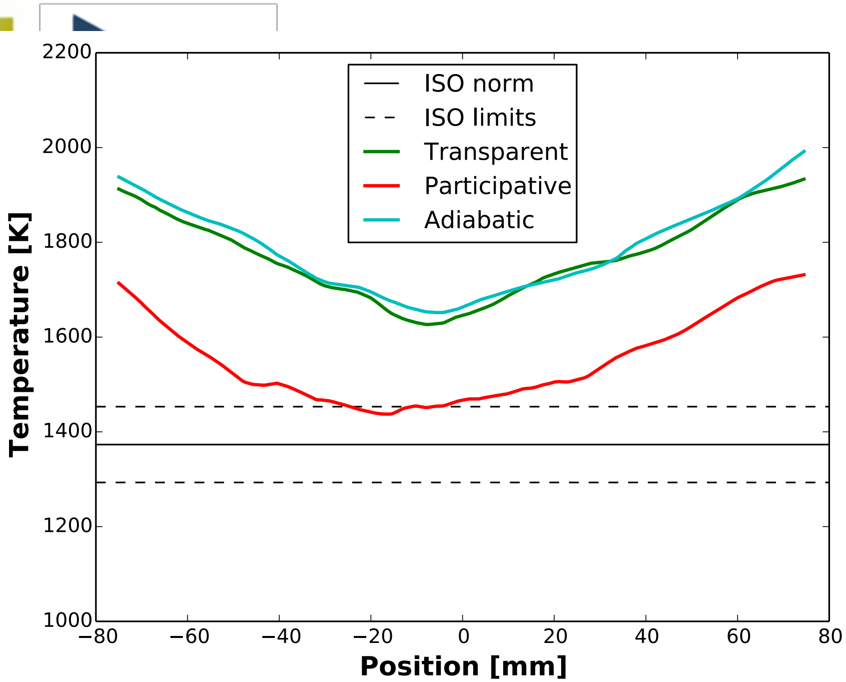


Temperature profiles

- **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
    - Too simple chemistry (2 reactions)
    - Any models for soot formation

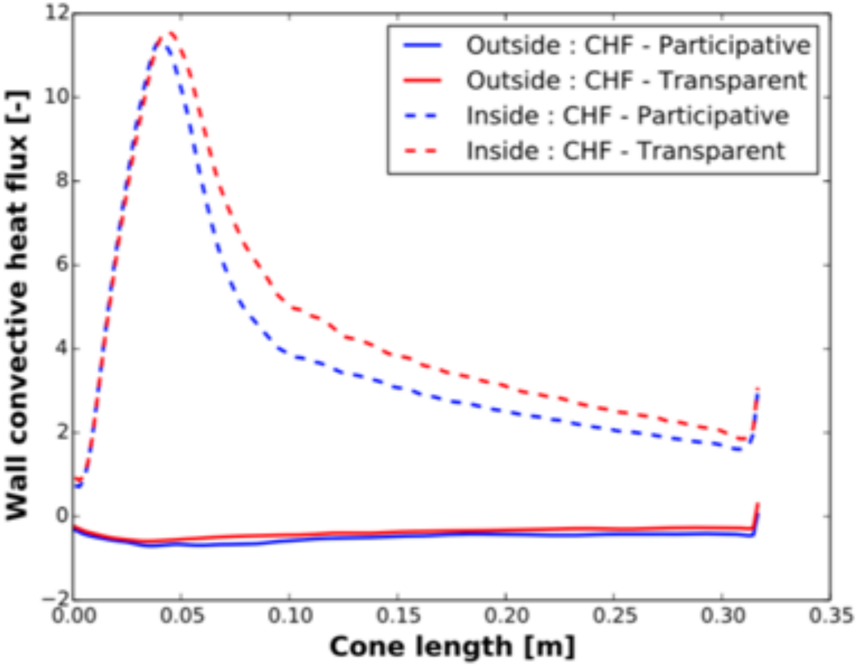




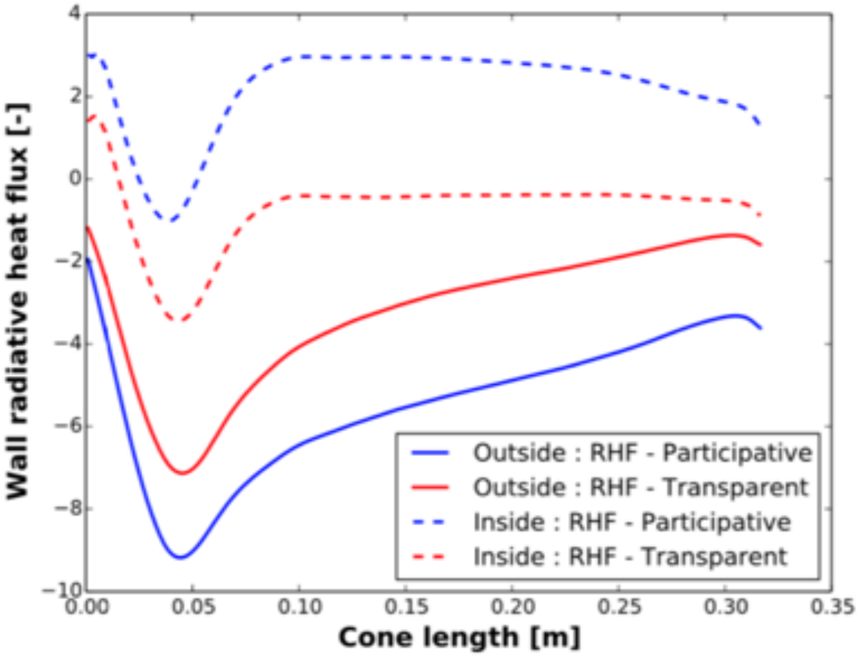


Fluxes at walls

Paroi	Interne		Externe	
Pertes thermiques	Convection	Rayonnement	Convection	Rayonnement
Transparent (%)	90.6	-9.4	15.1	84.9
Participative (%)	62.6	37.4	11.3	88.7

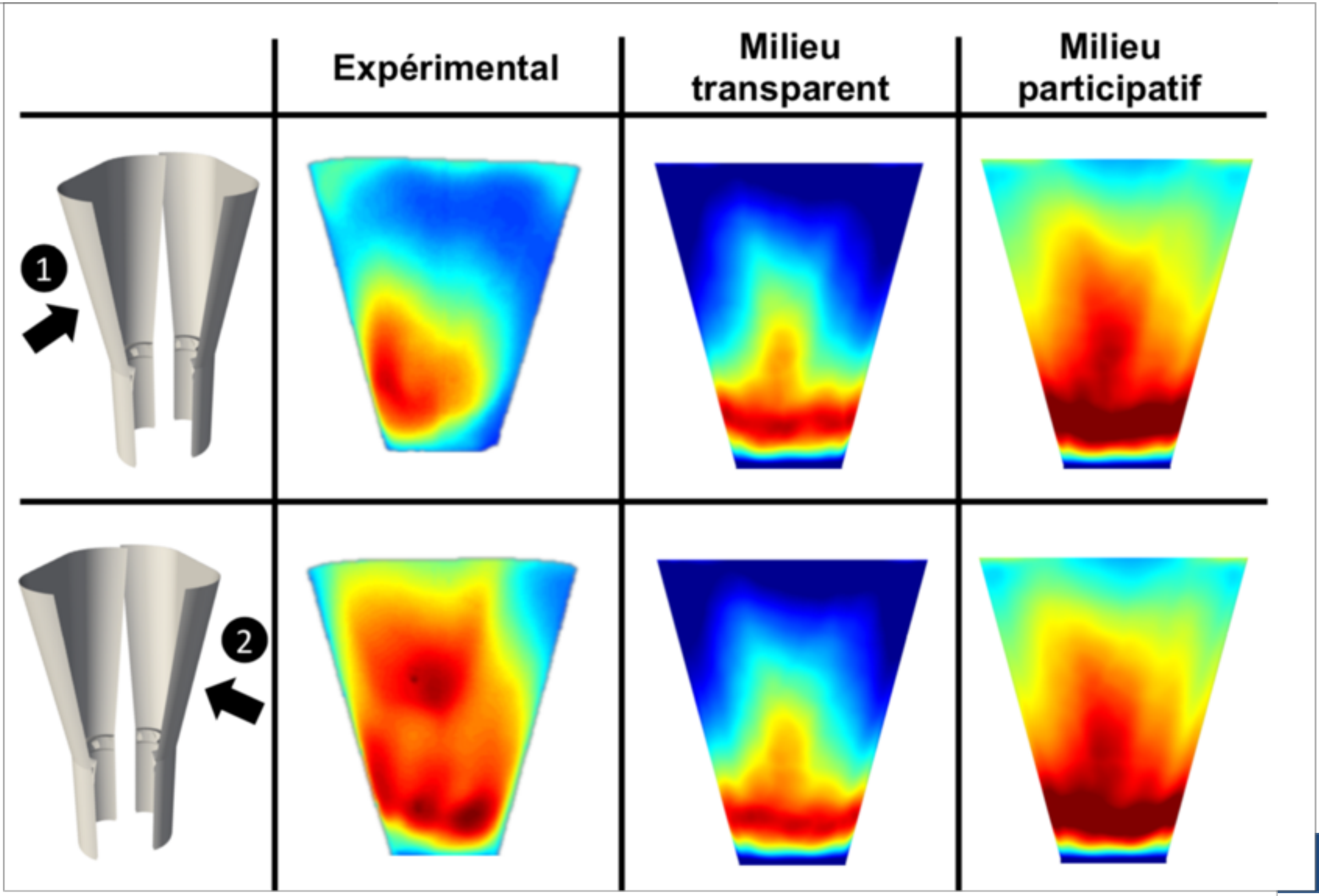


(a) Flux convectif



(b) Flux radiatif

External wall temperatures

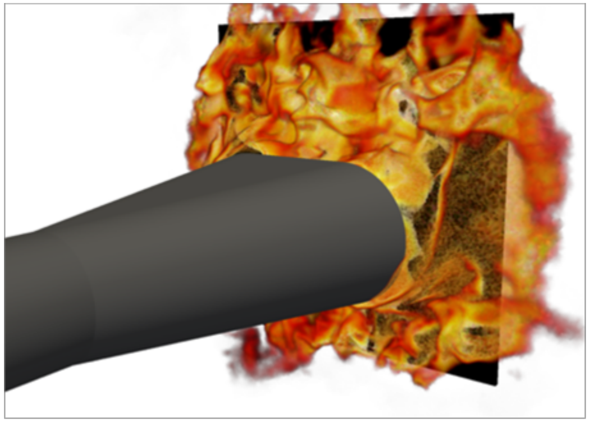


Conclusion & perspectives

- **INTRIG allowed to validate CHT & Radiation strategies**
  - Numerical results well reproduce with literature
  - Number of ang. directions can have an impact when doing CHT

- **In hot gases, influence of participative medium is vital**
  - To lower the gases temperature
  - To predict good levels of temperature at the outlet of the torch

- **What to do next?**
  - Comparison of T & ϕ on plane plate with exp. results
  - Simulate a real certification test with engine envelope
  - Include soot model and scattering



See you on December 20th at CORIA for Lancelot Ph.D. defense!