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Flashback prevention in a micro Gas Turbine fueled by hydrogen without any combustor redesign

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ERCOFTAC Autumn Festival 2023

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POLYTECH MONS

Thermal Engineering & Combustion Unit

Fluids-Machines Unit

energy
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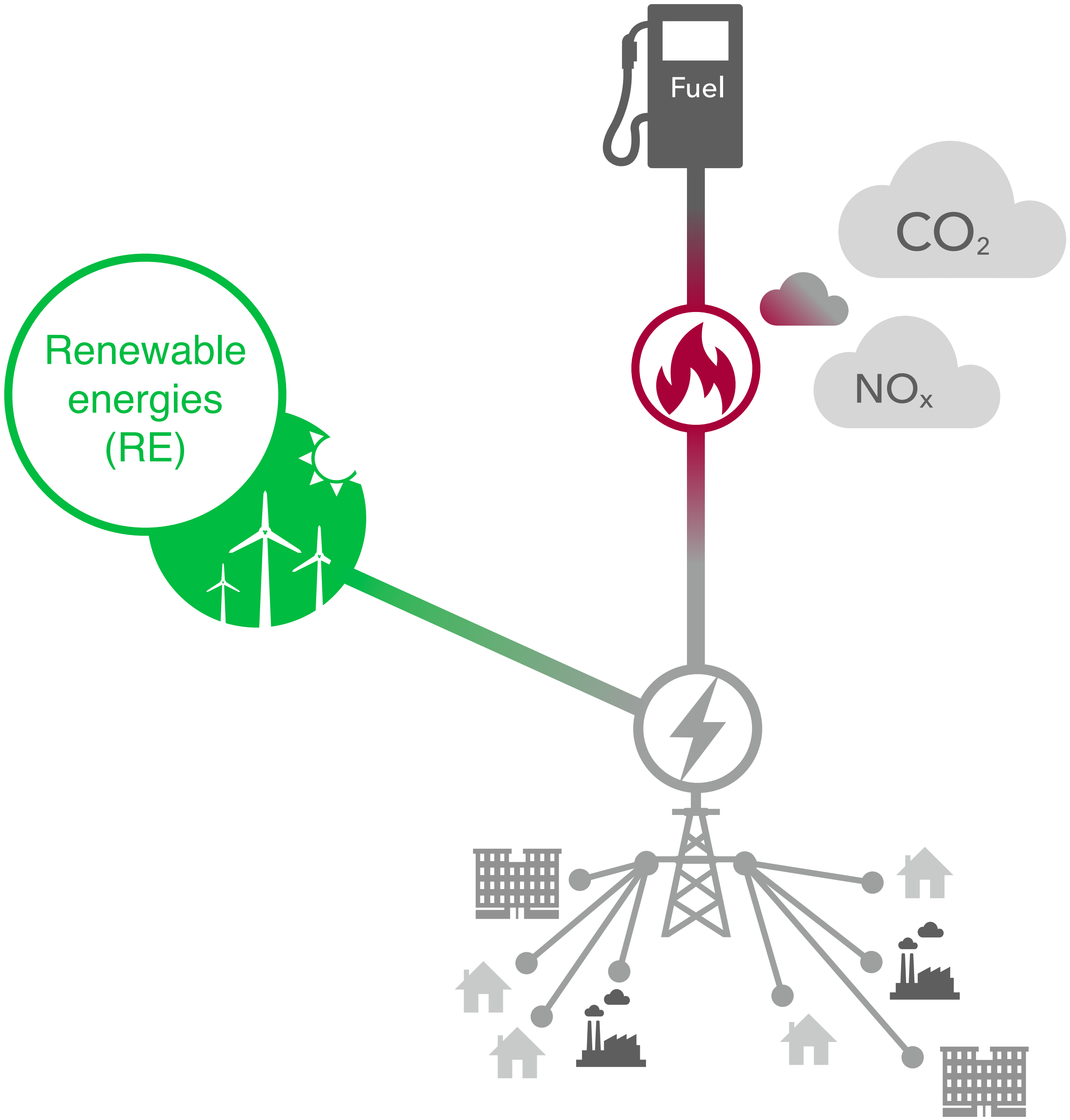


Combustion processes

inherent to

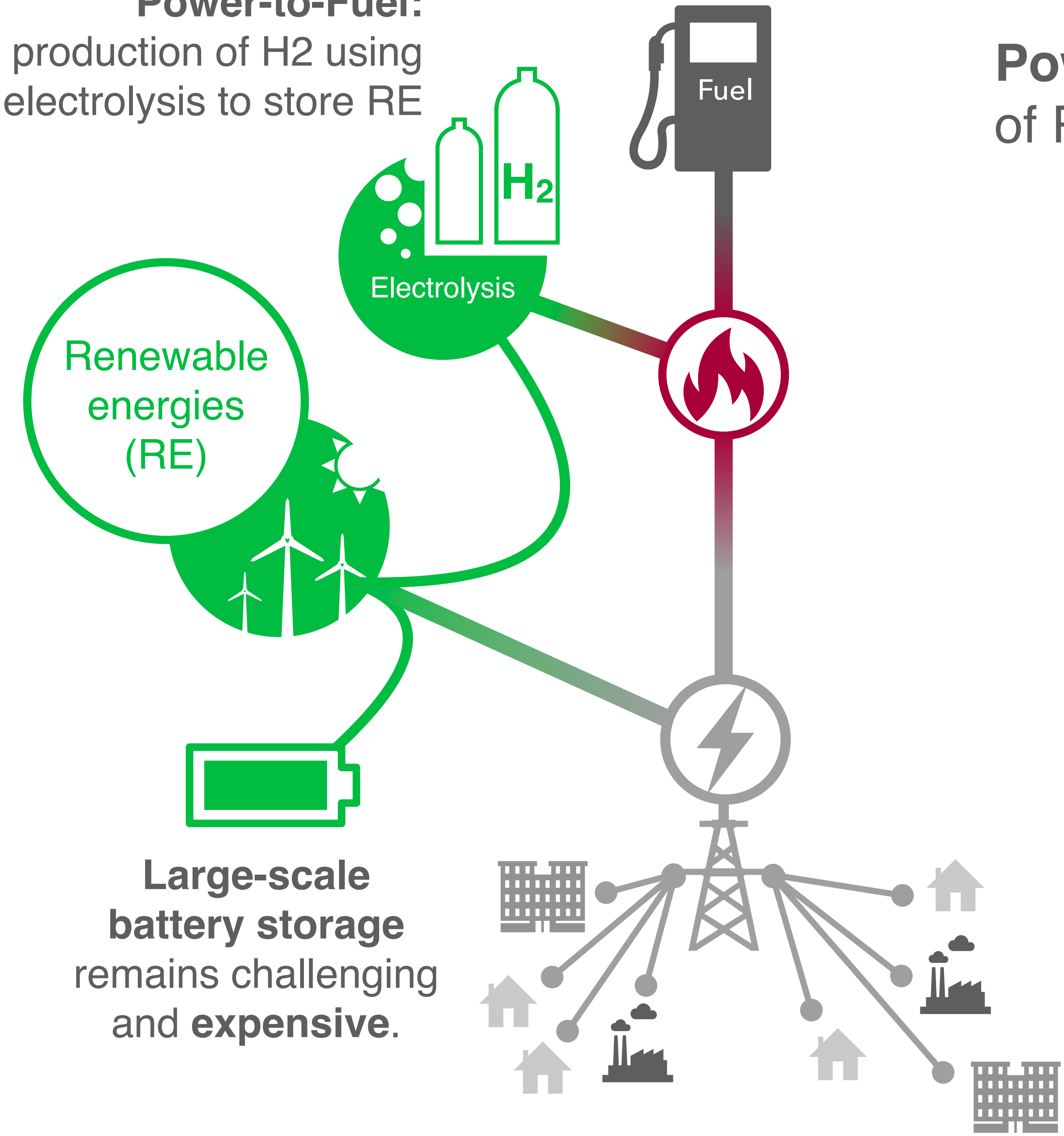
pollutant emissions.

Increased RE contribution

in electricity production

to **reduce CO_2** levels.

Fuel flexibility in micro Gas Turbines towards decarbonification



Power-to-Fuel: production of H2 using electrolysis to store RE

Large-scale battery storage remains challenging and **expensive**.

Power-to-fuel to facilitate the inclusion of RE (despite their lack of reliability).

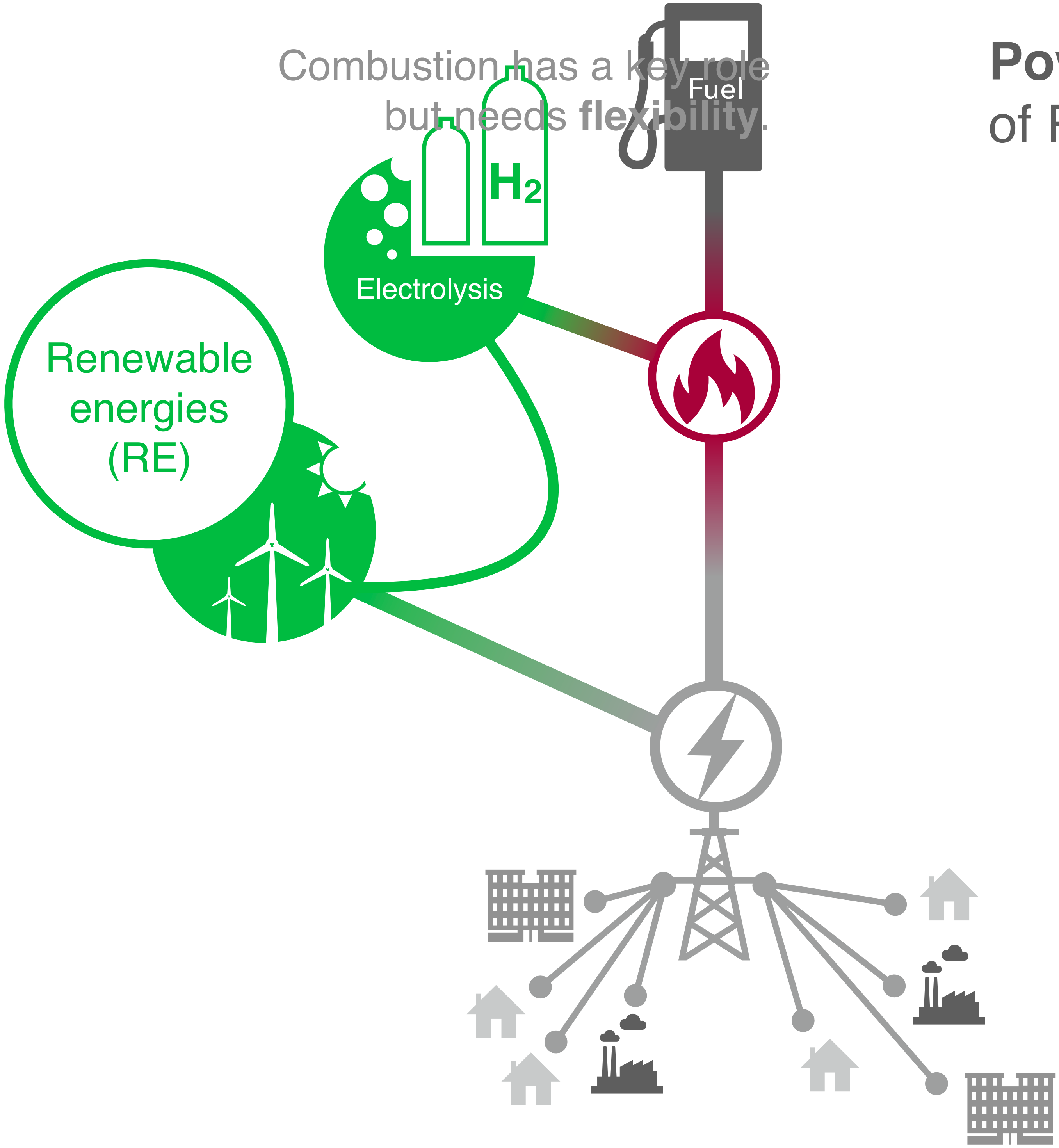
Lack of **reliability** of RE:

Unpredictable nature of RE sources.

➡ **Fluctuations**

Strong trend towards **storing** the excess of renewable electricity

Fuel flexibility in micro Gas Turbines towards decarbonification



Combustion has a key role
but needs **flexibility**.

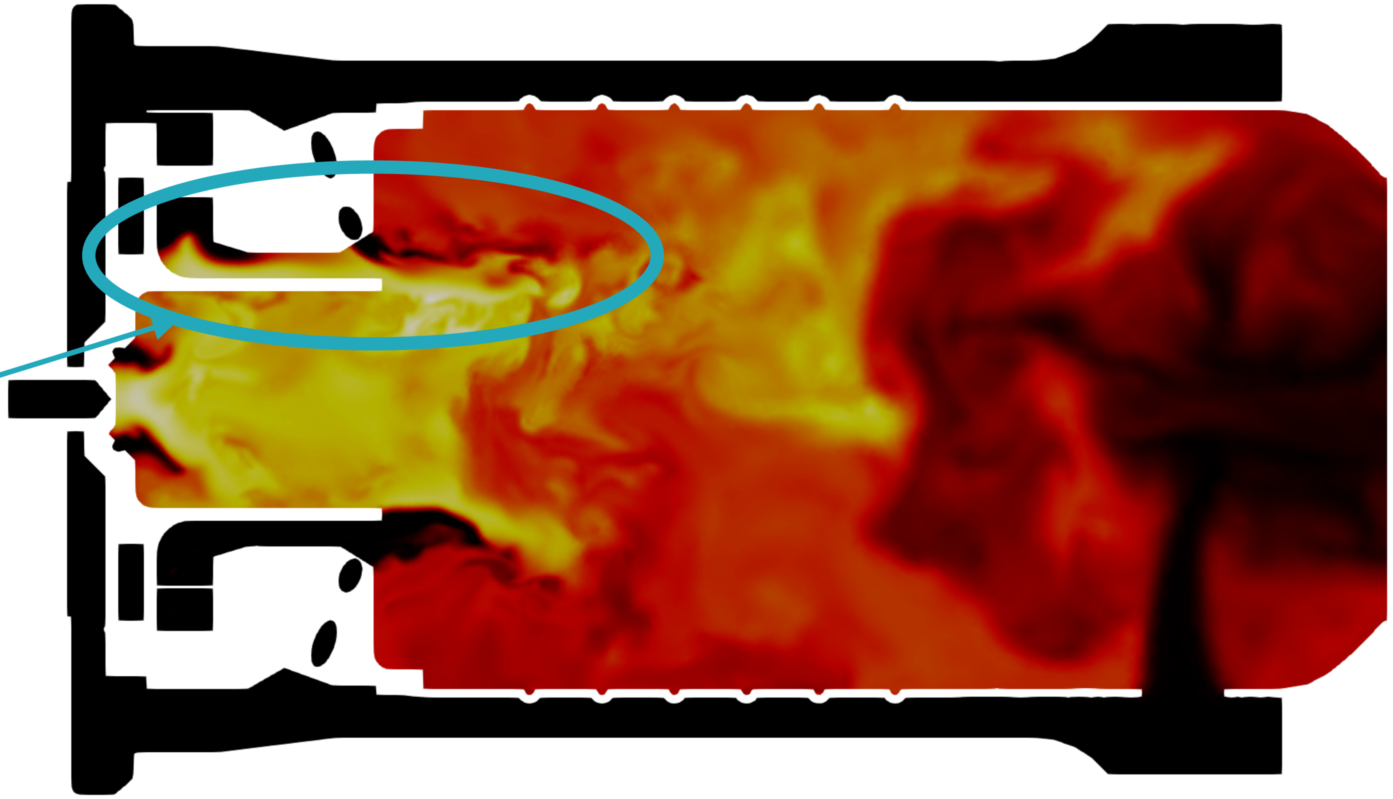
Power-to-fuel to facilitate the incursion of RE (intermittent behavior).

Fuel flexibility in micro Gas Turbines towards decarbonification

Power-to-fuel to facilitate the incursion of RE (intermittent behavior).

Premixed burners not adapted to burn hydrogen blends.

Hydrogen combustion leads to flame instabilities (risk of **flashback**).



Flame front going back in the fuel/air premixing room

Fuel flexibility in micro Gas Turbines towards decarbonification

Power-to-fuel to facilitate the incursion of RE (despite their lack of reliability).

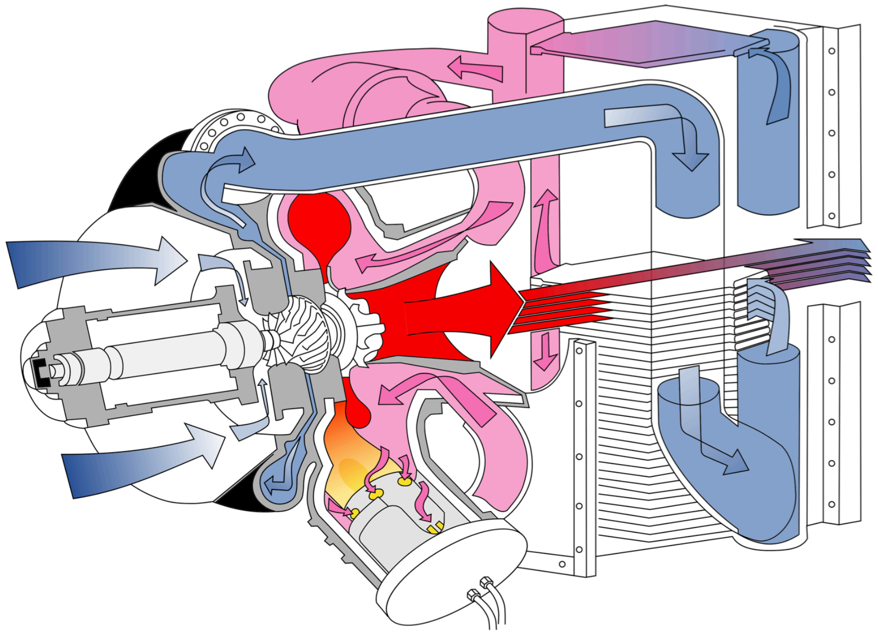
Hydrogen combustion leads to flame instabilities (risk of **flashback**).

For more flexibility, stabilization achieved **without any redesign** of the combustor.

Using diluted conditions from **existing** advanced cycles.

Humidification & EGR to slow down the reaction rate, temperature & flame speed.

mGTs have a large field of application for small-scale CHP production

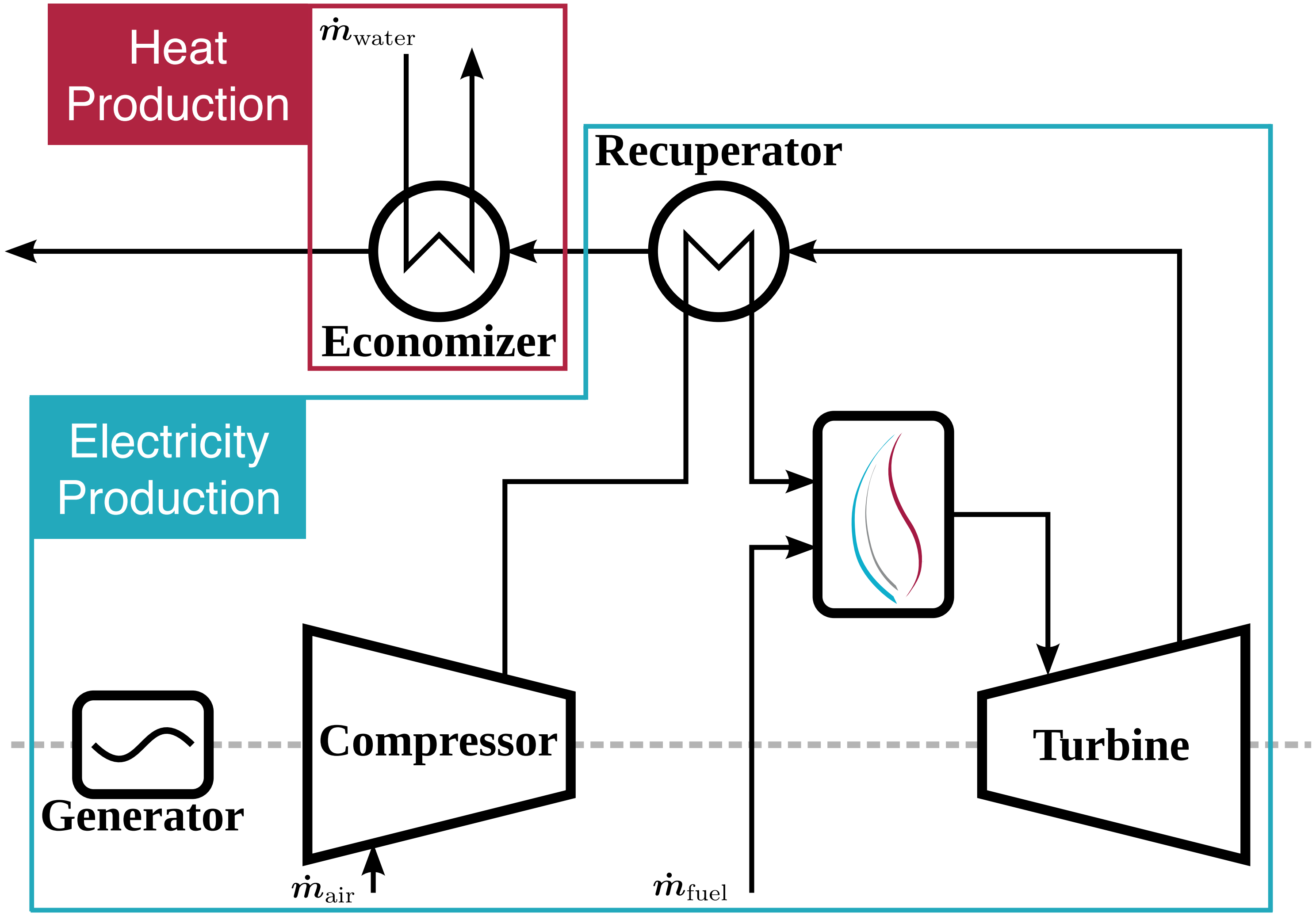


Sketch of Turbec T100

Global efficiency: ~80%
Electrical efficiency: ~30%

Micro Gas Turbines for small-scale Combined Heat and Power (CHP) production.

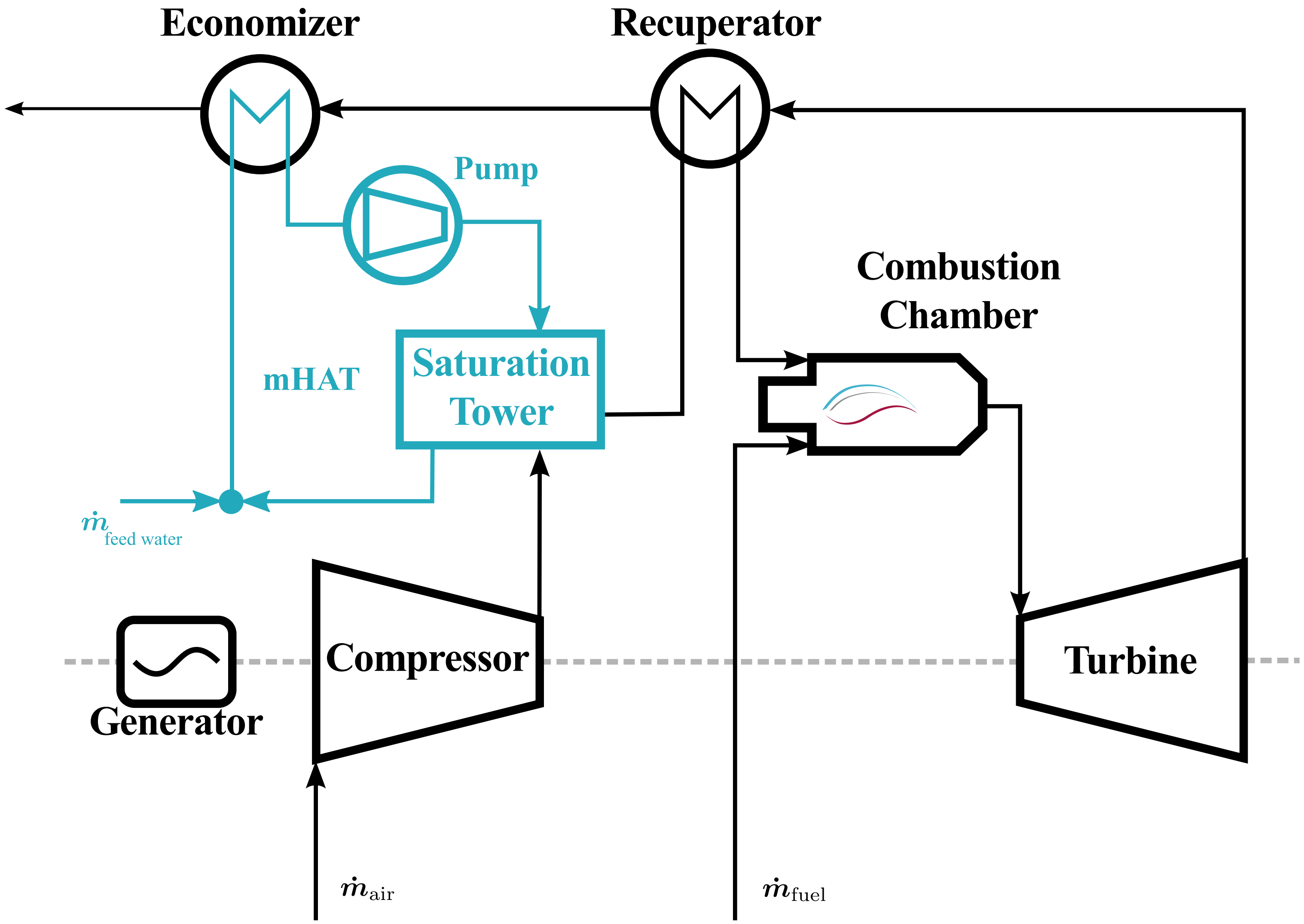
Net heat and electrical production ranging from 1kW up to a few 100kW



Taking benefit of existing advanced cycle modifications to avoid flashback

Allows advanced cycle modifications:

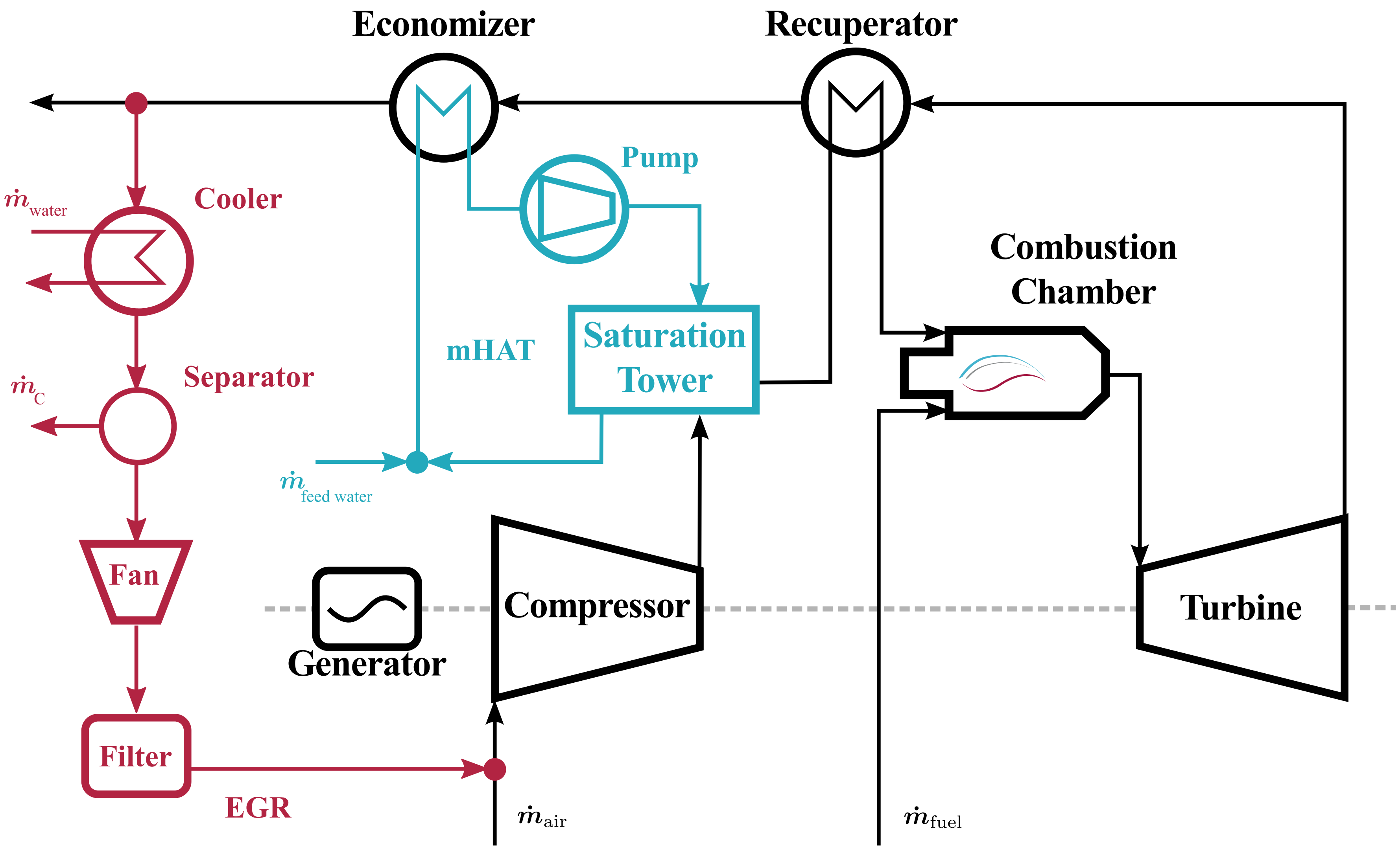
➡ **Humidification**: decoupling heat & electricity for increased electrical efficiency (when there is no heat demand).



Taking benefit of existing advanced cycle modifications to avoid flashback

Allows advanced cycle modifications:

- ➡ **Humidification**: decoupling heat & electricity for increased electrical efficiency (when there is no heat demand).
- ➡ **Exhaust Gas Recirculation** (EGR) for CO_2 reduction & performing Carbon Capture & Storage.



These diluted conditions have proven effective in **reducing** reaction rate, temperature, and flame speed.

Target

Flashback prevention for various H_2 blends **without** any **redesign** of a mGT combustor.

Considering humidification & EGR as solution.

1) 0D Chemical Reactor Network /1D Flame model.

- Low-cost chem & thermo flow properties assessment.
- Predetermination of the operating conditions to avoid flashback.

2) Large Eddy Simulations on the Turbec T100 geometry.

- Flashback phenomenology.
- Verification of the low-cost predetermination.
- Stability analysis.

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Outline

Burner layout & operating conditions

Large-Eddy Simulations

Conclusions

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Outline

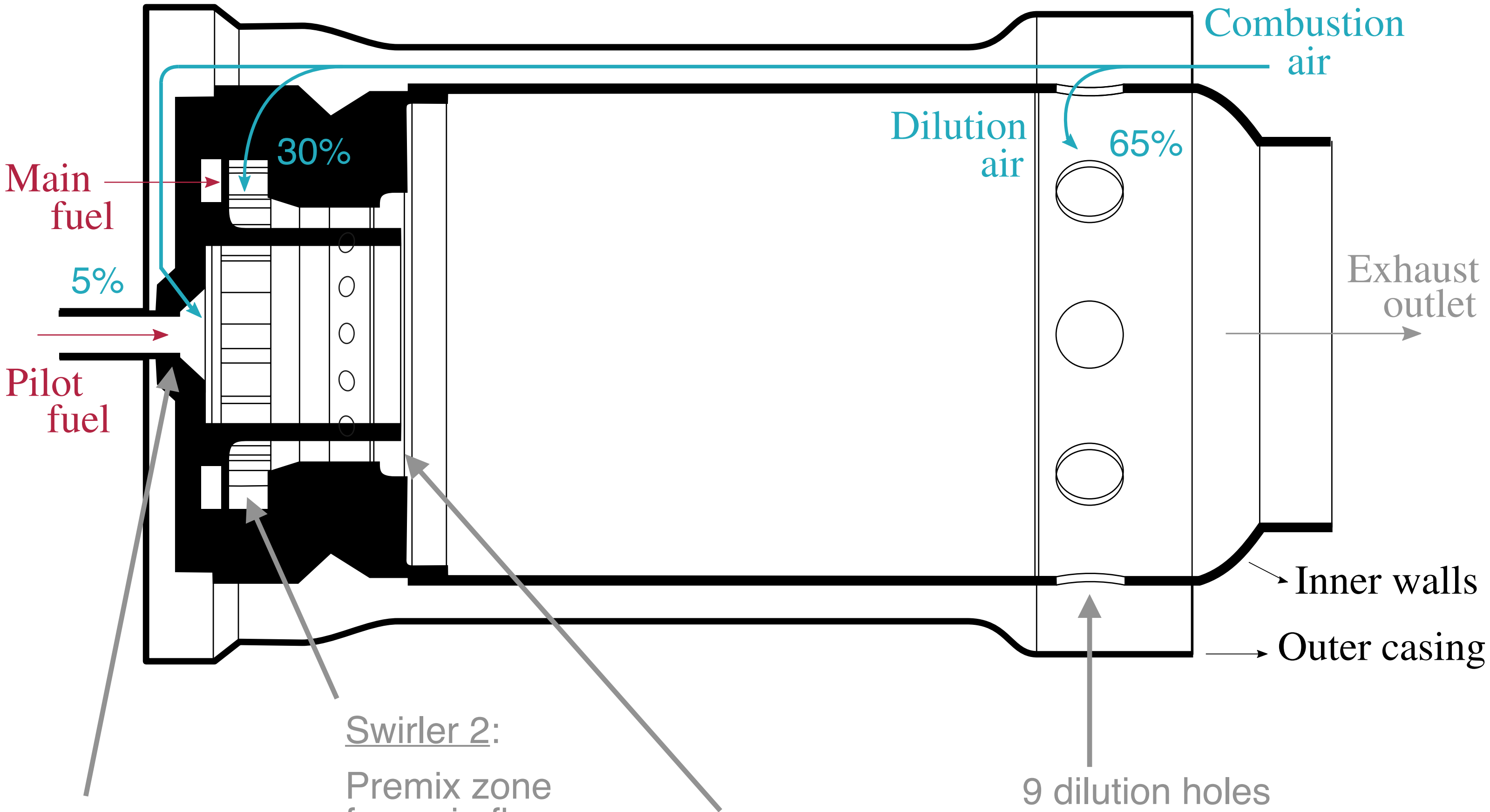
Burner layout & operating conditions

- mGT burner description
- 0D/1D hybrid model
- Optimized operating conditions

Large-Eddy Simulations

Conclusions

The combustor layout of the **Turbec T100 mGT** is a reverse (or counter-current) flow can burner.



Swirler 1:

Pilot diffusion flame:
- 12 air injectors
- 6 fuel injectors

Swirler 2:

Premix zone
for main flame

Swirler 3:

30 oxidizer inlets
for the premixed
main flame

9 dilution holes

Nominal conditions:

P_{th} = 333 kW_{th}

$\dot{m}_{air}$ = 800 g/s

p = 4 bar

$T_{air,in}$ = 865 K

$T_{f,in}$ = 300 K

For REF case (100% CH_4):

ϕ_{global} ~0.14

$\phi_{local,main}$ ~0.41

Mainly premixed burner:
not adapted to H_2 combustion

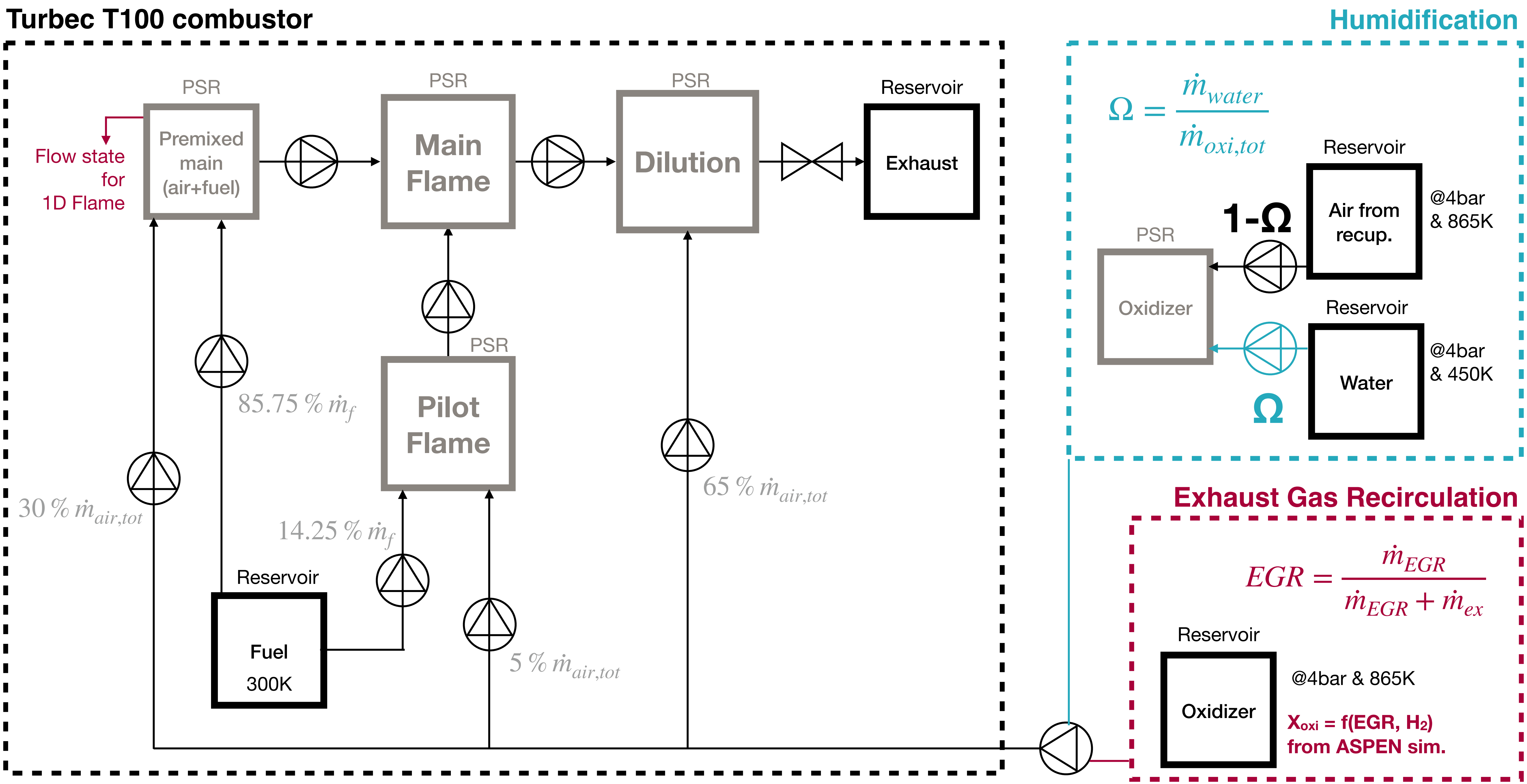
0D CRN to emulate the burner behavior using Perfectly Stirred Reactors.

1D Flame to compute the flame speed.

Detailed Chemical Reactor Network model: humidification & EGR emulation

$\Omega?$ $EGR?$

$S_{l,X_{H_2}} \simeq S_{l,ref}$



Turbec T100 combustor

Humidification

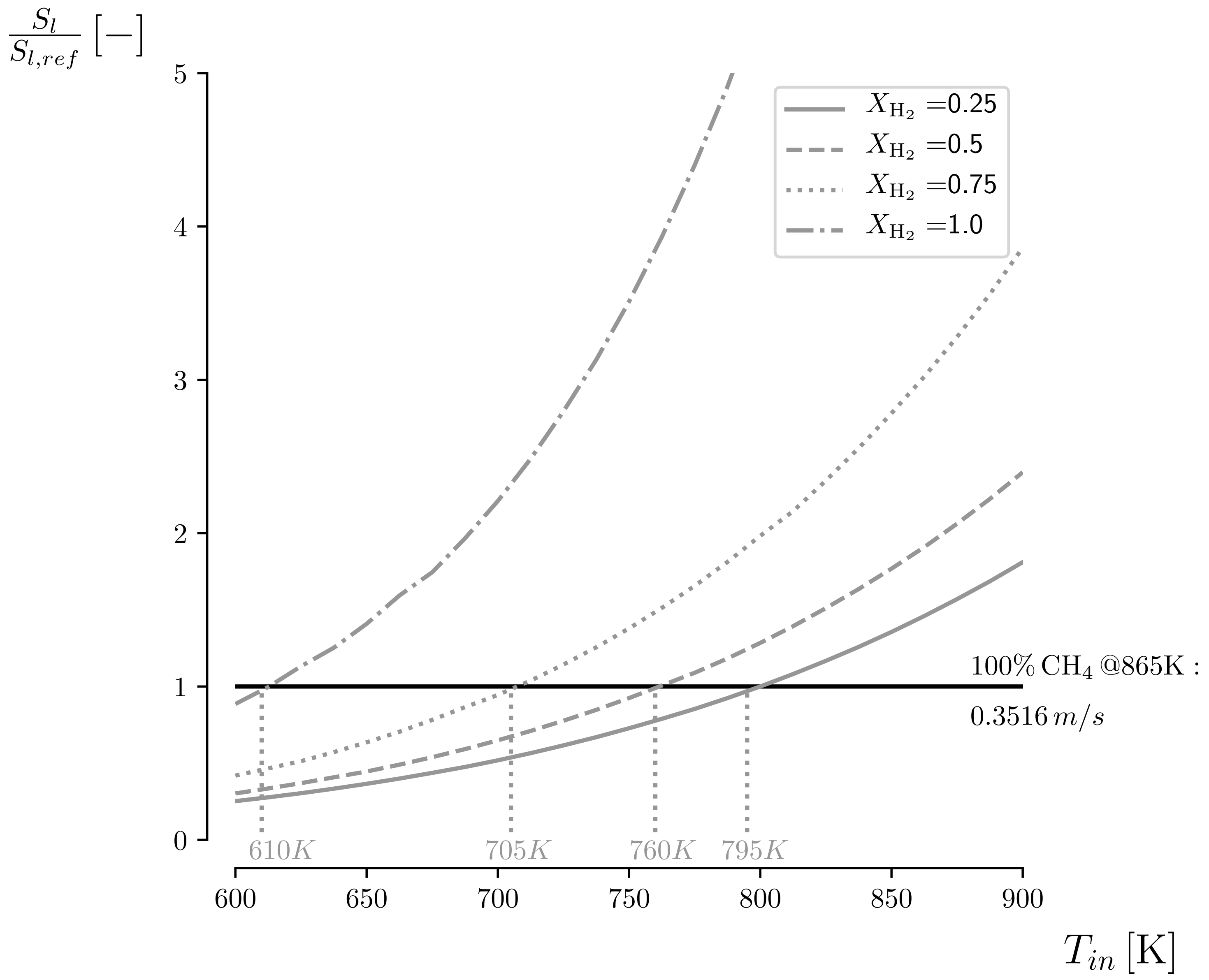
$$\Omega = \frac{\dot{m}_{water}}{\dot{m}_{oxi,tot}}$$

Exhaust Gas Recirculation

$$EGR = \frac{\dot{m}_{EGR}}{\dot{m}_{EGR} + \dot{m}_{ex}}$$

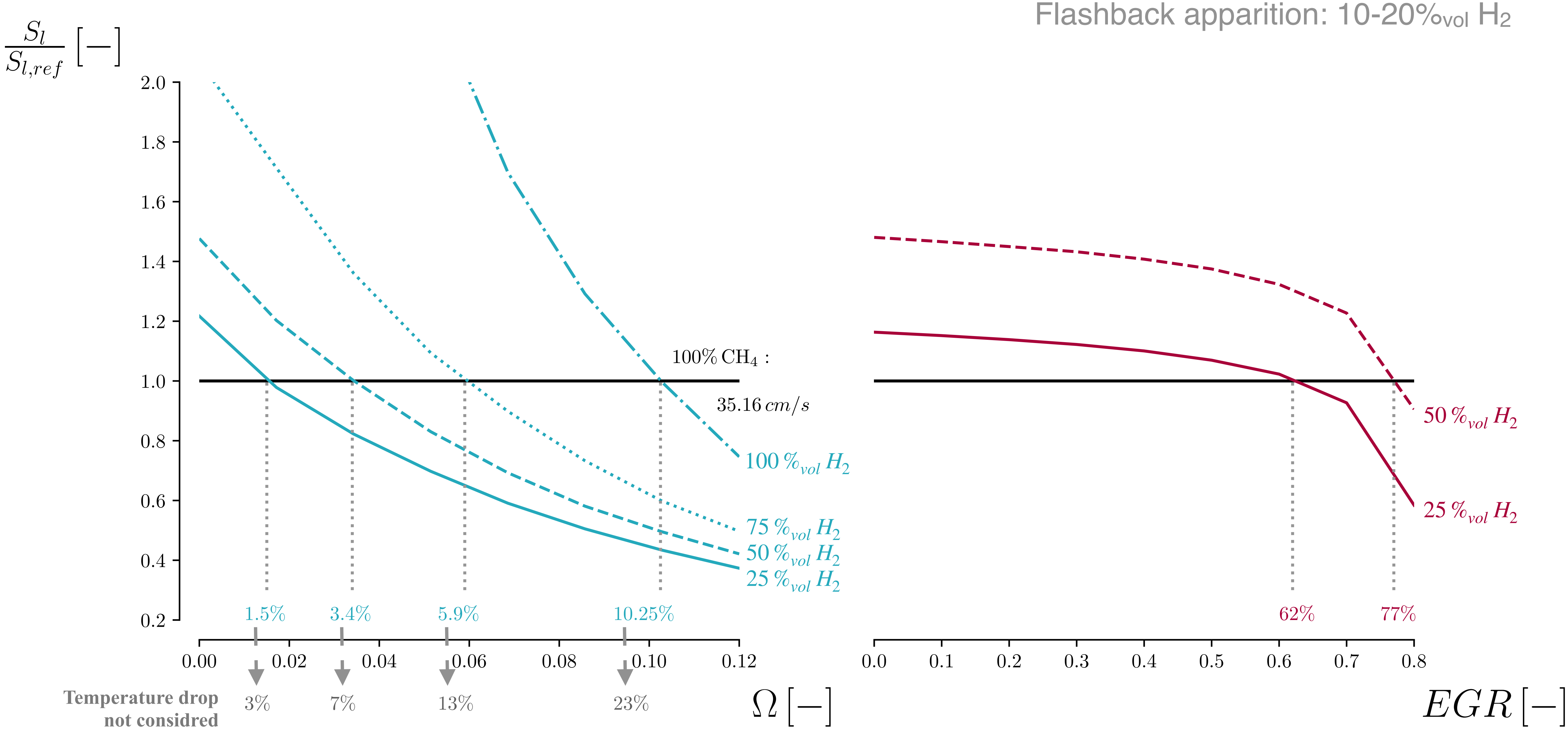
Inlet temperature has an important impact on the laminar flame speed

Burning up to **100% H_2** requires to **decrease** the inlet temperature **down to 610K**.



0D CRN/1D Flame on various H_2 blends: comparison humidification & EGR

Flashback apparition: 10-20%$_{vol}$ H_2



Considered cases for the LES simulations

Case	Fuel composition	Dilution	Operating conditions
Ref	$100\,\%_{vol}\,CH_4$	-	Turbec T100 nom. cdts
FB	$50\,\%_{vol}\,CH_4\,/\,50\,\%_{\mathrm{vol}}\,H_2$	-	Turbec T100 nom. cdts
50H₂LT	$50\,\%_{vol}\,CH_4\,/\,50\,\%_{\mathrm{vol}}\,H_2$	-	Lower premix temp. (760K)
50H₂Ω	$50\,\%_{vol}\,CH_4\,/\,50\,\%_{\mathrm{vol}}\,H_2$	$\Omega = 3.4\,\%$	Turbec T100 nom. cdts
50H₂EGR	$50\,\%_{vol}\,CH_4\,/\,50\,\%_{\mathrm{vol}}\,H_2$	$EGR = 77\,\%$	Turbec T100 nom. cdts
100H₂Ω	$100\,\%_{vol}\,H_2$	$\Omega = 10.25\,\%$	Turbec T100 nom. cdts

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Flashback prevention for various H_2 blends **without** any **redesign** of a mGT combustor.

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Burner layout & operating conditions

Large-Eddy Simulations

- Numerical set-up
- Flashback phenomenology
- Stability analysis

Conclusions

Numerical set-up of the LES

CFD code: YALES2

Solver: Variable Density (Low-Mach N-S eq.)

Sub-grid scale stresses model:
Dynamic Smagorinsky

$Re = 37500$ $y^+ = 38$ (in the main swirler)

Wall model: Classical log-law

Heat losses: Adiabatic wall condition

Complex chemistry
+ reduced kinetic scheme: DRM19

21 species - 84 reactions

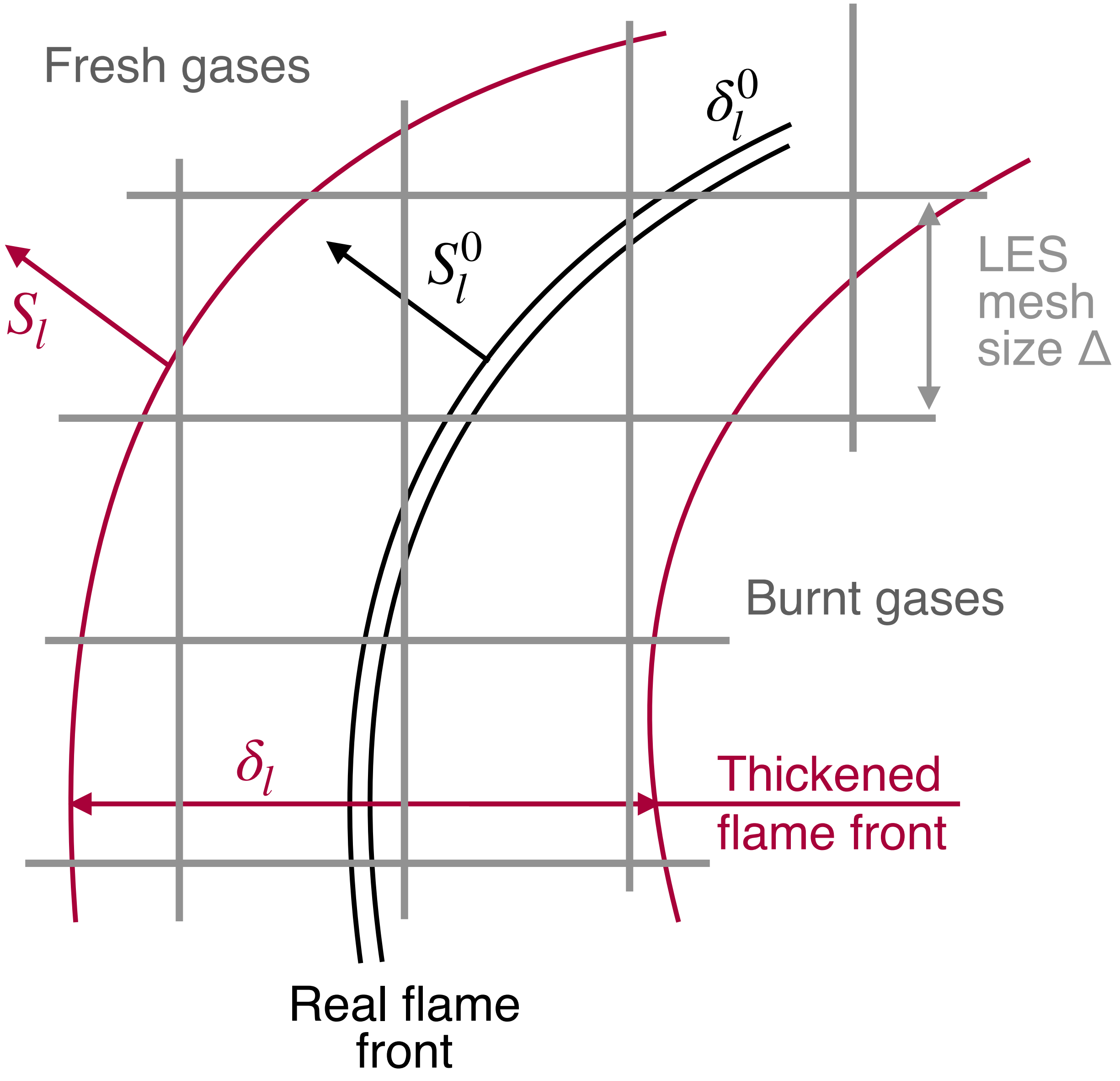
Combustion model: DTFLES

The DTFLES model artificially thicken the flame front without modifying the flow dynamic

$\Delta > \delta_l^0$

Flame front
thickened
of a factor F

Efficiency E function to
compensate the surface
reduction & avoid wrinkling
issues

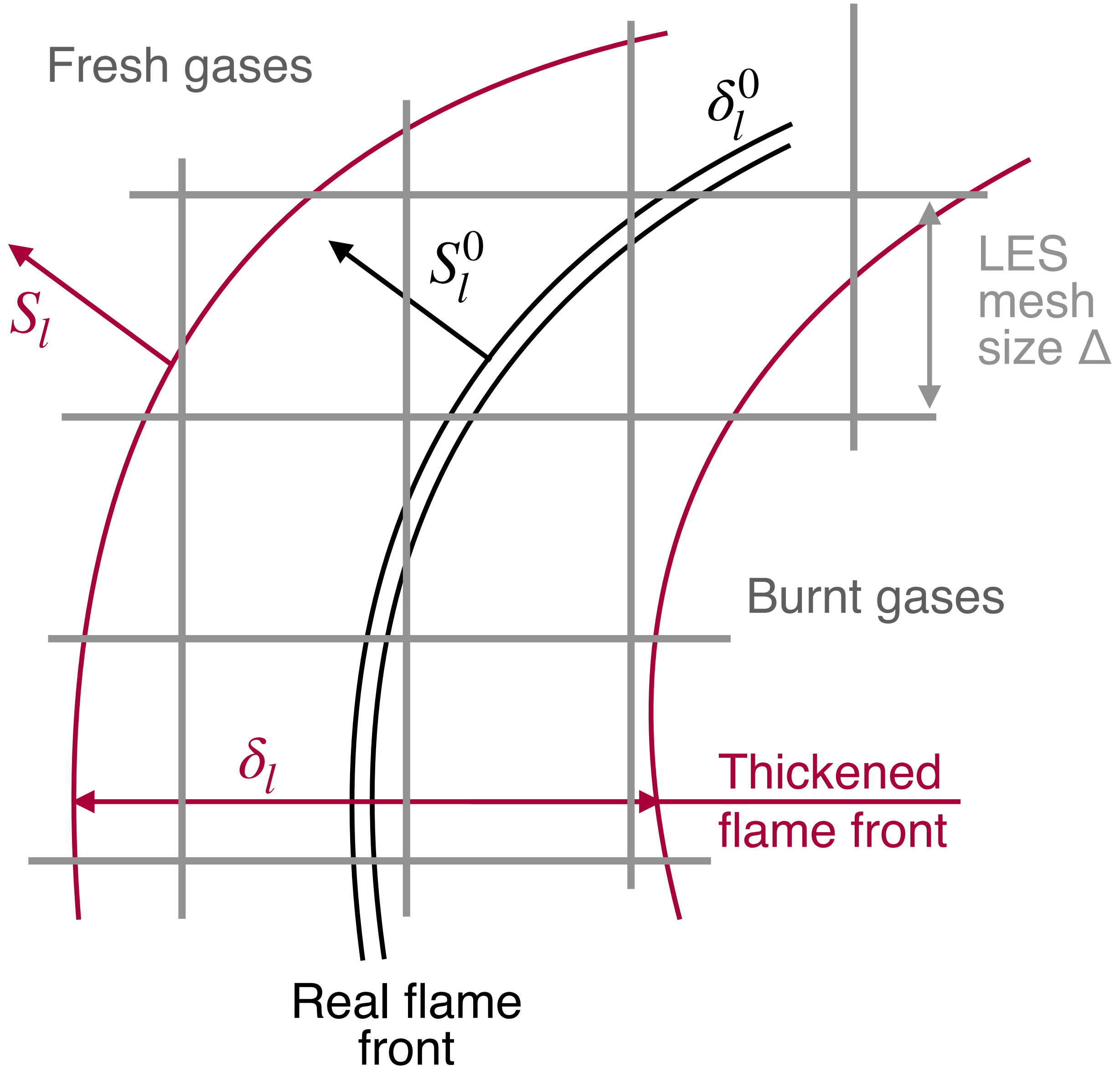


The DTFLES model artificially thicken the flame front without modifying the flow dynamic

Dynamic formulation of the TFLES model to handle **premixed** and **non-premixed** flames:

F is not constant on the domain.

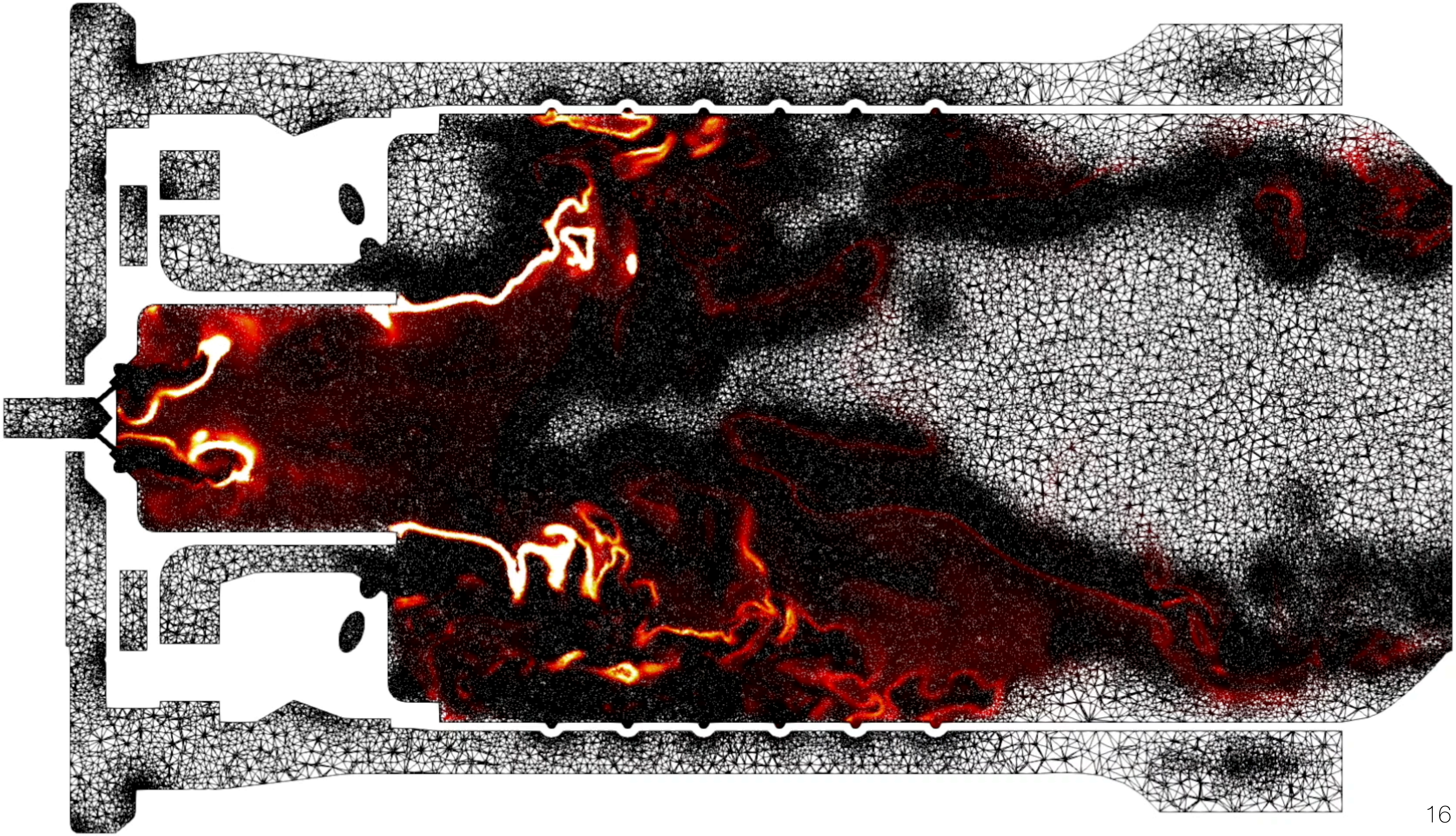
Flame sensor (reaction rate) to detect where the reaction takes place.



Dynamic Adaptive Mesh Refinement performed to capture the flame front

Dynamic AMR
±80.10^6 cells
Δ_{min} = 0.7mm
Δ_{max} = 3mm

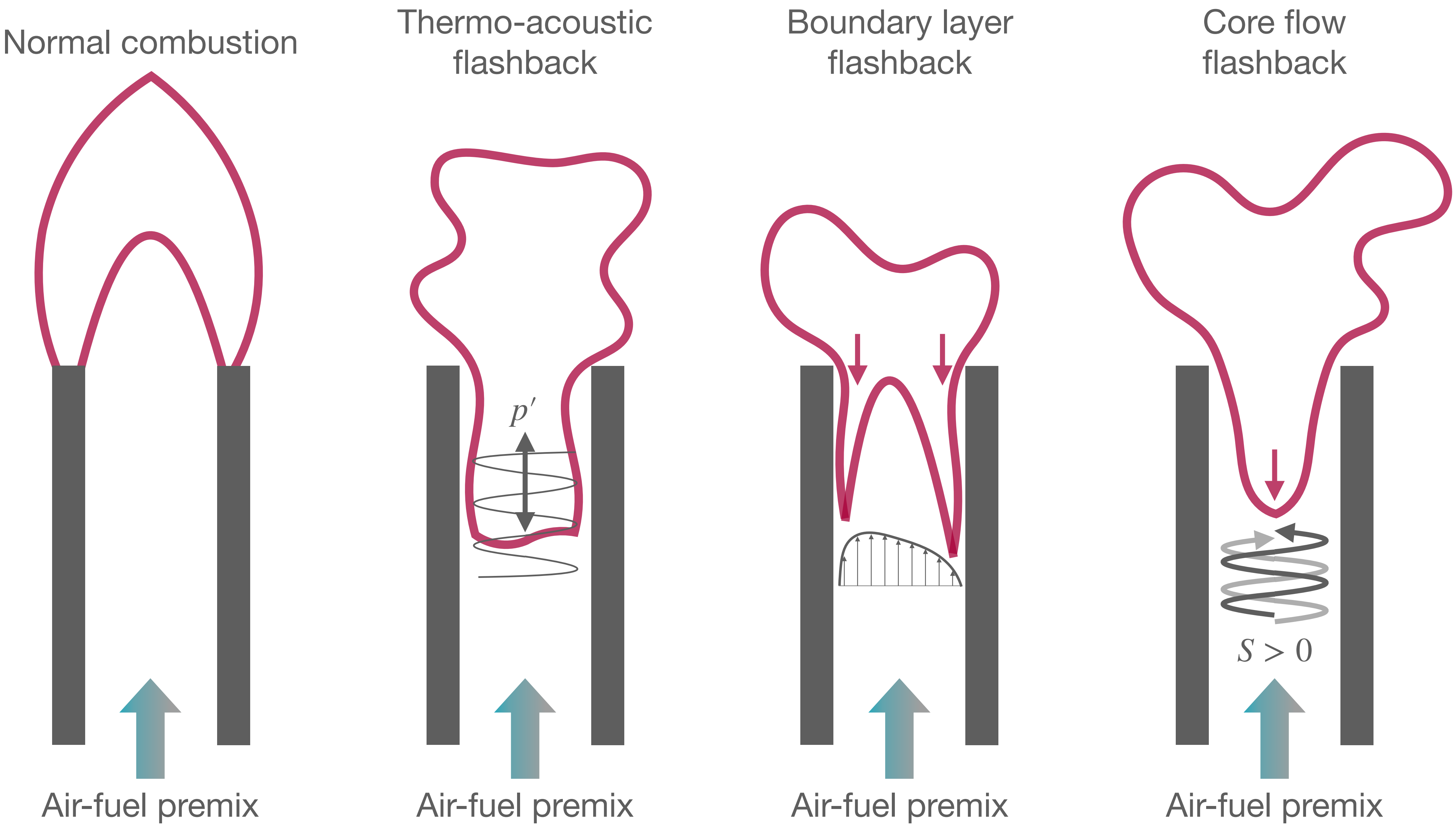
Cost: 1-10% total CPU load



Stability analysis, allowed by LES, shows no flashback for 50%$_{vol}$ H_2 — Ω=3.4%

CPU cost: ~ **576k CPUh**
(~ 25sim x 24h x 960CPU)
on Zenobe

Flashback phenomenology: three distinctive mechanisms of fast upstream traveling of the flame front



Normal combustion

Thermo-acoustic flashback

Boundary layer flashback

Core flow flashback

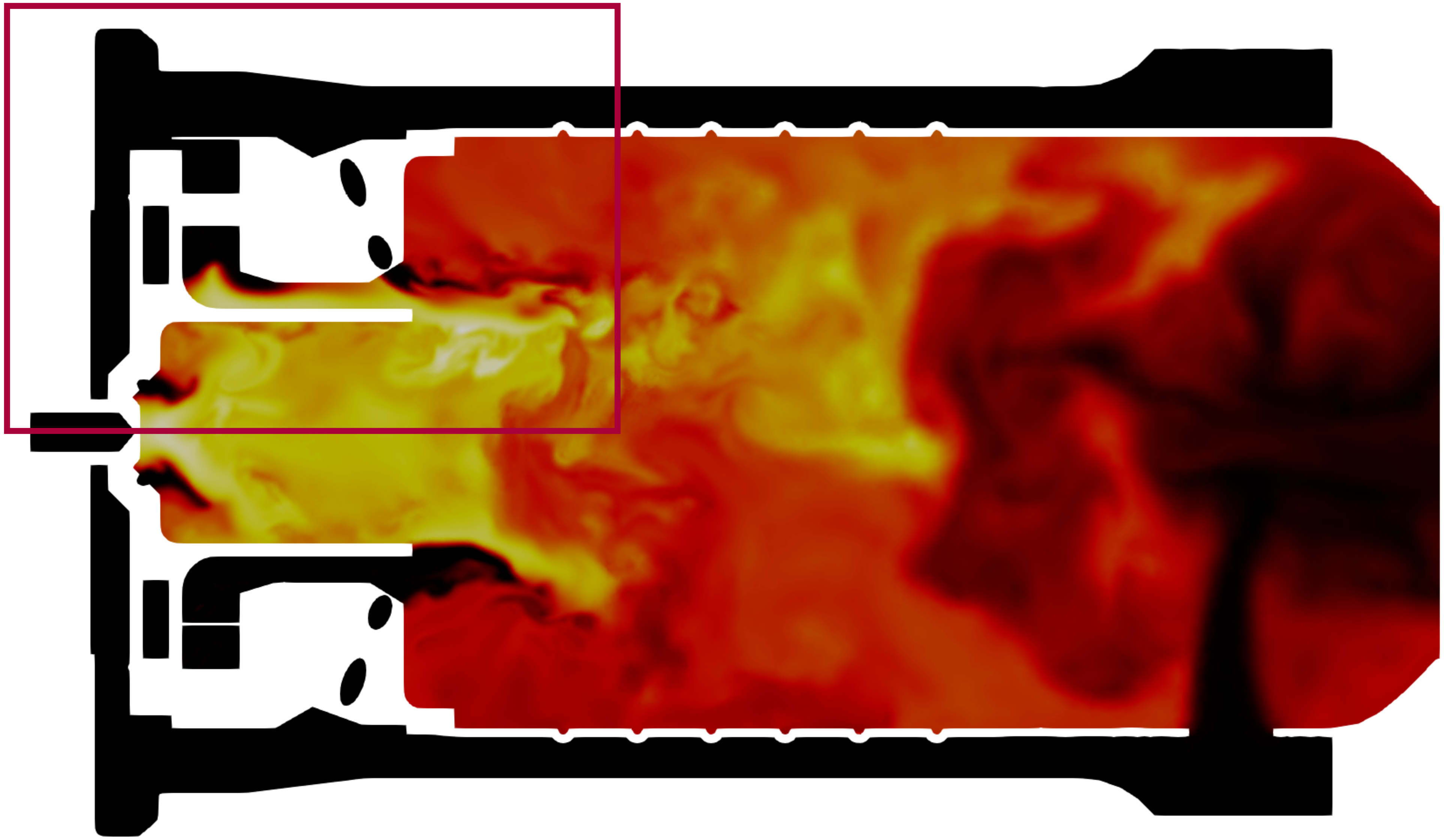
Air-fuel premix

Air-fuel premix

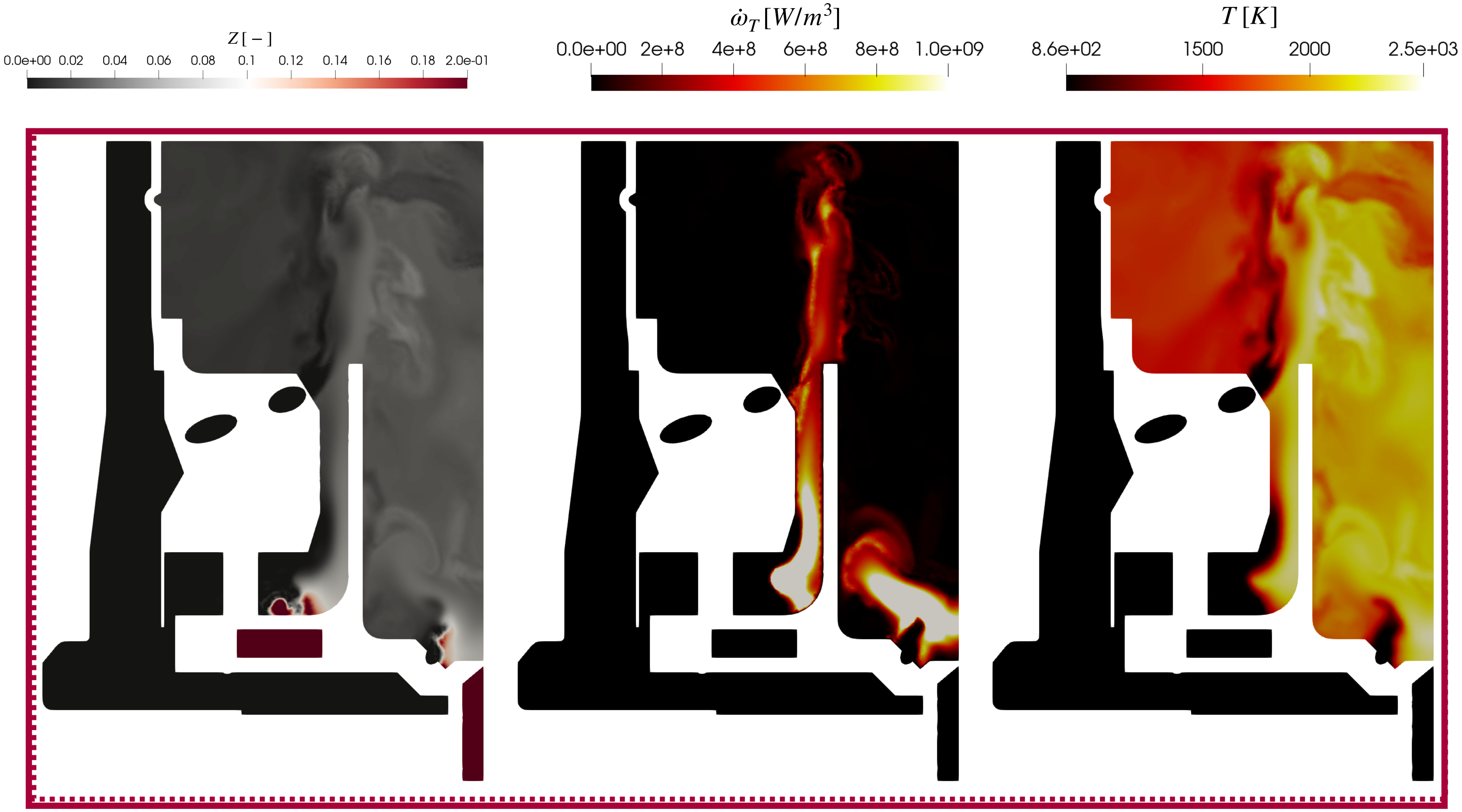
Air-fuel premix

Air-fuel premix

Flashback phenomenology: boundary flashback



Flashback phenomenology: boundary flashback



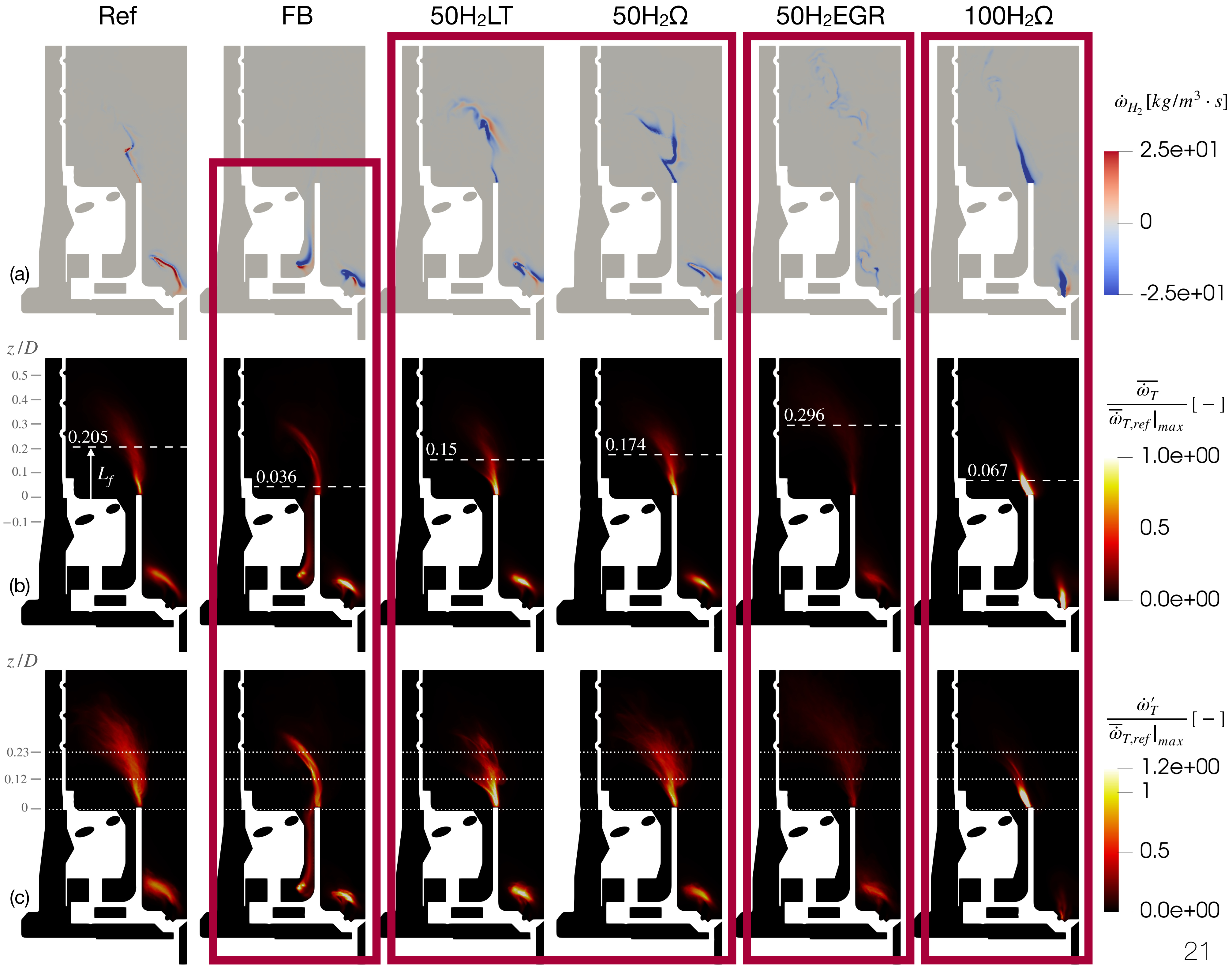
FB case

$50\%_{vol}$ H_2

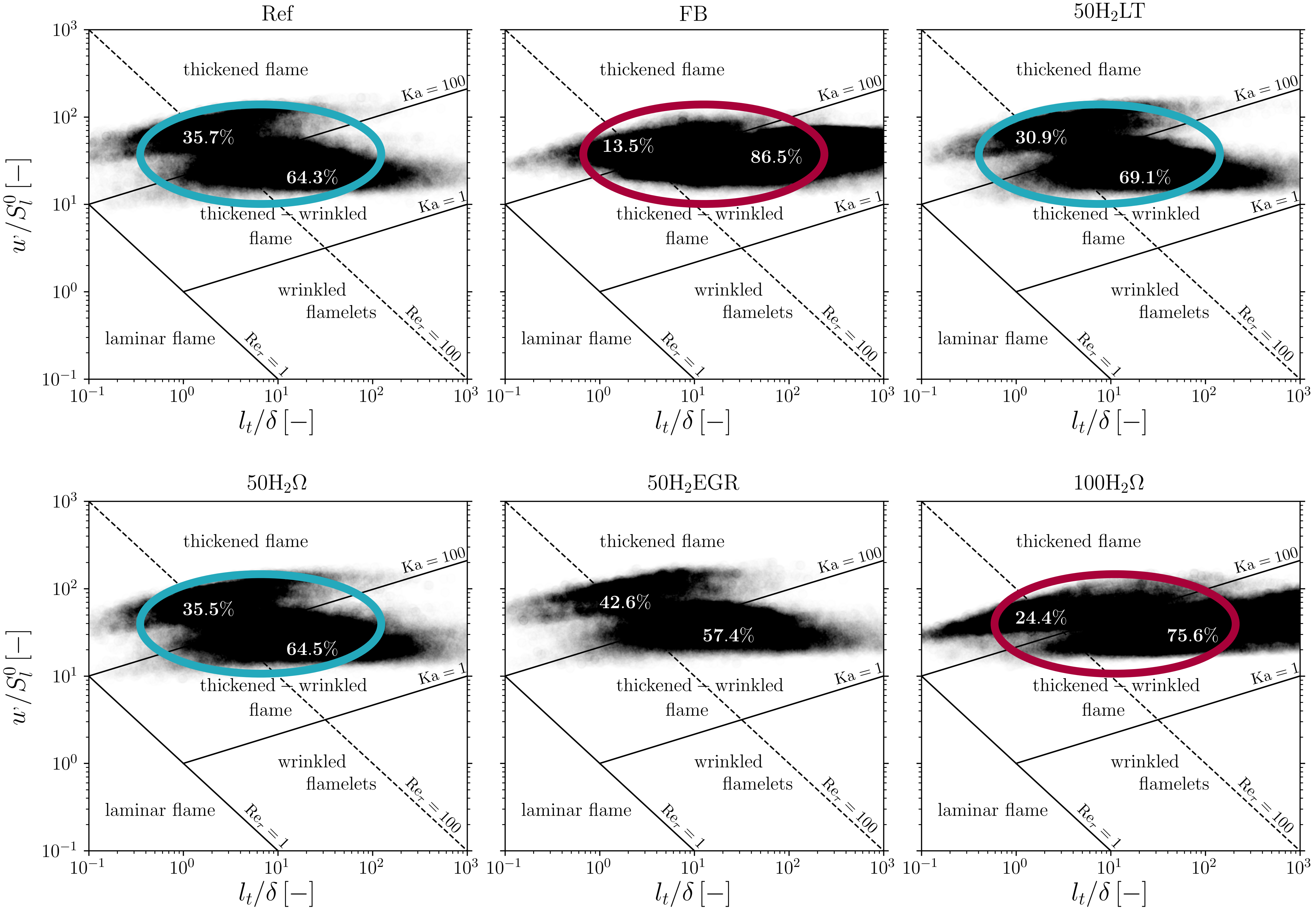
All solution cases are not showing any flashback

H_2 source term shows the production and consumption rates.

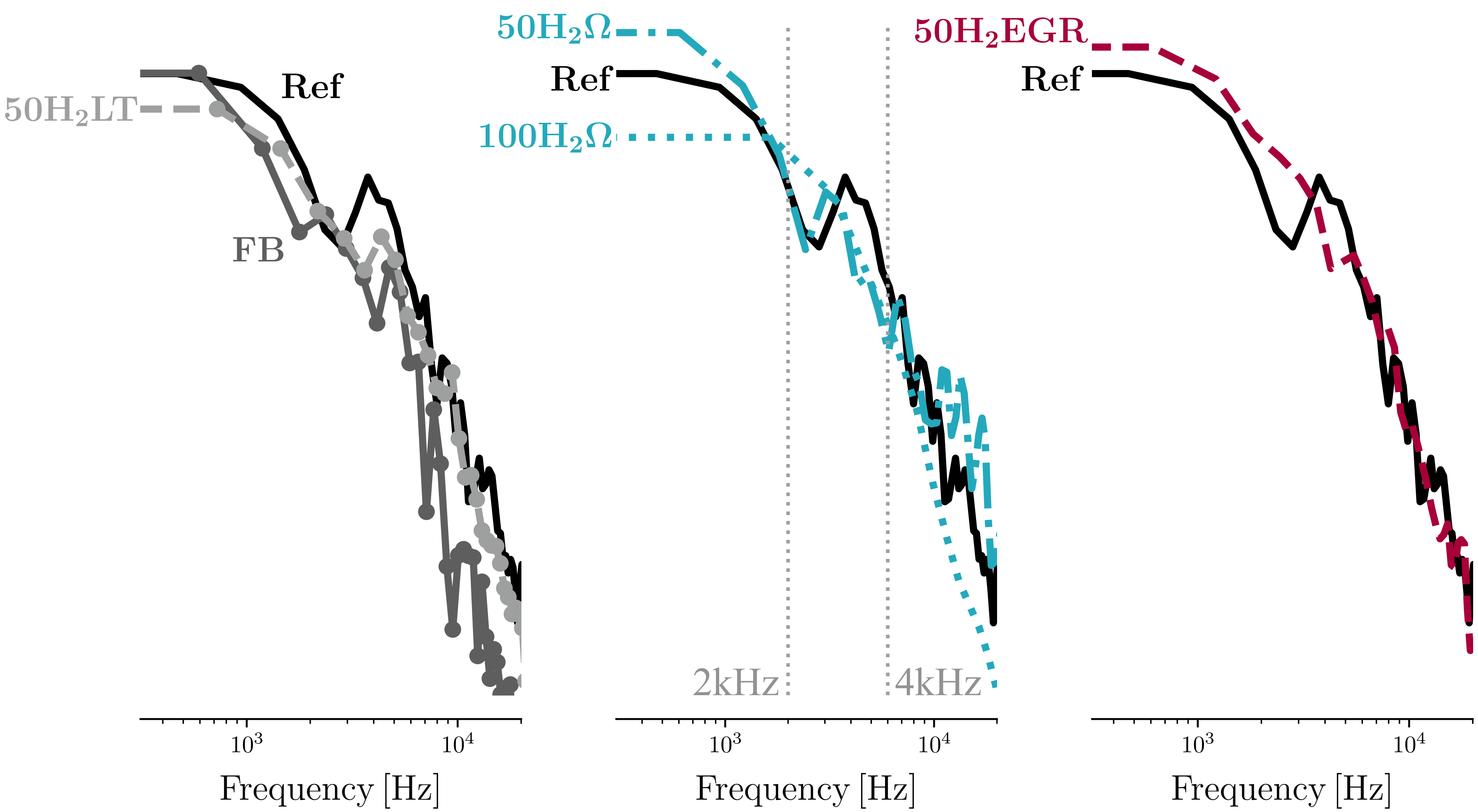
$$L_f = \frac{\int z\,\overline{\dot{\omega}}_{T,xy}\,dz}{\int \overline{\dot{\omega}}_{T,xy}\,dz}$$



Combustion regime diagrams showing scatter plots of injector fresh gases



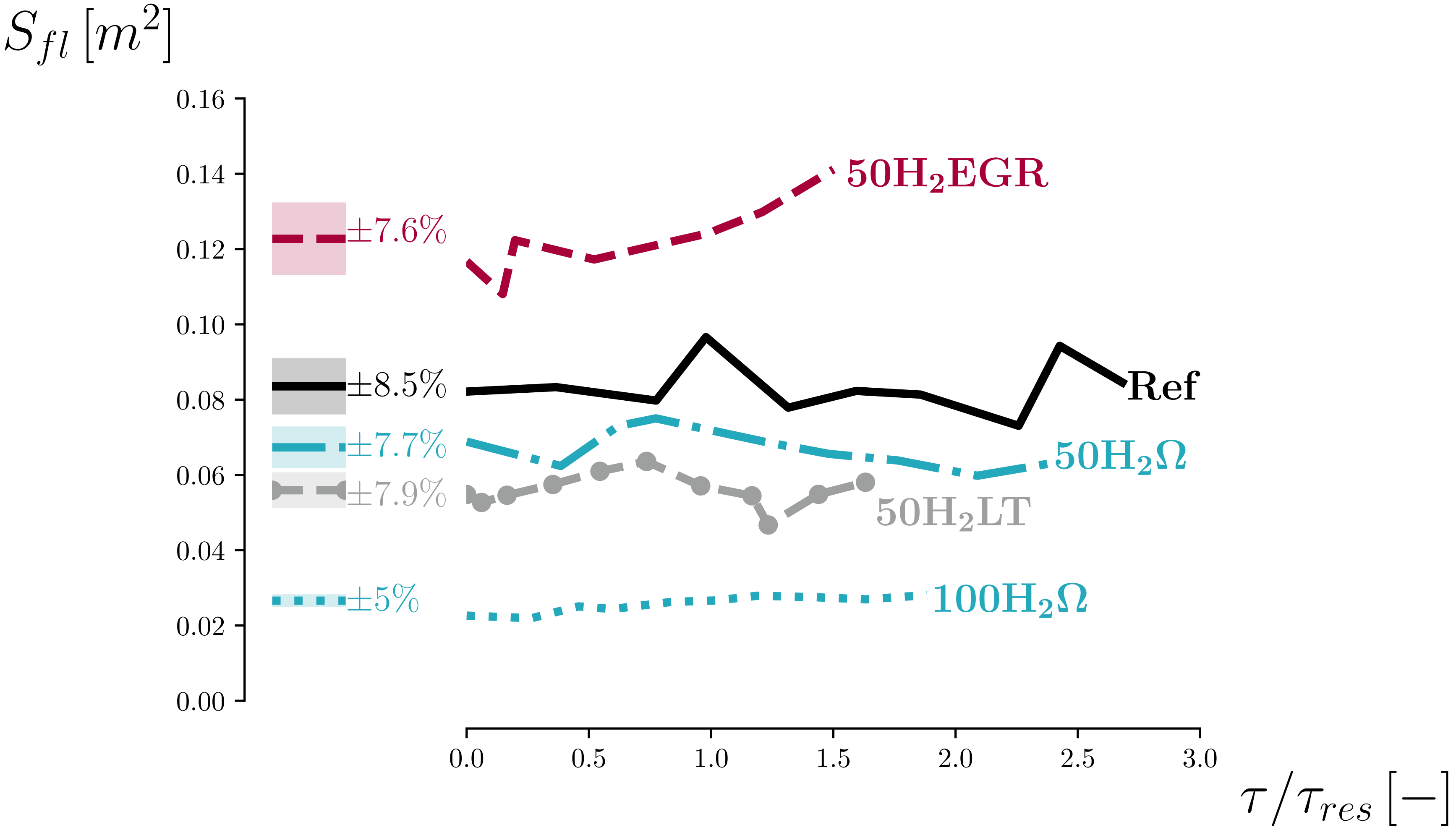
Normalized PSD of the axial velocity:
Ref mode only reproduced by $50\%_{vol}$ H_2 — Ω=3.4%



Comparison of the flame surface gives a clue on the flame ability to sustain perturbations

Fluctuations
= flame able to sustain perturbations

Increasing surface
= sign of thermo-diffusive instabilities or blow-out issues



Target

Flashback prevention for various H_2 blends **without** any **redesign** of a mGT combustor.

Considering humidification & EGR as solution.

Outline

Burner layout & operating conditions

Computational Fluid Dynamics

Conclusions

Flashback prevention without any redesign of the mGT combustor

Low computational
cost predictions
using 0D CRN / 1D Flame

100% H_2 can be reached when performing humidification while only 50%$_{vol}$ H_2 with EGR.

No flashback was observed for all considered cases.

However, potential **risk** of **flashback** apparition for the **100%H_2Ω**.

- Advanced simulations are required, including wall heat transfer.

Risk of **less stable** flame observed for the **50%H_2EGR**.

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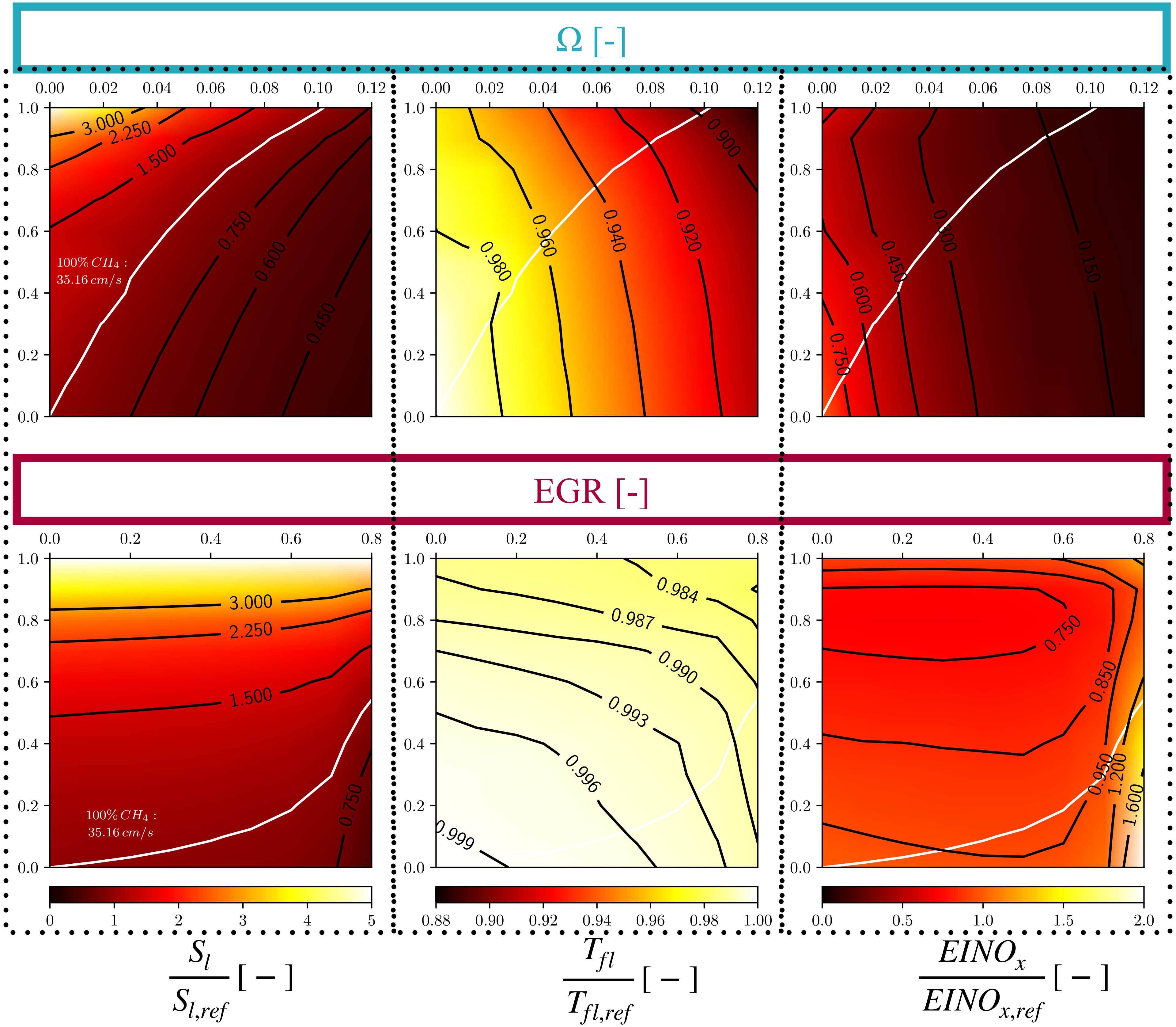
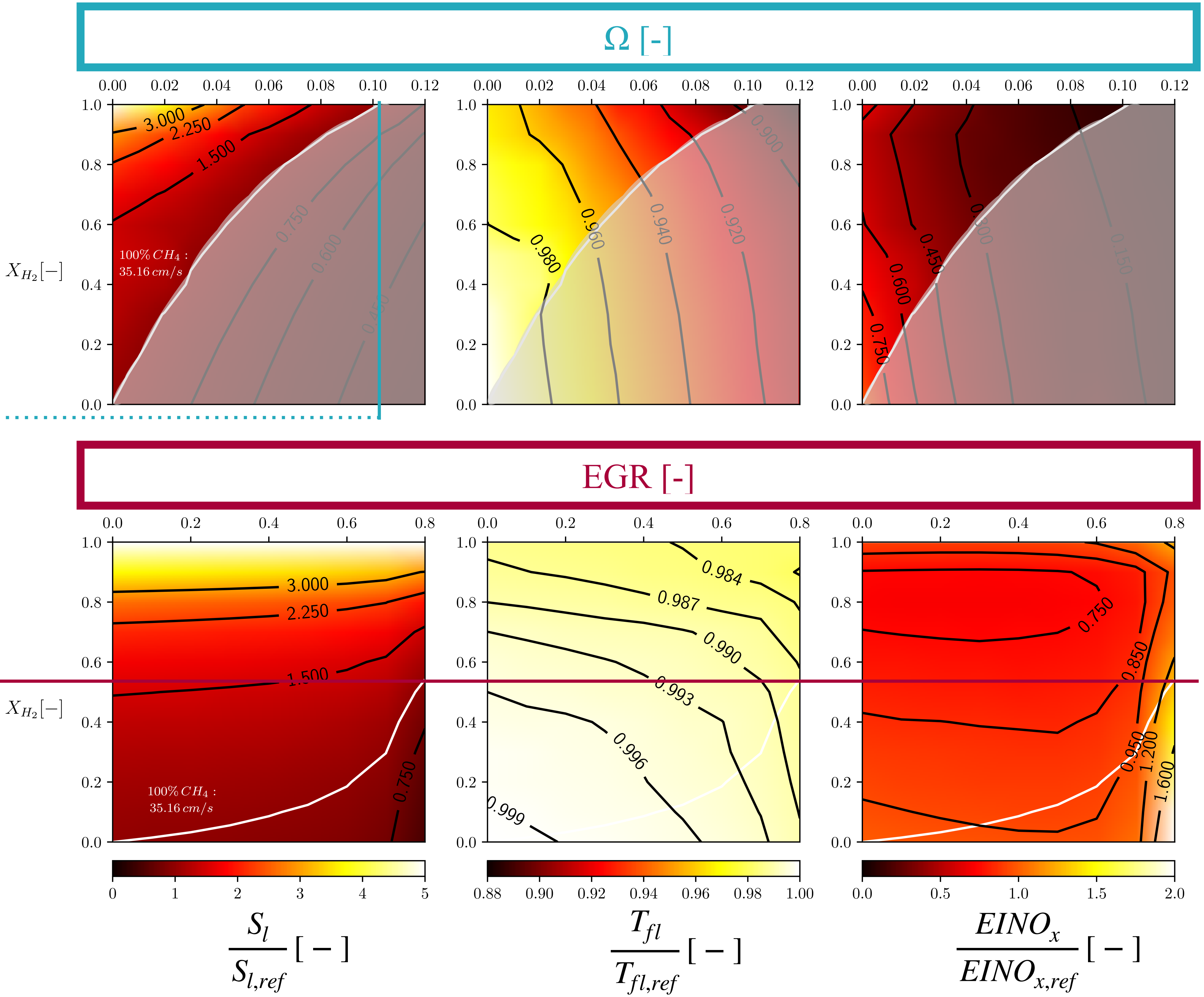
0D CRN/1D Flame on various H_2 blends: comparison humidification & EGR

$$EINO_x = \frac{X_{NO_x} \cdot \dot{m}_{oxi}}{P_{el}}$$



0D CRN/1D Flame on various H_2 blends: 100% H_2 requires only Ω=10.3%



$S_l < S_{l,ref}\ \forall X_{H_2}$ ✓

$\Omega = 10.3\ \%$

$S_l > S_{l,ref}$ ✗

$X_{H_2} > 55\ \%$

0D CRN/1D Flame on various H_2 blends: decrease of T and NOx with humidification

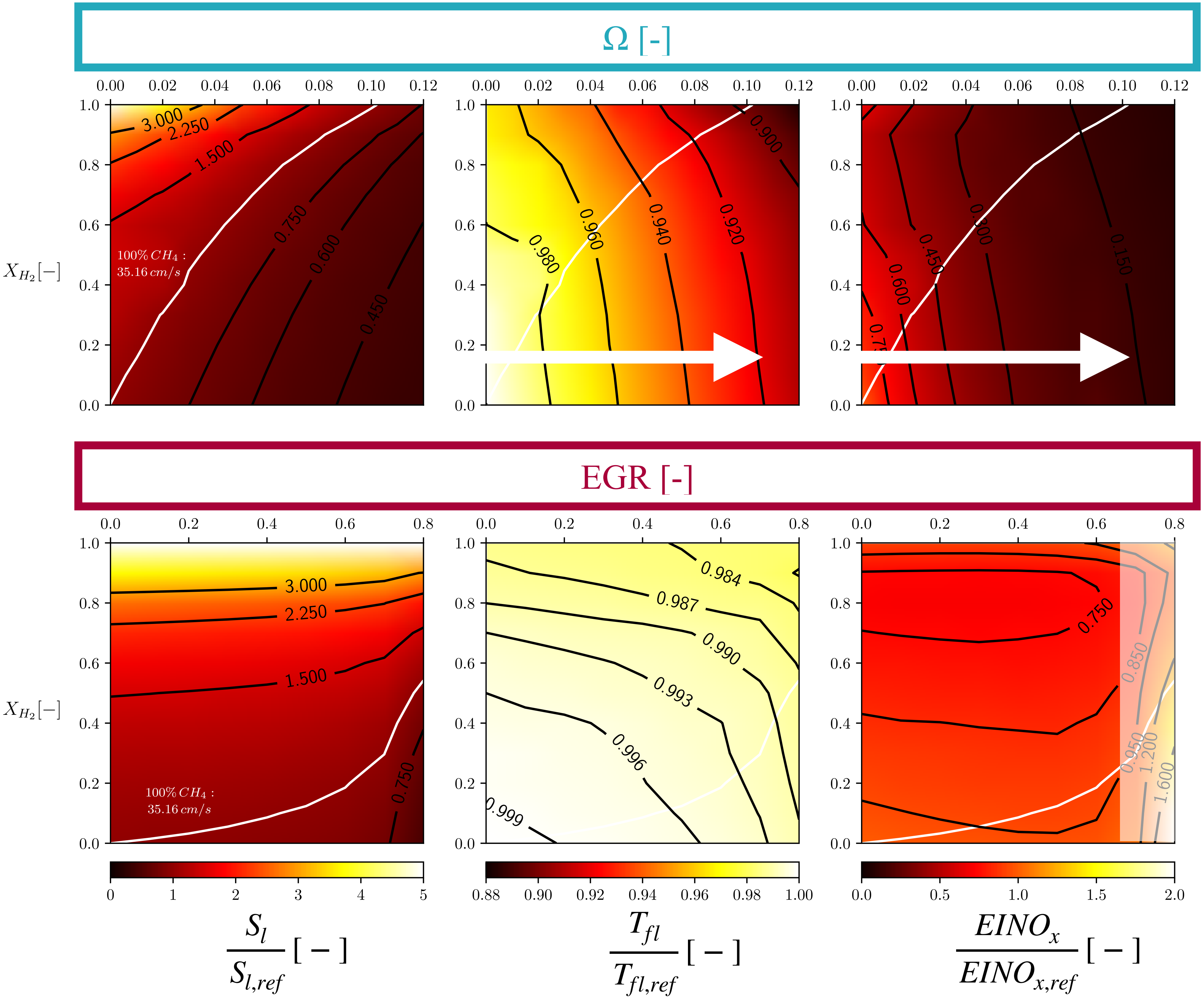
Temperature decrease of **~10%** with water addition,

inducing a **decrease** in the **NOx** levels.

No significative **temperature** decrease (**~0.2%**),

while the **NOx** levels actually **increase** (**~30-60%**).

N_2 ↗ with EGR



Evolution of T_{fl} with X_{H2} ↗ & fixed Ω: T_{fl} ↘

@ fixed thermal power and oxidizer flow rate

REF:

$f = CH_4$

X_{H2} ↗

(ϕ ↘)

100% H_2:

$f = H_2$

$$\begin{array}{ccccccccccccccccc}
 & & \sim 2.2\,kJ/kgK & & & & & & & & & & & & & & \\
\dot m_f & \cdot & Cp_f & \cdot & T_f & + & \dot m_{oxi} & \cdot & Cp_{oxi} & \cdot & T_{oxi} & = & \dot m_{mix} & \cdot & Cp_{mix} & \cdot & T_{mix} \\
\vee & & \begin{array}{c}\wedge\\ \wedge\\ \wedge\end{array} & & \begin{array}{c}\parallel\\ 300K\\ \parallel\end{array} & & & & & & & & \overset{*}{\cong} & & \begin{array}{c}\wedge\\ \wedge\end{array} & & \vee \\
\dot m_f & \cdot & Cp_f & \cdot & T_f & + & \dot m_{oxi} & \cdot & Cp_{oxi} & \cdot & T_{oxi} & = & \dot m_{mix} & \cdot & \underbrace{Cp_{mix}}_{\nearrow} & \cdot & \underbrace{T_{mix}}_{\searrow} \\
 & & \sim 14.3\,kJ/kgK & & & & & & & & & & & & & &
\end{array}$$

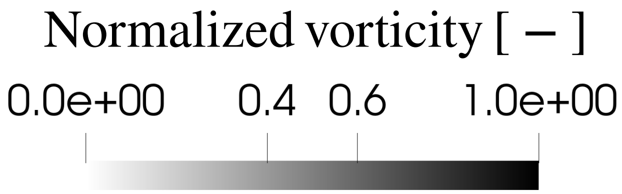
* $\dot m_f <<< \dot m_{oxi}$

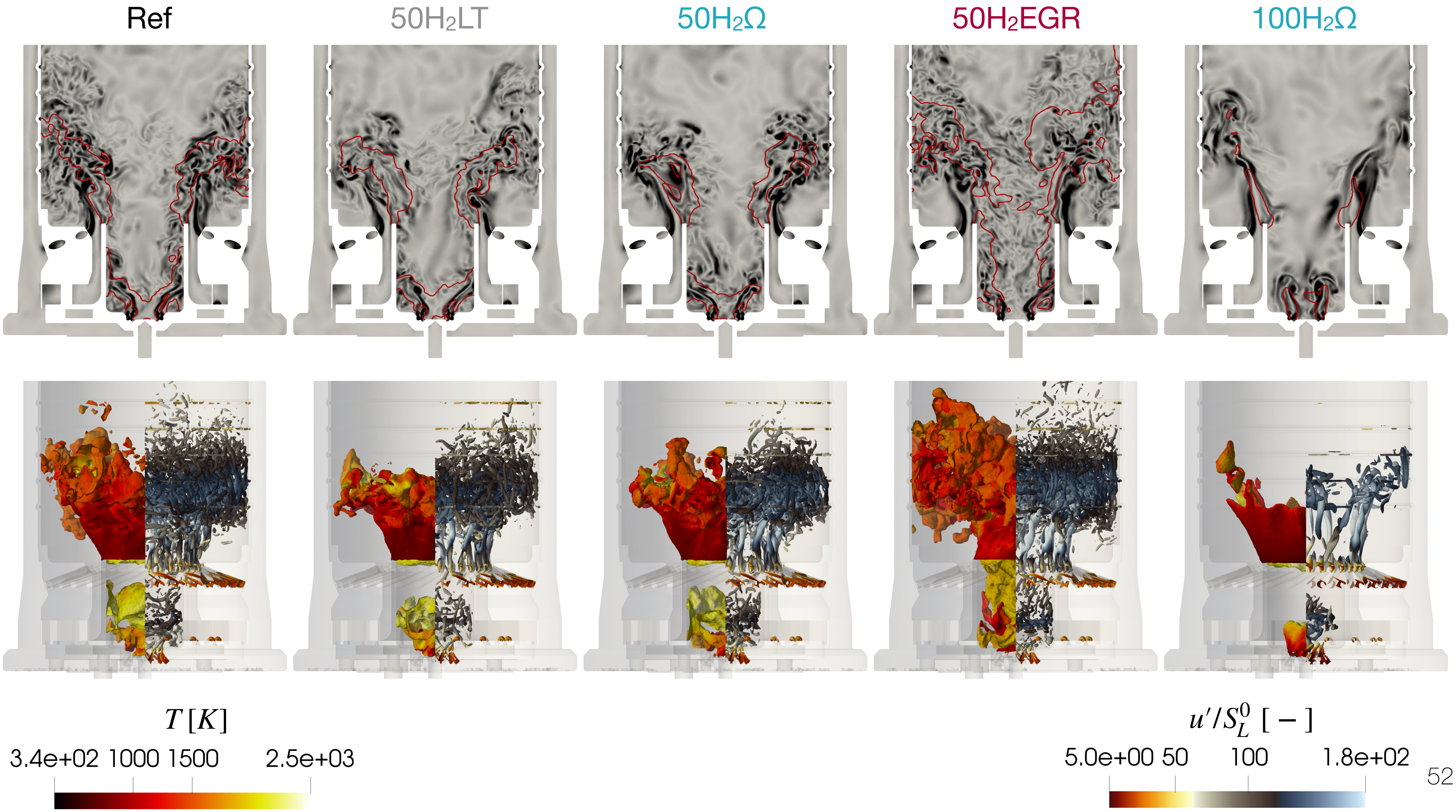
$$T_{mix} \searrow \longrightarrow T_{fl} \searrow$$

Dilution impact on the flame-turbulence interaction

Thickened-wrinkled flame regime = Turbulence thickens the flame preheat zone, but not the reaction zone (only wrinkled)

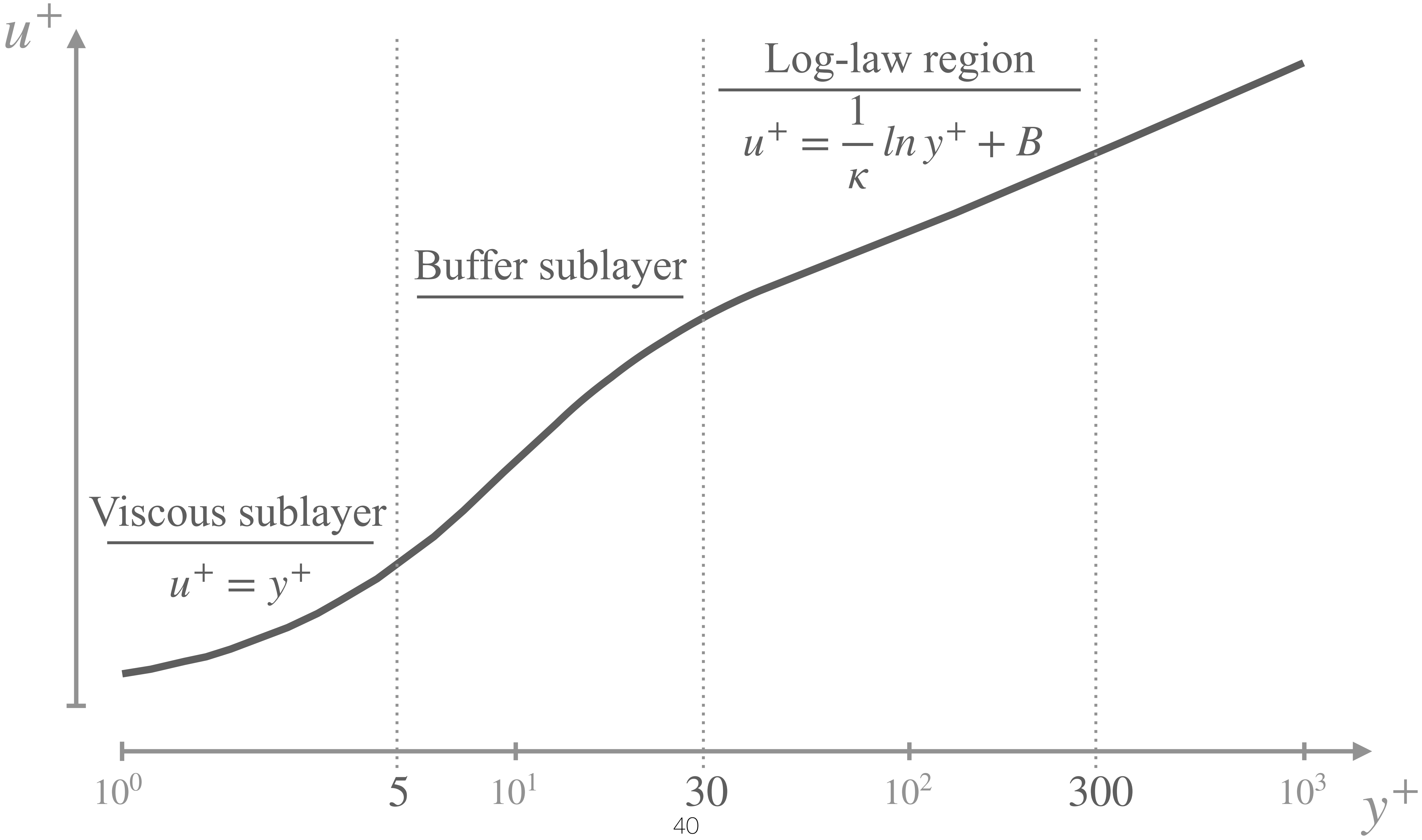
Thickened flame regime = Turbulence penetrates the inner flame structure & affects both diffusion &reaction zones



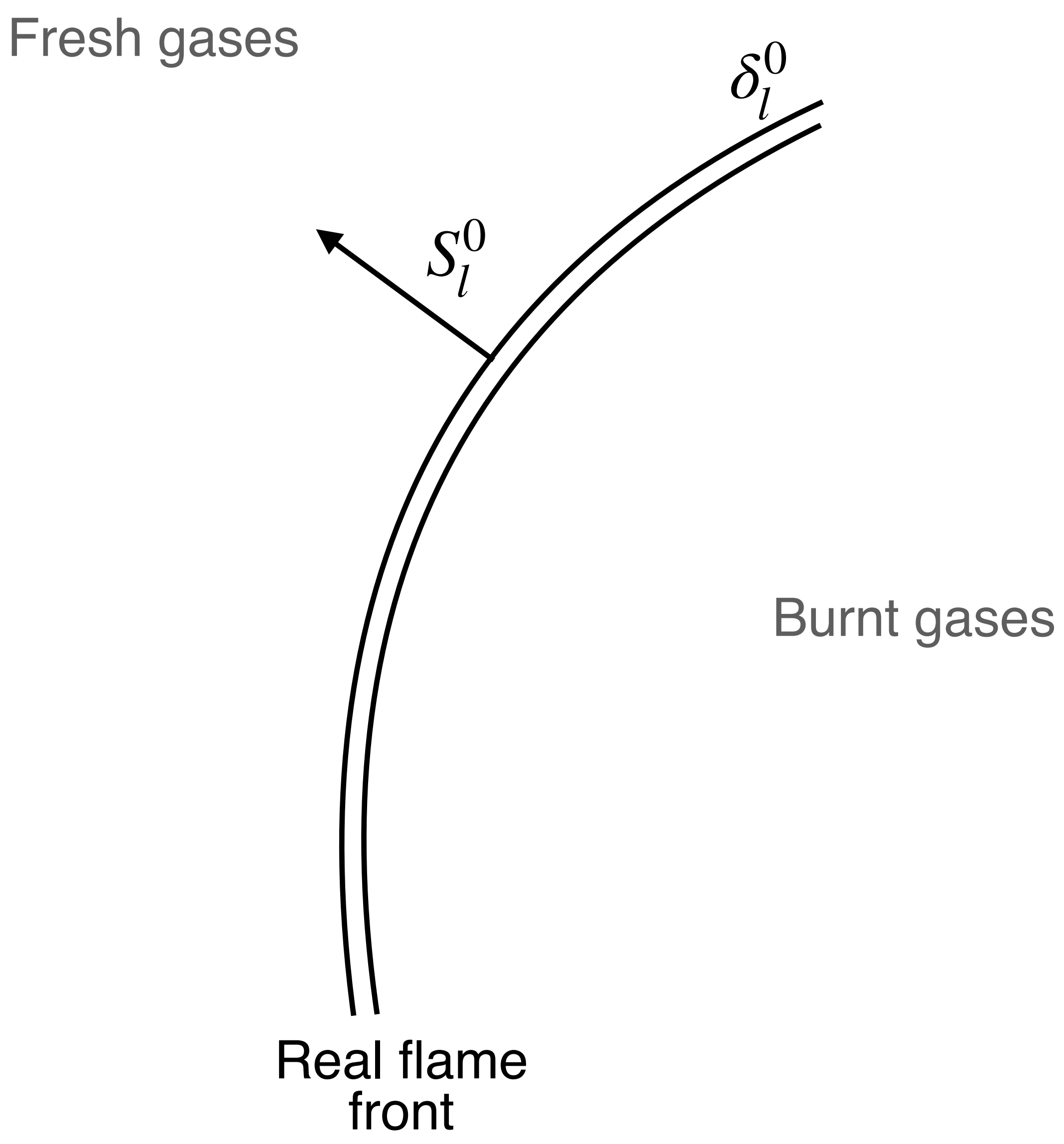


Thickened Flame Model

Near-wall flows



The DTFLES model artificially thicken the flame front without modifying the flow dynamic



Fresh gases

δ_l^0

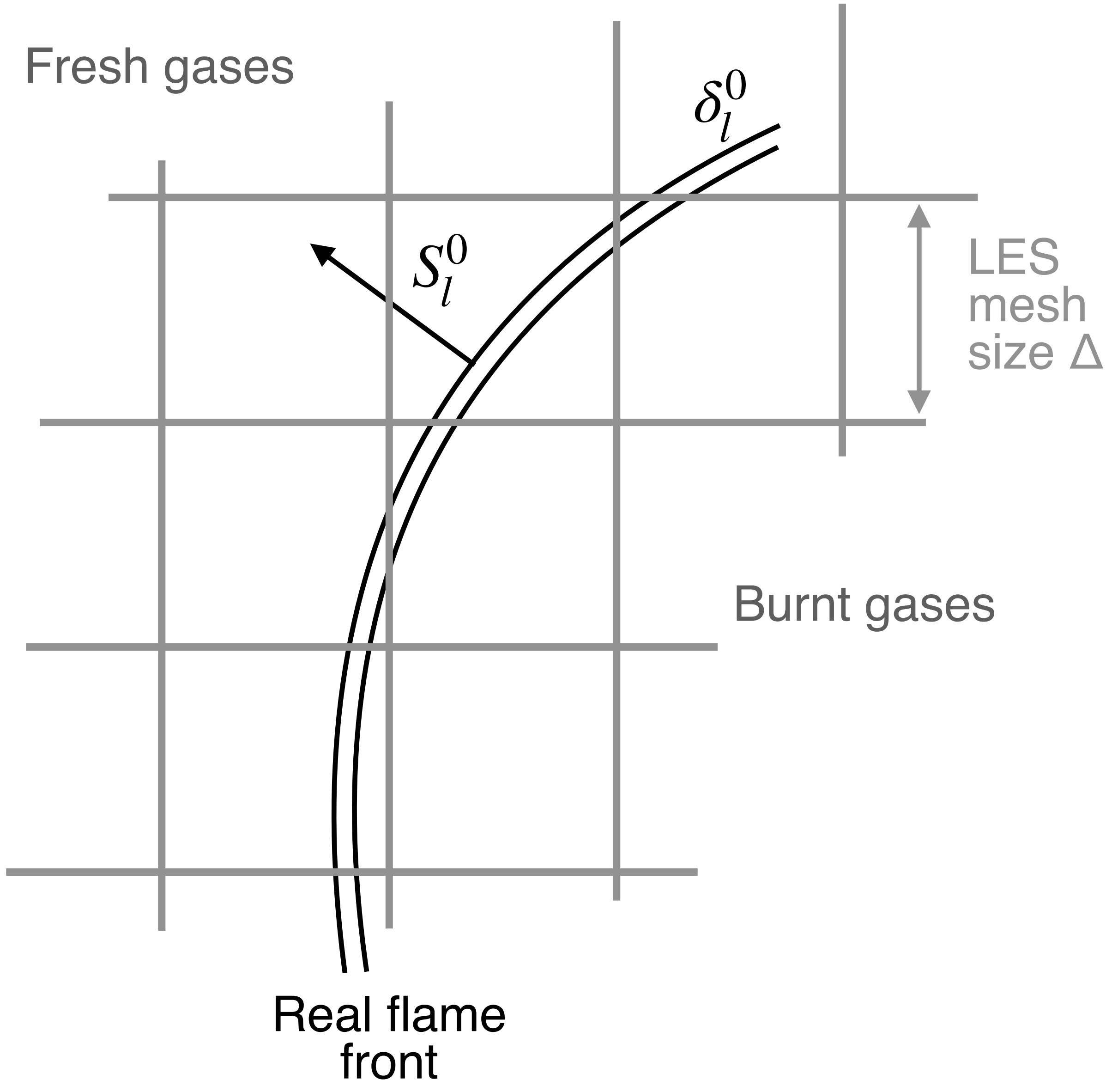
S_l^0

Burnt gases

Real flame front

The DTFLES model artificially thicken the flame front without modifying the flow dynamic

$\Delta > \delta_l^0$



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$\Delta > \delta_l^0$

Flame front
thickened
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Efficiency E function to
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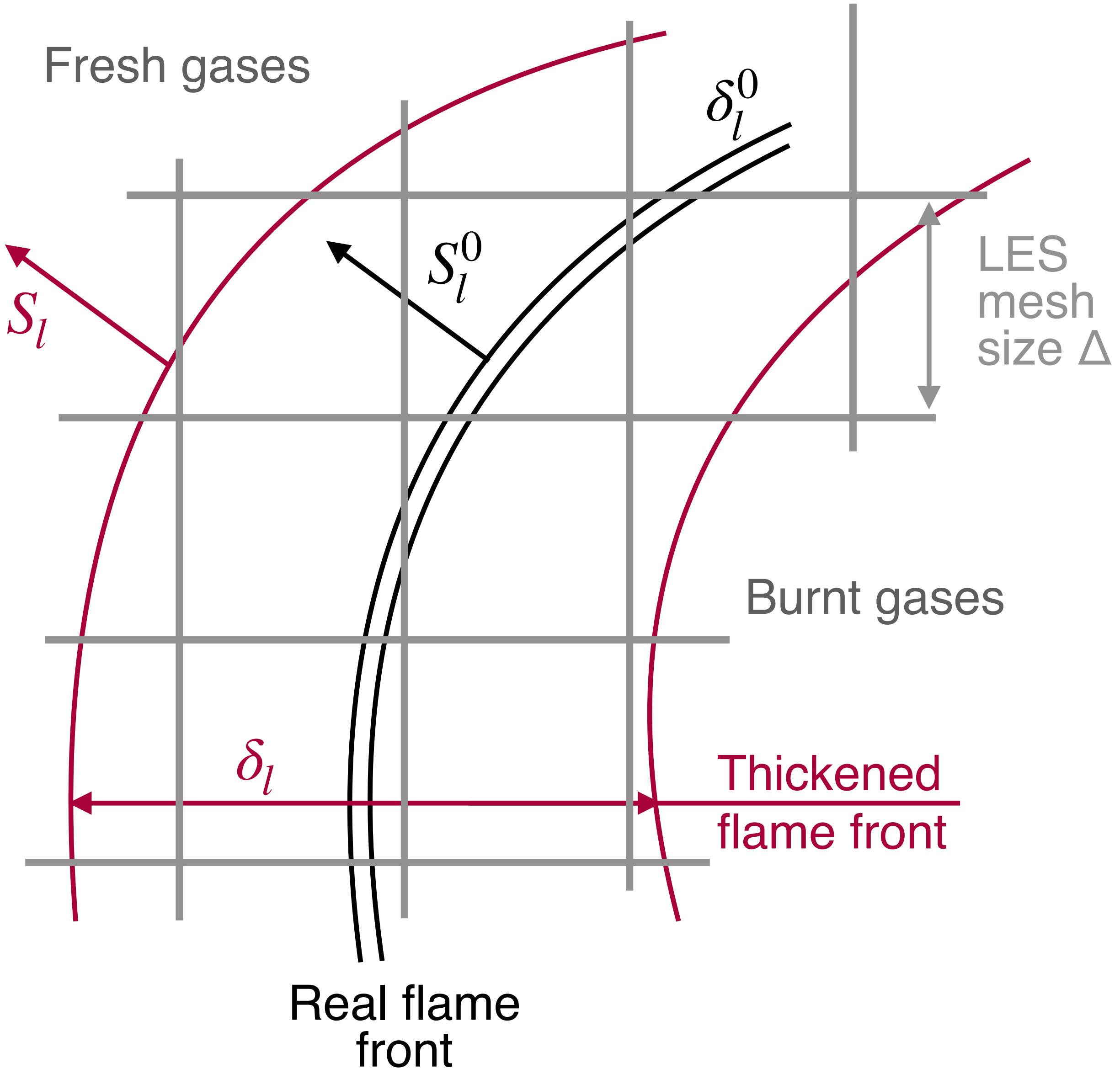
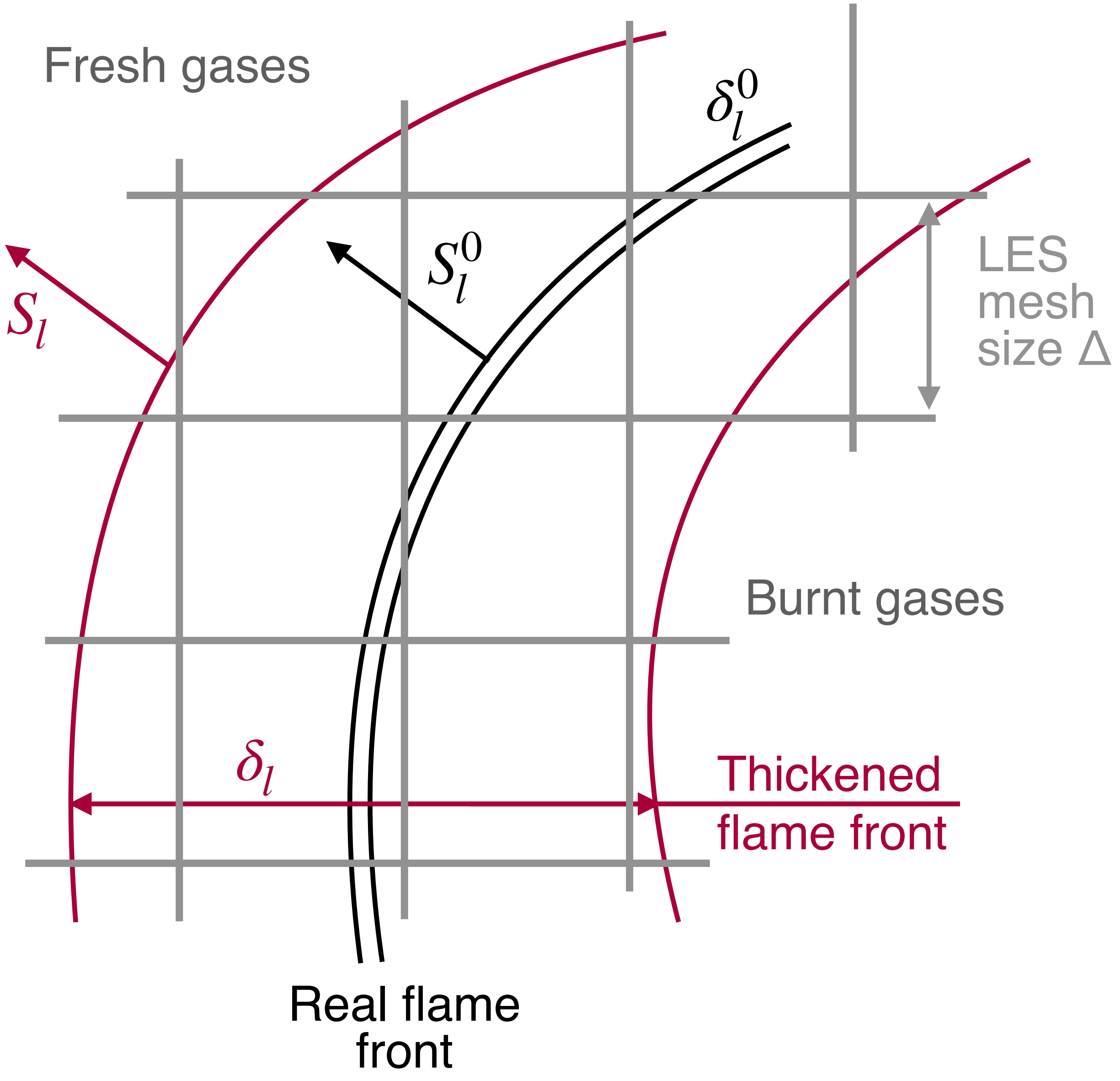


The DTFLES model artificially thicken the flame front without modifying the flow dynamic

Dynamic formulation of the TFLES model to handle **premixed** and **non-premixed** flames:

F is not constant on the domain.

Flame sensor (reaction rate) to detect where the reaction takes place.



The flame is artificially thickened to predict correctly the combustion

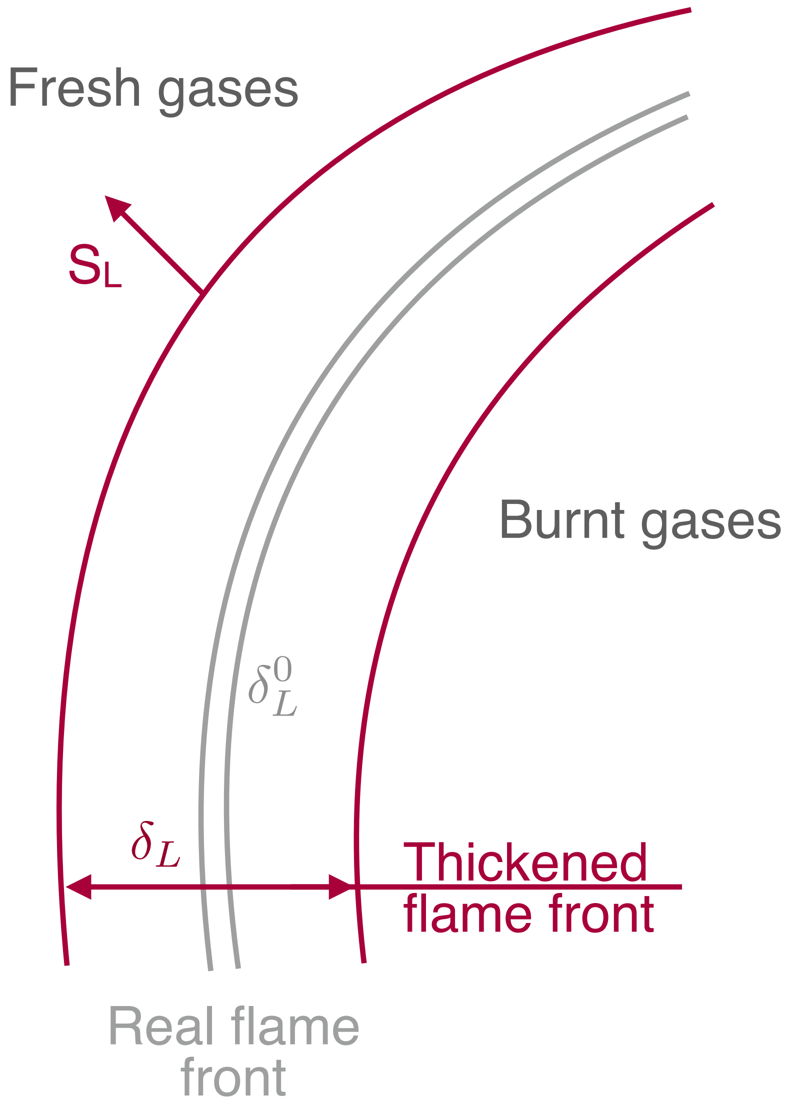
Theoretical unstrained 1D laminar flame simulated in the same operating conditions than the considered case.

The cells size is not refined enough in the region of the flame front:

- The thermal flame thickness $\delta_L^0 = 102\mu m$
- $250\mu m \leqslant \Delta \leqslant 1000\mu m$

➡ The source terms of the species could be under-resolved

The flame is artificially thickened to predict correctly the combustion



TFLES model modifies the conservation equations with a thickening factor F:

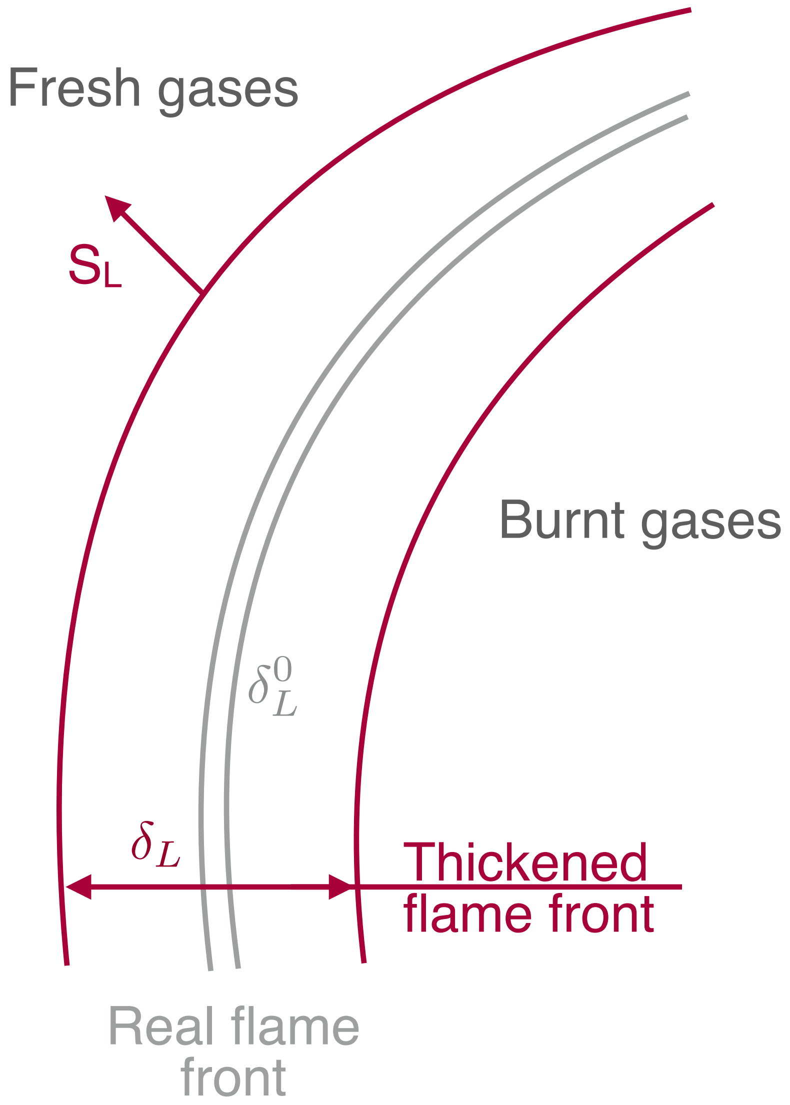
- $\delta_L = F \cdot \delta_L^0$

Thicken only the zone where reactions take place, identified by a flame sensor, and F=1 where $\dot{\omega_k} = 0$.

In the reaction zones, F depends on the ratio of the mesh size to the flame thickness, adjusted to have typically 3 to 5 points.

The flame is thickened but the laminar flame speed S_L is constant.

The flame is artificially thickened to predict correctly the combustion



TFLES model modifies the conservation equations with:

- a thickening factor F
- an efficiency function E of Charlette considering a static formulation with β=0.5

In reaction zones, both diffusivity and reaction rate are modified to ensure the flame thickening.

The flame is artificially thickened to predict correctly the combustion

$$\delta_L^0 = \frac{\Delta T}{\nabla T}\Big|_{max}$$

$$S_L^0 = \frac{\int_V \dot{\omega}_k dV}{Y_k^{out} - Y_k^{in}}$$

$$\delta_T^0 = F \cdot \delta_L^0$$

$$S_T^0 = E \cdot S_L^0$$

$$\delta_L^0 \propto \frac{D_{th}}{S_L^0} = \sqrt{\frac{D_{th}}{B}}$$

$$S_L^0 \propto \sqrt{D_{th} B}$$

Thermal diffusivity: $D_{th} \longrightarrow F \cdot D_{th} \longrightarrow E \cdot F \cdot D_{th}$

Preexponential constant: $B \longrightarrow \dfrac{B}{F} \longrightarrow E \cdot \dfrac{B}{F}$

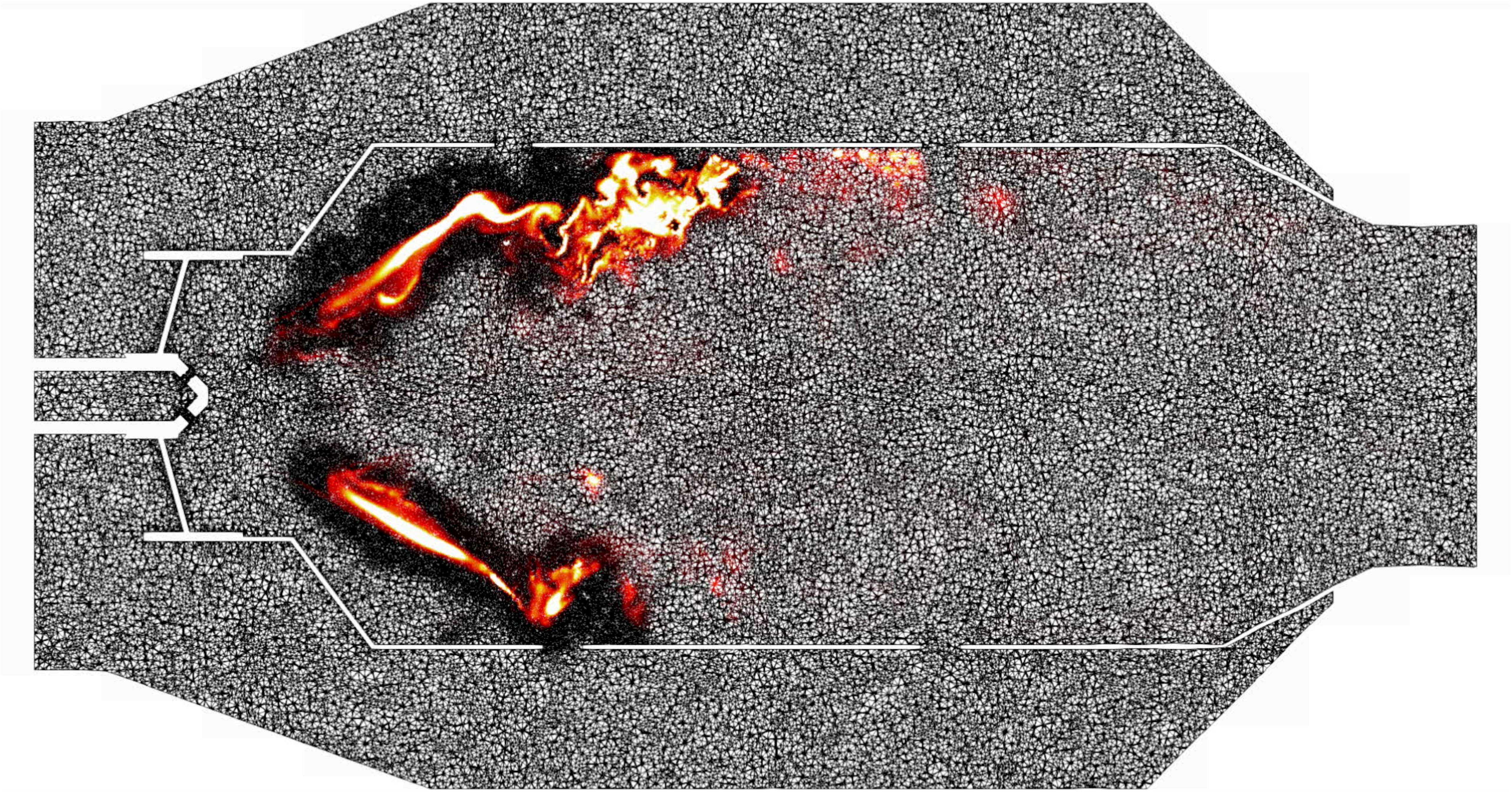
Adaptive Mesh Refinement

Appendix A

Appendix B

Flame front evolution followed by the Adaptive Mesh Refinement

Adaptation criterion based on the heat release using the flame sensor of the TFLES model.



Combustor layout of the MTT Enertwin.

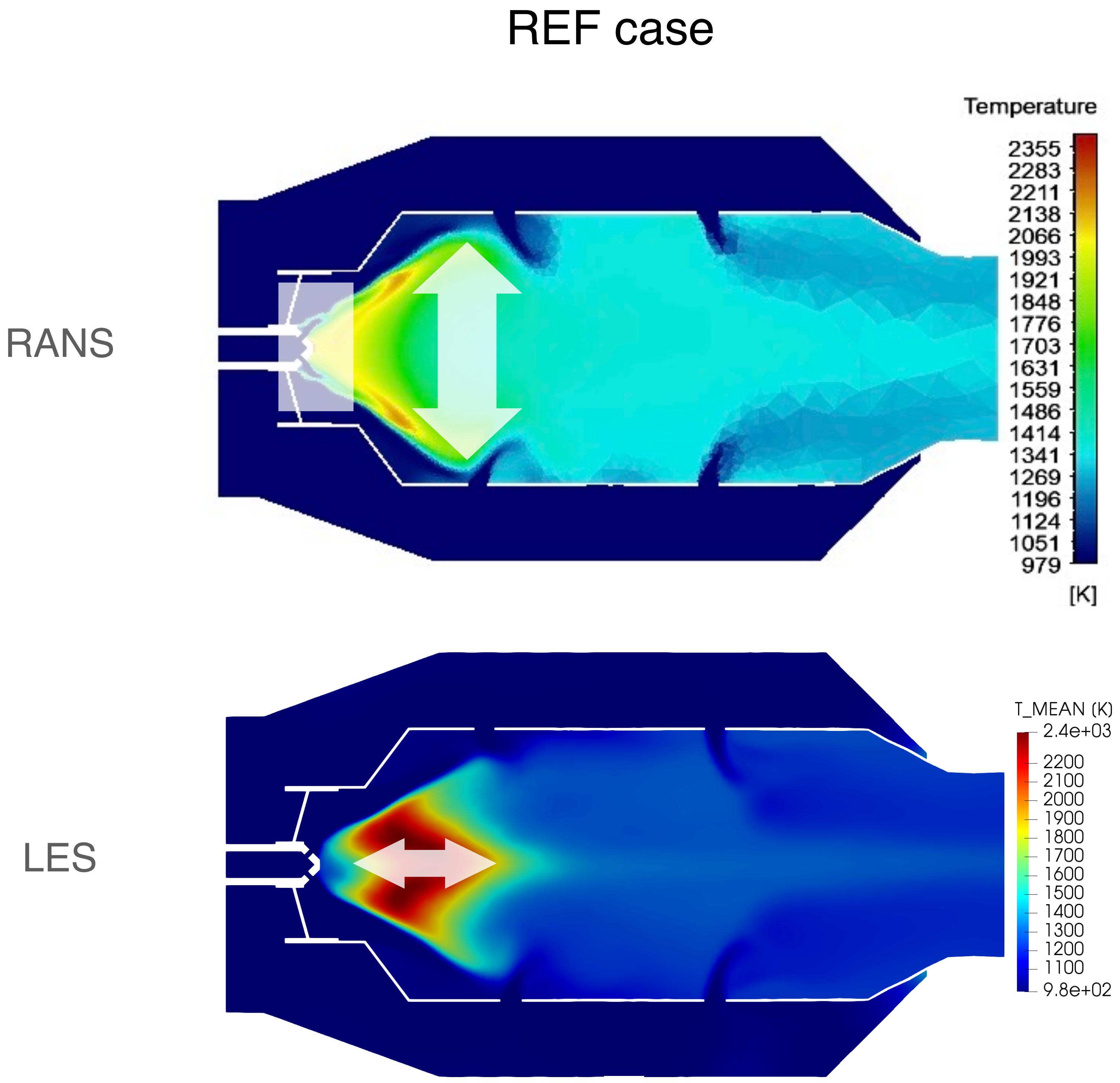
ASME Turbo Expo: GT2021-59618.

Color maps of the time-averaged temperature show higher temperature range and axial shift of the reaction area with LES

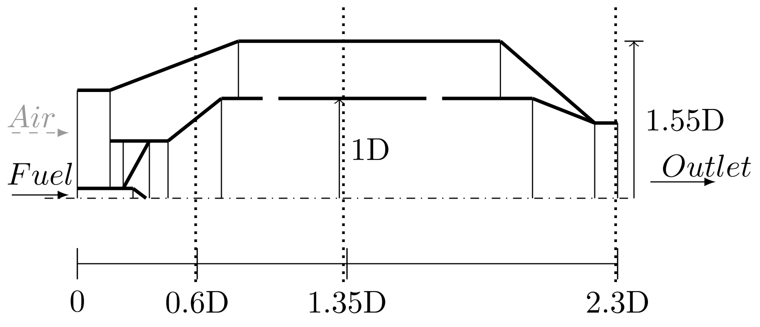
RANS predicts a larger flame with a **higher radial expansion** of the front spreading beyond the first row of dilution holes.

LES results show a more **centered peak** where this front is expanding along the centerline.

RANS shows also a more **attached** reacting region to the **fuel injector**.



LES shows higher temperature variation for the REF case while both approaches provide similar trends for the Syngas case

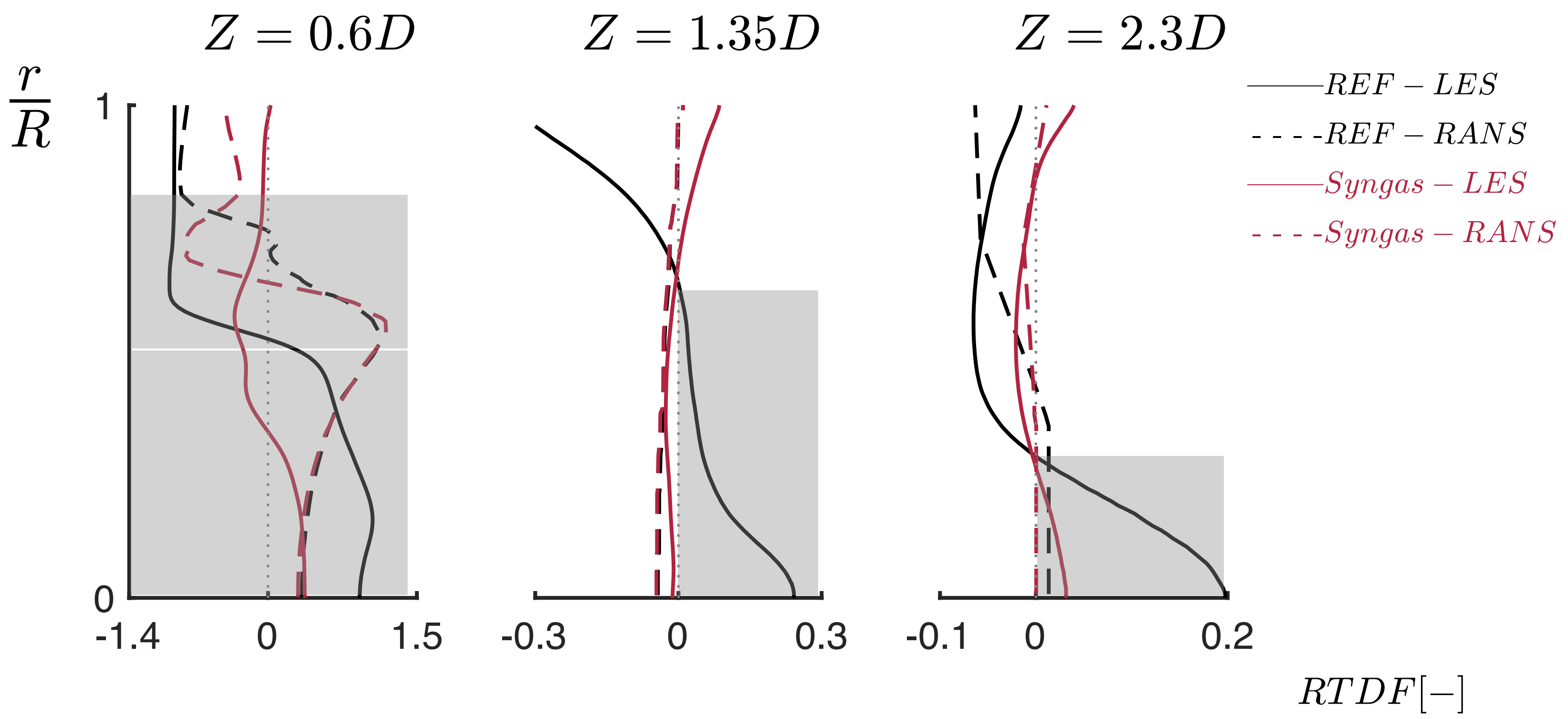


Aim of the Radial Temperature Distribution Function: quantify the radial evolution of the mean azimuthal temperature variation from the mean planar value.

Differences essentially appear for high radial positions. The peak of temperature is located closer to the centerline in LES.

- As an effect of different resolution of the swirled air injection.

Less penetrating air jet in RANS involves a radial expansion of hot products (higher temp. located at higher radial position).



Combustor outlet conditions and emissions comparison shows a slight overestimation of CO fraction with LES

	REF			Syngas	
	RANS	LES	Literature	RANS	LES
Outlet temperature $\langle \overline{T} \rangle$ [K]	1273	1268	1250 (1)	1224	1228
Y_{O_2} [%mass]	20.2	20.2	-	19.4	19
Y_{CO_2} [%mass]	2	2	-	4.6	4.6
Y_{CO} [ppm$_{mass}$]	75	94	50 (2)	37	65
Y_{NO_x} [ppm$_{mass}$]	5.5	-	1 (2)	2	-

(1) Visser et al., J.of Eng. for Gas Turbines and Power, 2011, 133 (pp. 042301-1-8)

(2) MTT Enertwin CHP system: specifications

Adaptive Mesh Refinement implemented and adapted to combustion cases

Dynamic adaptation **in the flame region** all along the simulation.

Refinement **criterion** based on the flame sensor (**reaction rate**) of the DTFLES model.

Metric size defined in the flame and the background

Triggering adaptation: **Error metric-based** (from the defined interface and background metrics).

$$\epsilon = \max\left(\left|\frac{M_{current} - M_{target}}{M_{target}}\right|\right)$$

Dynamic mesh adaptation aims to automatically refine flame region over time

Refinement criteria based on Flame sensor

S=1 into flame front (stiff reaction zone)

S=0 downstream (slow reactions) and upstream the flame (thermal diffusion zone)

$$\dot{\omega}_c = \dot{\omega}_{CO_2} + \dot{\omega}_{CO} + \dot{\omega}_{H_2O}$$
$$S = 1 \ if \ \dot{\omega}_c > 0.1 \ max(\dot{\omega}_c)$$
$$S = 0 \ else$$

Target Metrics

Interface metric = 1mm

Background metric = 5mm

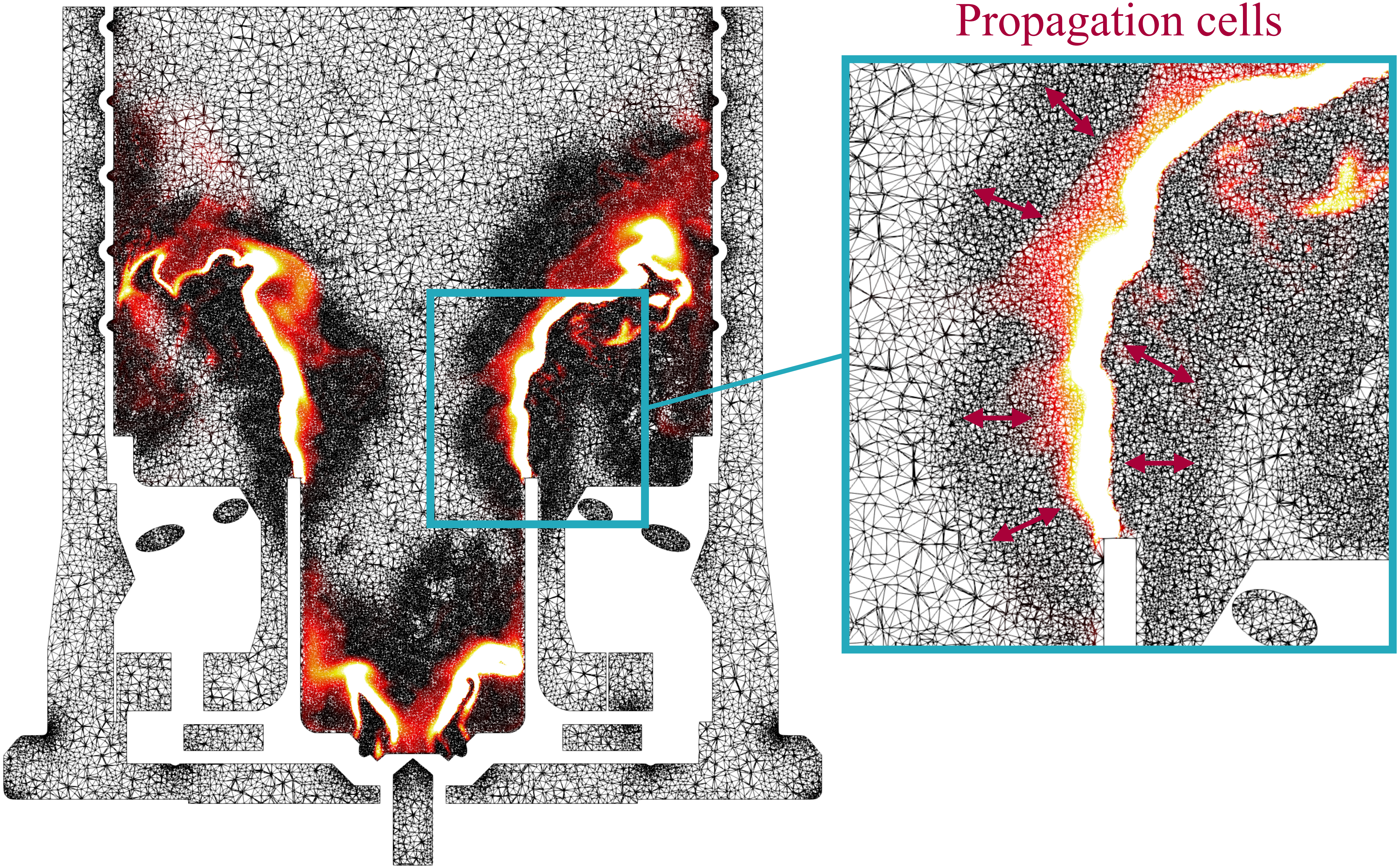
Triggering adaptation

Depend on flow dynamics ←

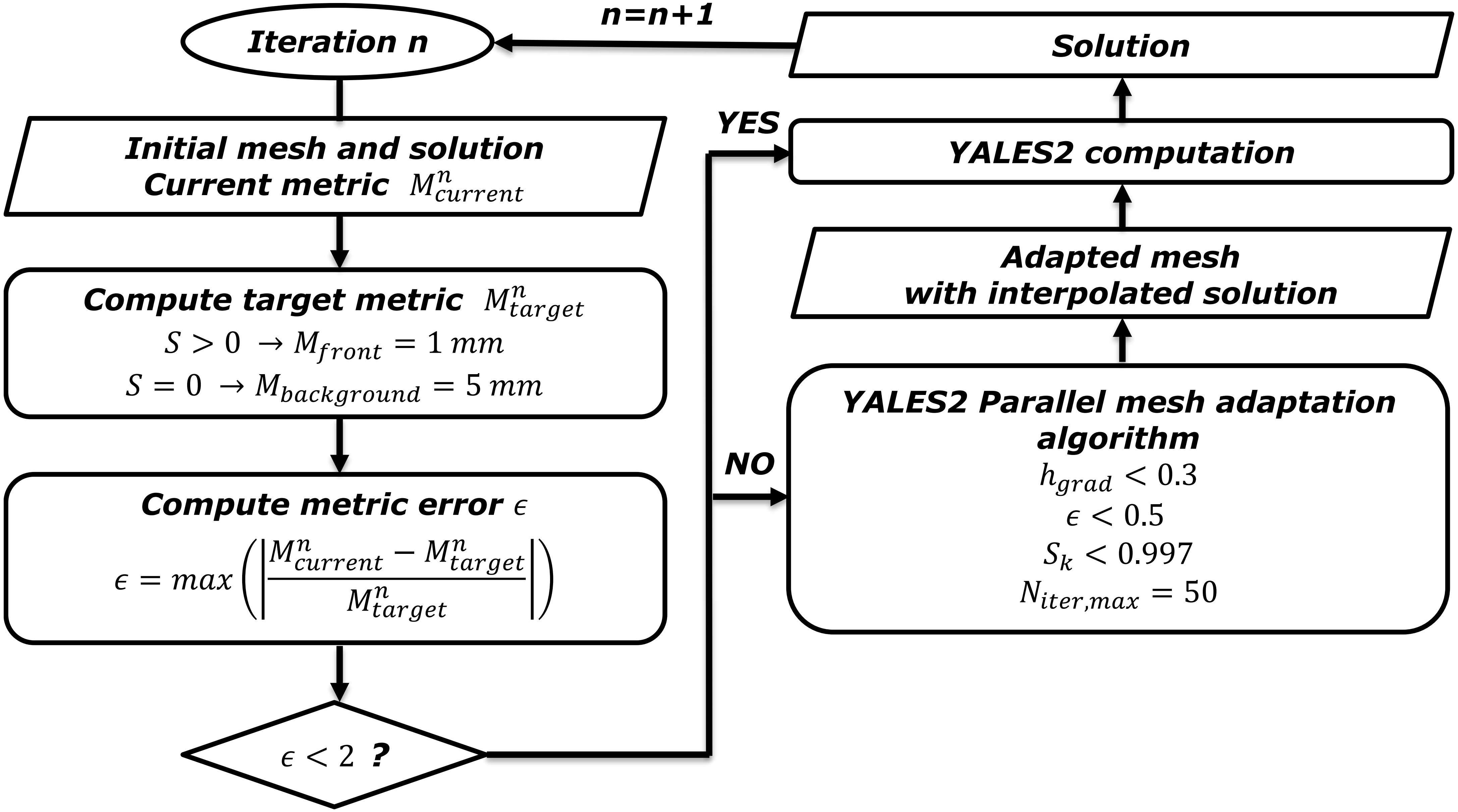
~~Time period based (triggered at each Δt)~~

Error metric-based (triggered at each $\varepsilon > \varepsilon_{max}$)

Propagation cells to prevent fluctuations and avoid unnecessary re-meshing



Mesh adaptation procedure ensures a refined mesh in flame region before computation at each iteration



Iteration n

n=n+1

Solution

Initial mesh and solution
Current metric $M^n_{current}$

Compute target metric M^n_{target}
$S > 0 \rightarrow M_{front} = 1\,mm$
$S = 0 \rightarrow M_{background} = 5\,mm$

Compute metric error ϵ

$$\epsilon = max\left(\left|\frac{M^n_{current} - M^n_{target}}{M^n_{target}}\right|\right)$$

$\epsilon < 2$ **?**

YES

YALES2 computation

Adapted mesh
with interpolated solution

NO

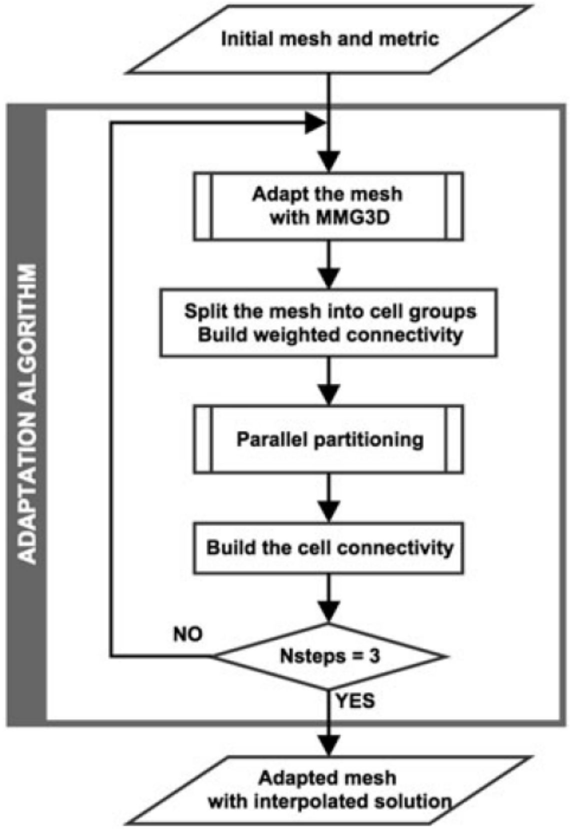
YALES2 Parallel mesh adaptation algorithm
$h_{grad} < 0.3$
$\epsilon < 0.5$
$S_k < 0.997$
$N_{iter,max} = 50$

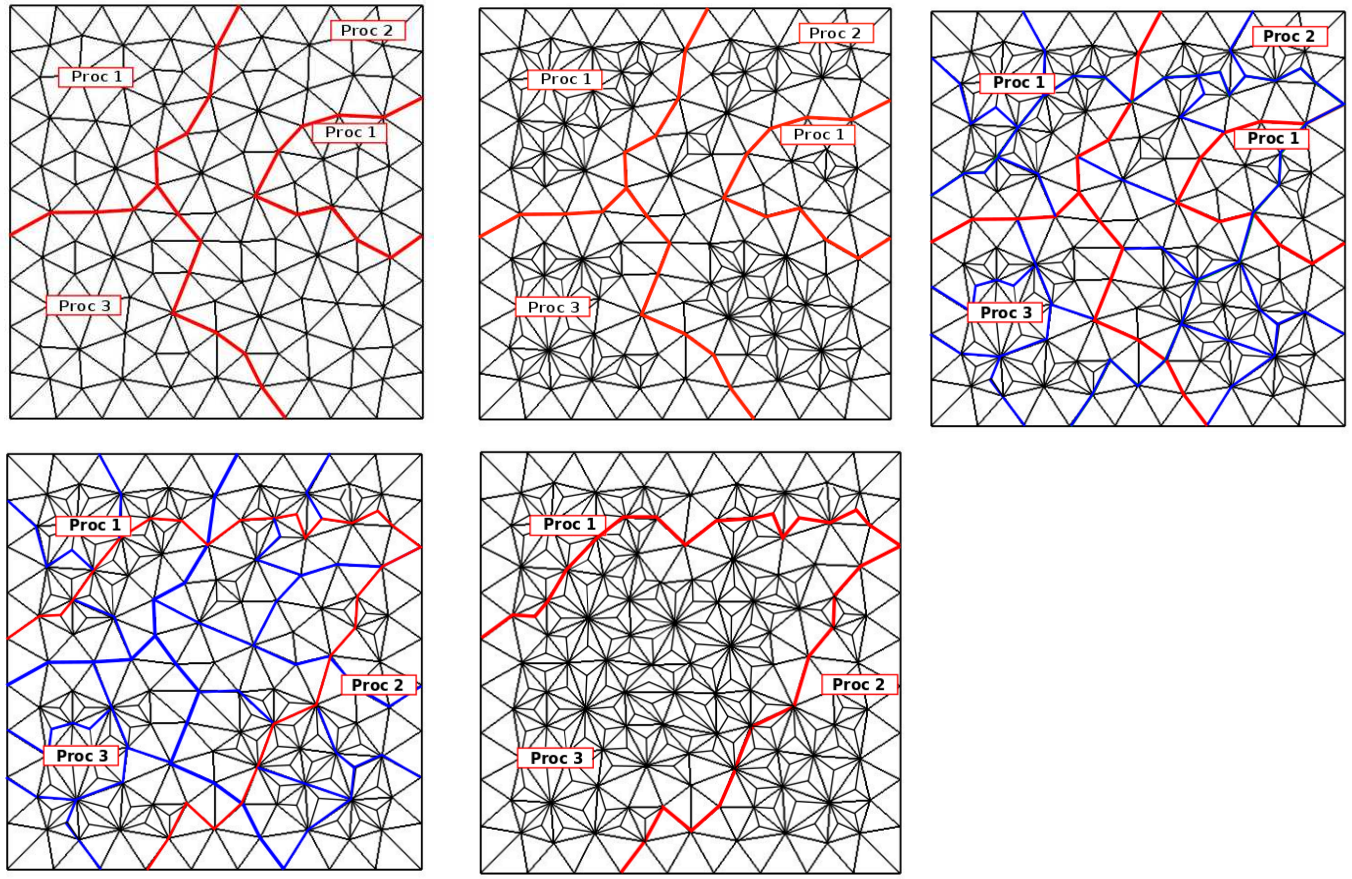
Results from the Master Thesis of Antoine Verhaeghe 2020

The coupling between YALES2 and MMG3D allows the mesh to be adapted over the entire domain

MMG3D library: adaptation and optimisation of tetrahedral meshes

Problem : MMG3D does not allow remeshing on boundaries





Results from the Master Thesis of Antoine Verhaeghe 2020

Operational flexibility

Fuel flexibility

Simplified mGT layout

mHAT

Dry EGR

Wet EGR

3 diluted cases compared to

Typical NG combustion

Energy (2022), EGY-123446

$50\%_{vol}\ H_2 + \Omega = 10\%$

$\simeq$

$100\%\ CH_4$

J. of Eng. for Gas Turbines and Power (2021), GTP20-1620

Tool developments

Adaptive Mesh Refinement

LES >< RANS (justify LES)

0D CRN / 1D Flame predet.

Tool developments

Adaptive Mesh Refinement

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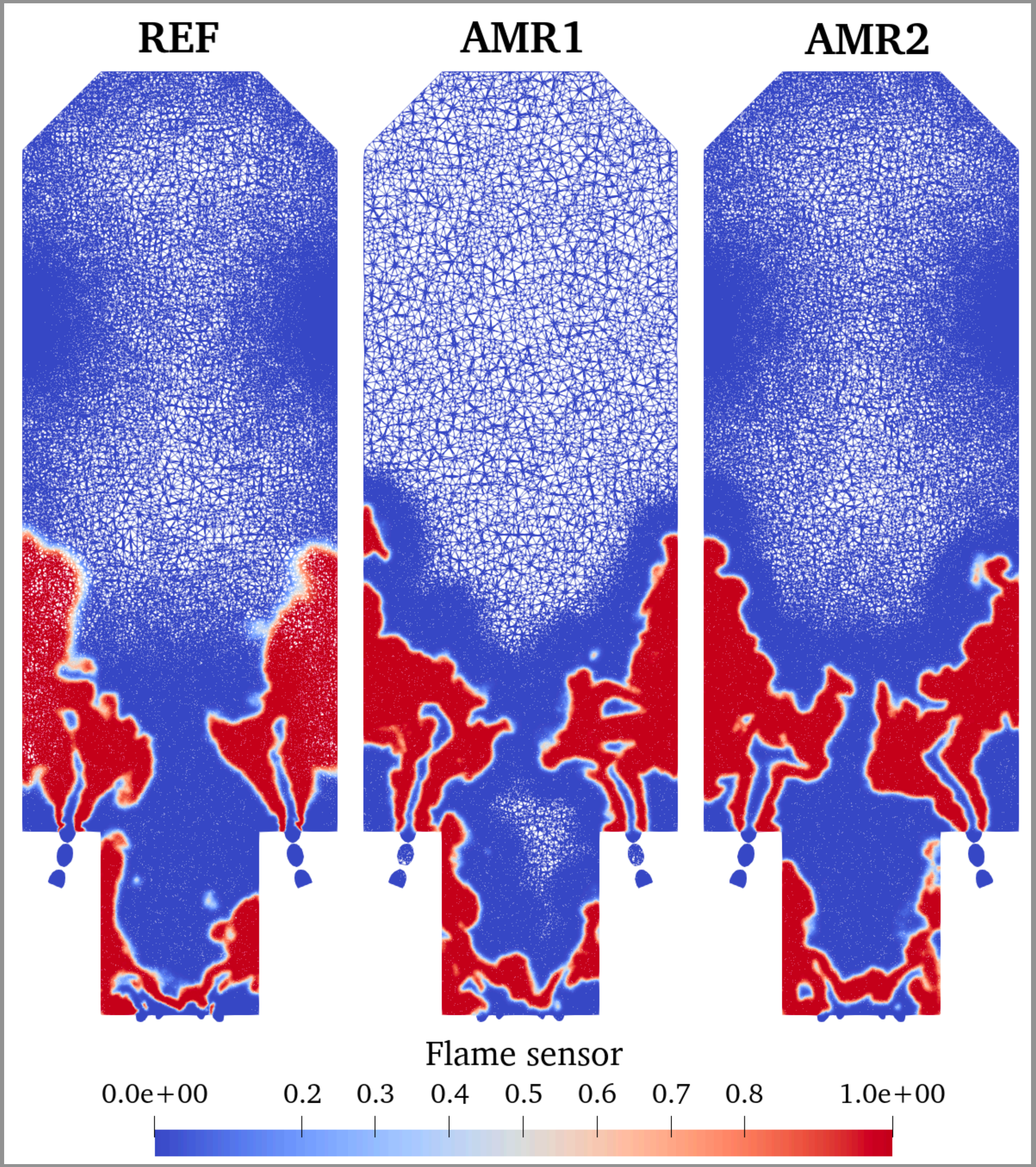


Dynamic adaptation **in the flame region** all along the simulation.

Refinement **criterium** based on the flame sensor (**reaction rate**) of the TFLES model.

Triggering adaptation: **Error metric-based** (from the defined interface and background metrics).

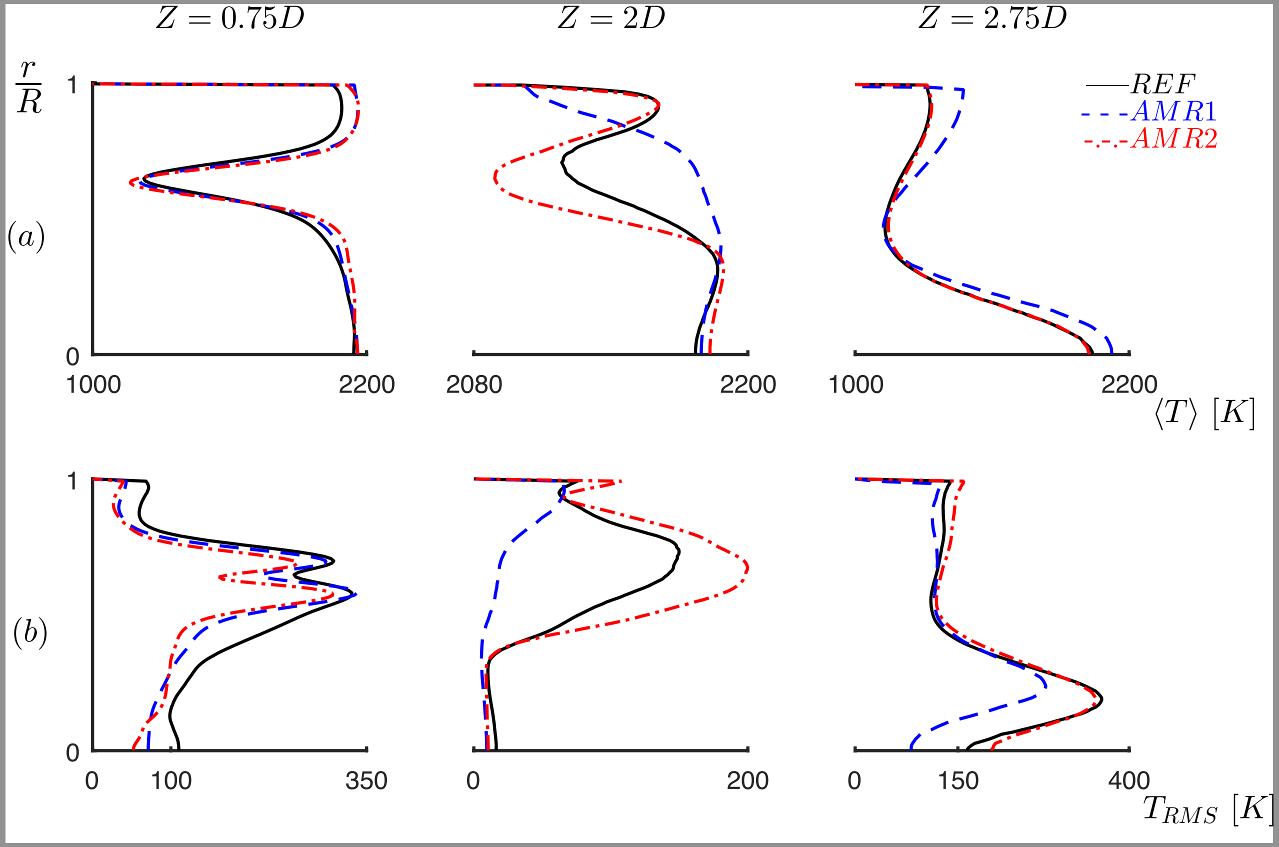
REF: Initial mesh with a typical distribution - 33*10^6 cells

AMR1: Flame region refinement only - 19.6*10^6 cells

AMR2: Initial mesh + flame region refinement - 34.5*10^6 cells

Draft ready for submission to *Computers & Fluids*

Adaptive Mesh Refinement



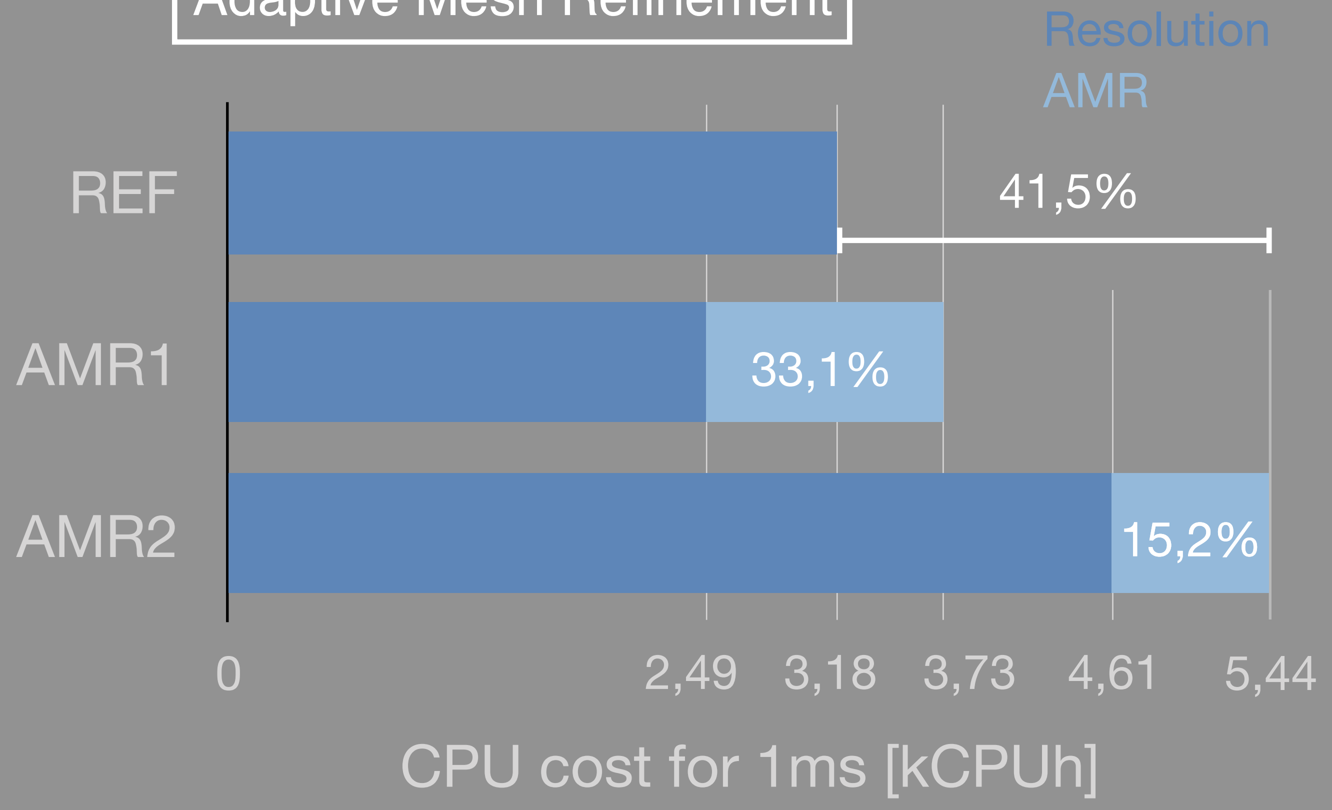
	REF	AMR1	AMR2
Y_{CO} $[ppm]$	34	48	35

Main conclusions:

- Finer resolution of the flame for both AMR cases.
- AMR1 losses information after the flame.

Draft ready for submission to *Computers & Fluids*

Adaptive Mesh Refinement



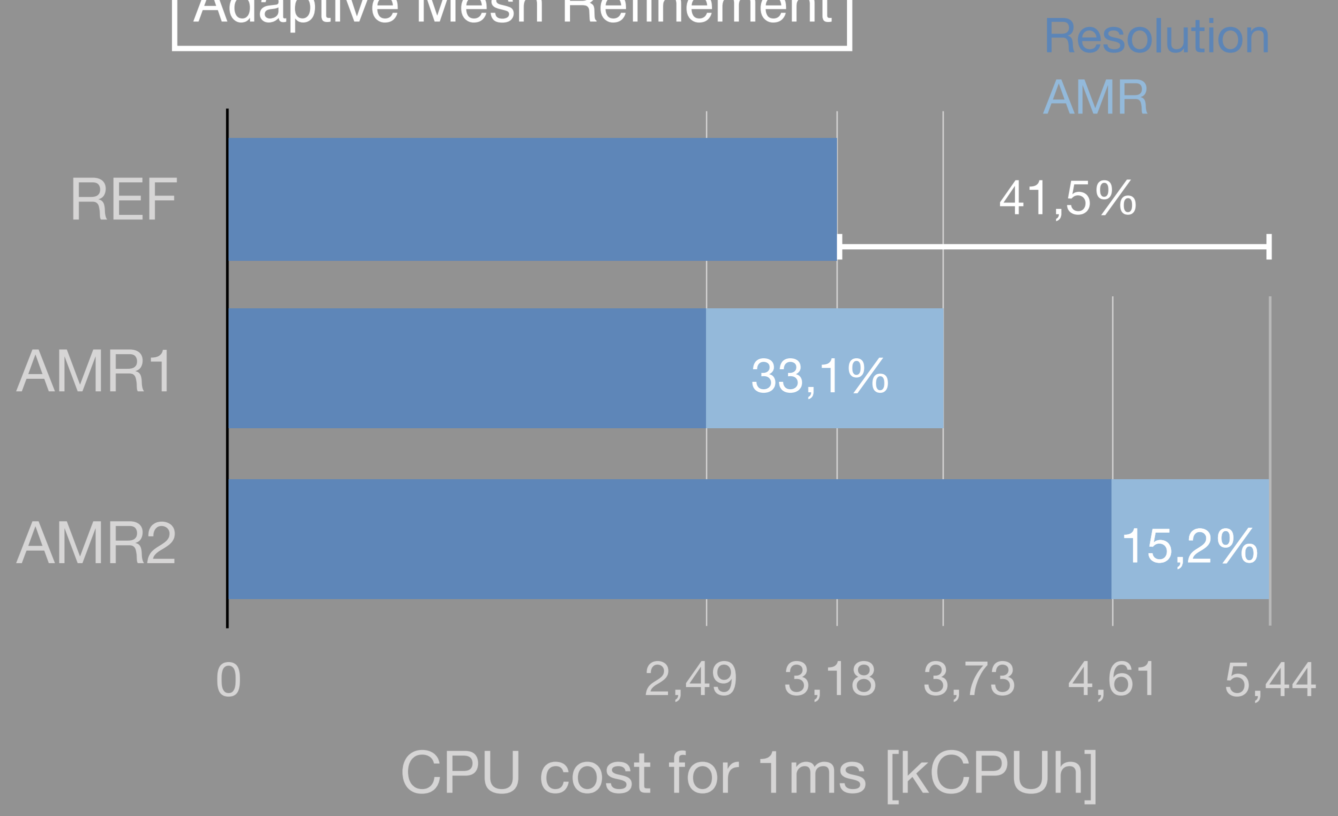
Main conclusions:

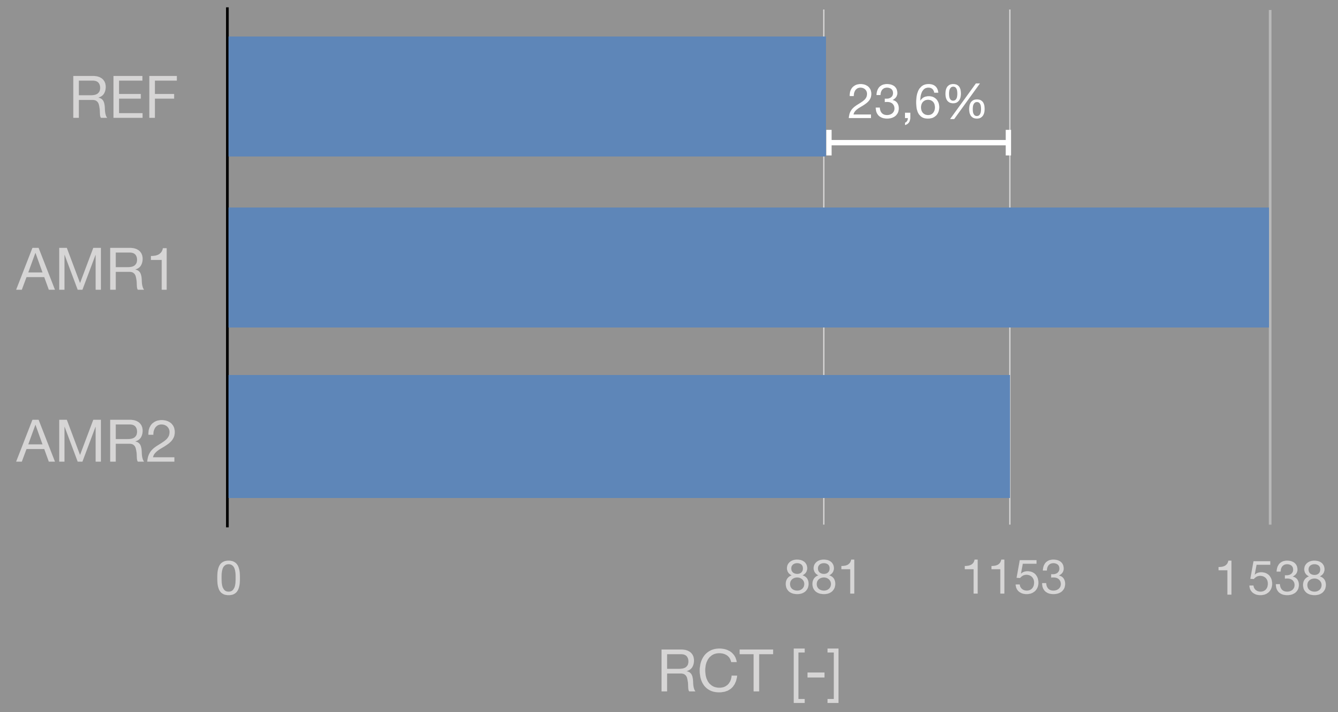
- Finer resolution of the flame for both AMR cases
- AMR1 shows a lost of information after the flame
- **Adaption** for AMR2 costs only **15.2%** of the total cost.
- AMR2 case requires **41.5%** more than the REF case.

Draft ready for submission to *Computers & Fluids*

Tool developments

Adaptive Mesh Refinement





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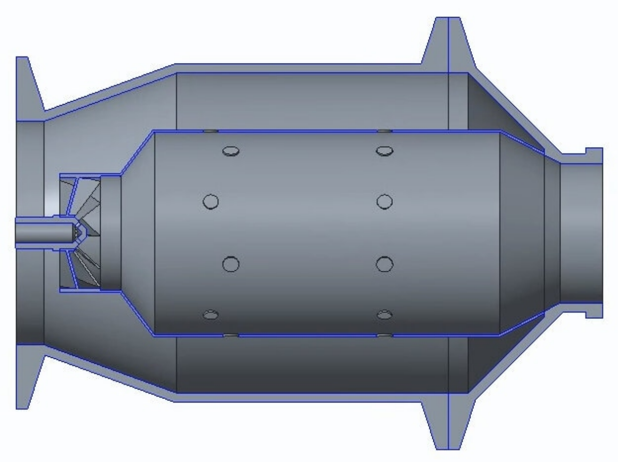
Reduced Computational Time,

$$RCT = \frac{WCT \cdot N_{CPU}}{N_{iter} \cdot N_{node}}$$

Draft ready for submission to *Computers & Fluids*

LES >< RANS (justify LES)

From collaboration with
University of Bolzano.



Aim: Justify LES in an industrial context (**RANS vs LES**).

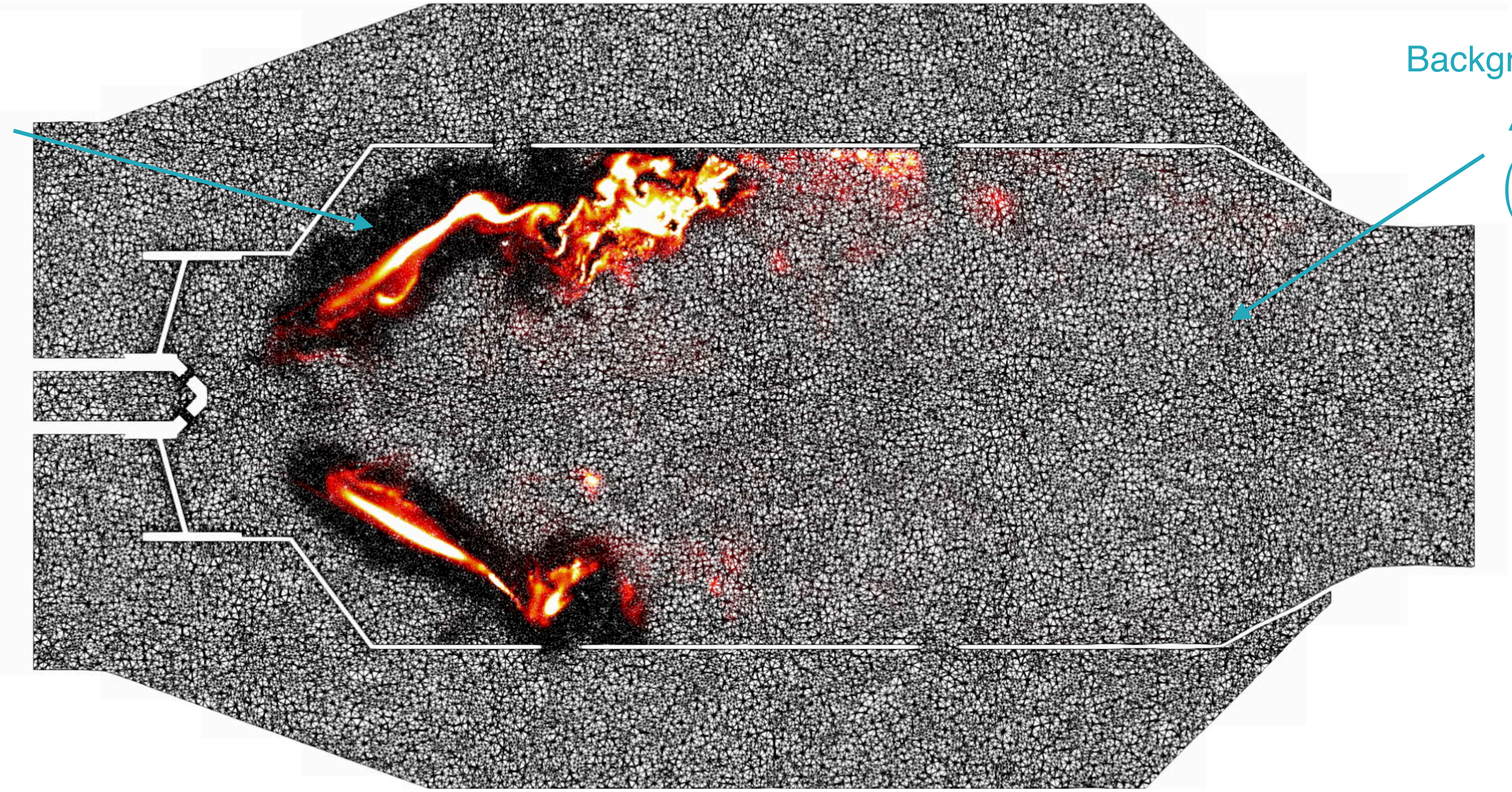
Comparison RANS >< LES on **Enertwin MTT** (3kW mGT).

LES >< RANS (justify LES)

Aim: Justify LES in an industrial context (**RANS vs LES**).

Comparison RANS >< LES on **Enertwin MTT** (3kW mGT).

AMR implemented for the LES.



Target metric

$\Delta = 4 \cdot 10^{-4} m$

$\left(\frac{\Delta}{D} = 0.0066\right)$

Background metric

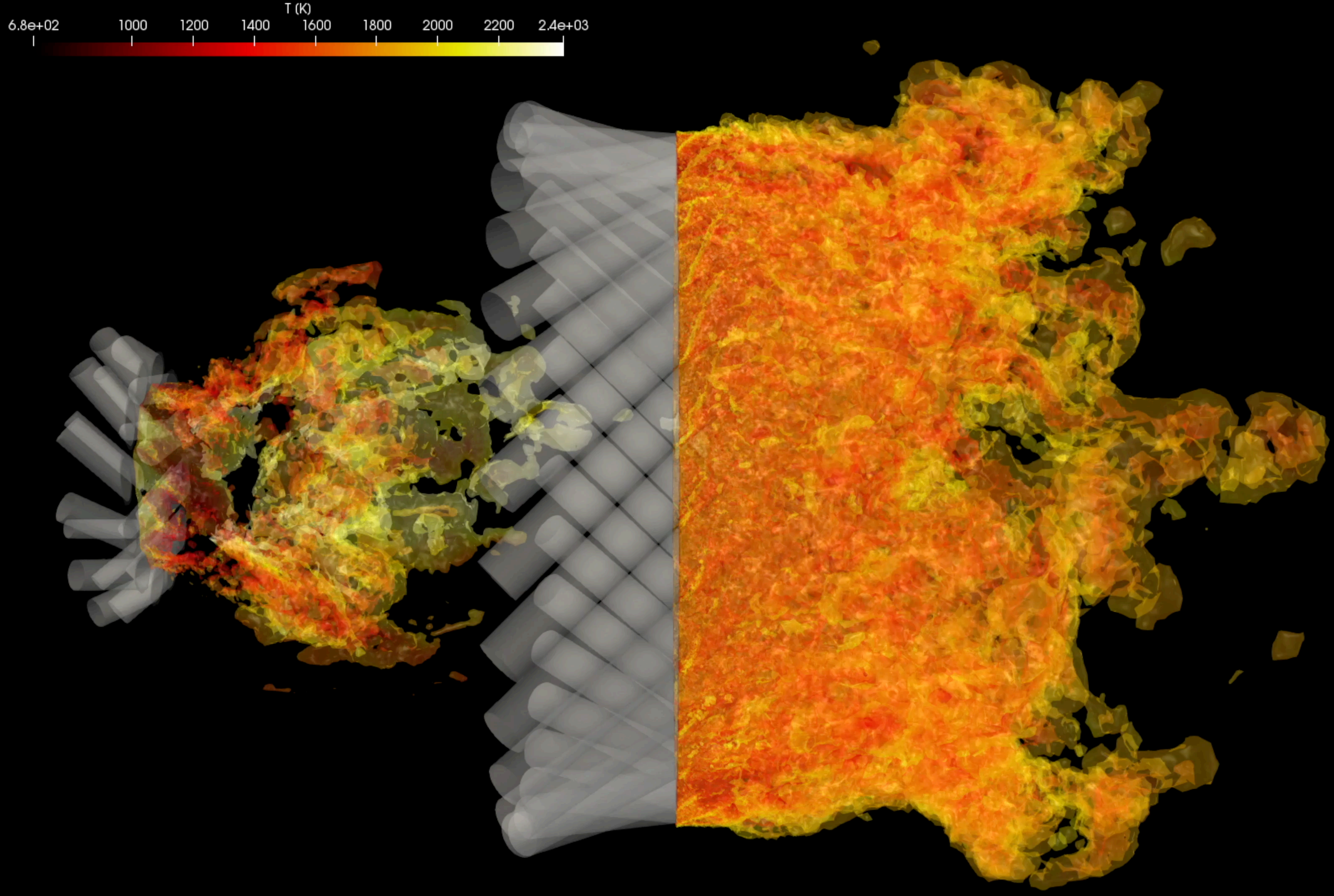
$\Delta = 10^{-3} m$

$\left(\frac{\Delta}{D} = 0.0164\right)$

Numerical set-up summary to compare both methods

	RANS	LES
Mesh cell number (x 10^6)	6.3	25
CFD code	ANSYS Fluent 19.1	YALES2
Turbulence model	k-ε Realizable	Sub-grid scale stresses model: Dynamic Smagorinsky
Combustion model	Partially Premixed with diffusion FGM	Complex chemistry + TFLES model
Kinetic scheme	DRM19	DRM19
Heat losses	Adiabatic condition	Adiabatic condition
Total CPU cost	480 CPUh for REF 1200 CPUh for Syngas	70560 CPUh for each case

Flame fronts of the reference case highlighted by the reaction rate iso-surface



Simplified layout of the Turbec T100.