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Reacting Flows in Industrial Duct-burners of a Heat Recovery Steam Generator

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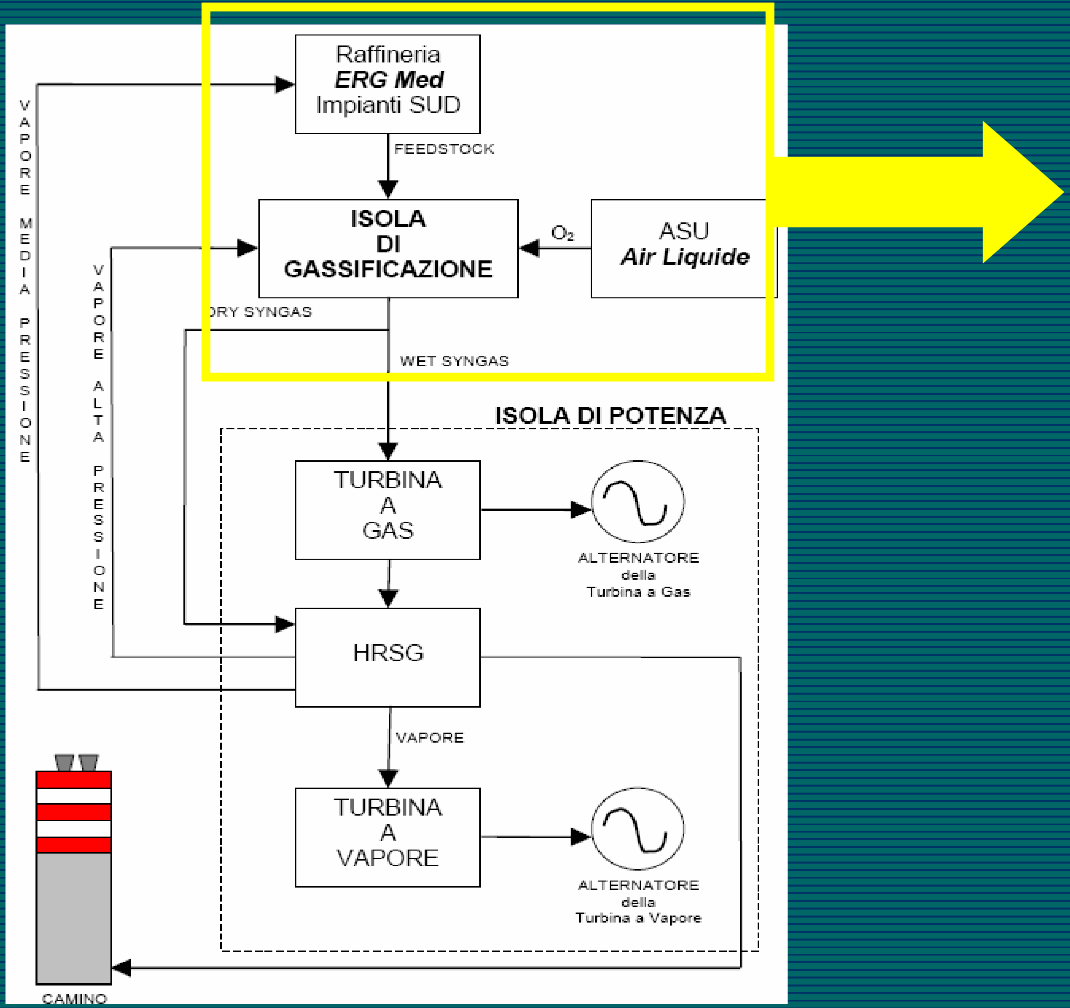
Motivation

Technological inconveniences concerning maintenance of the post-firing section of a Heat Recovery Steam Generator (HRSG) of an Integrated Gasification Combined Cycle (IGCC) power plant

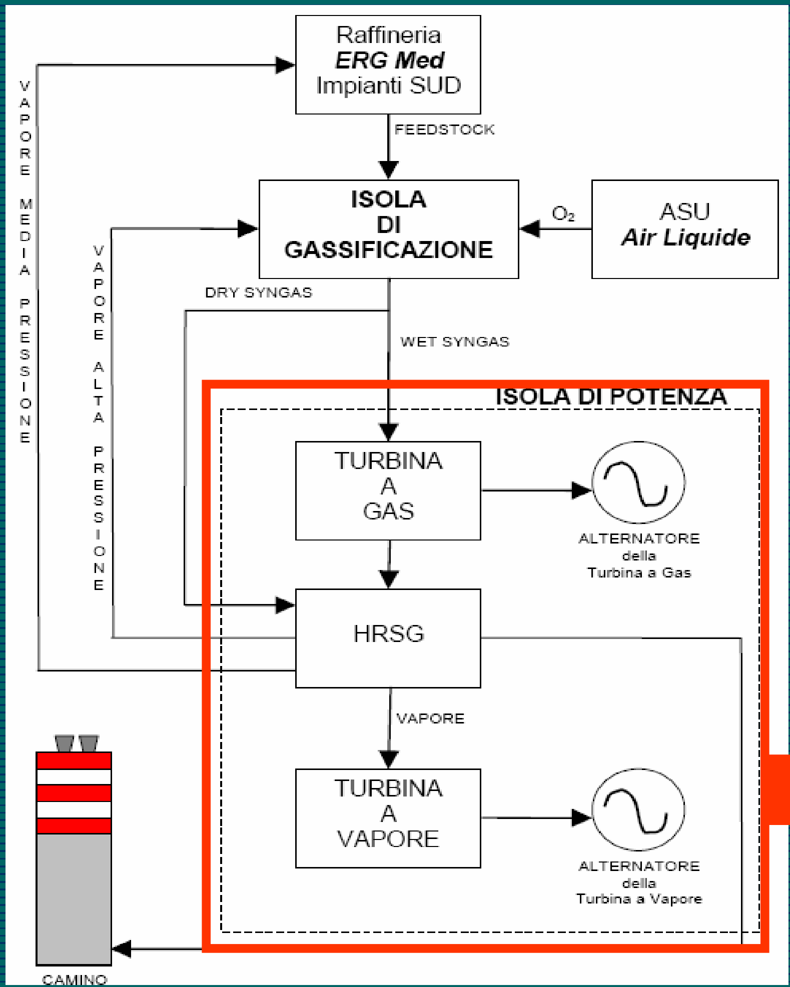
Layout of an IGCC power plant



Gasification Island

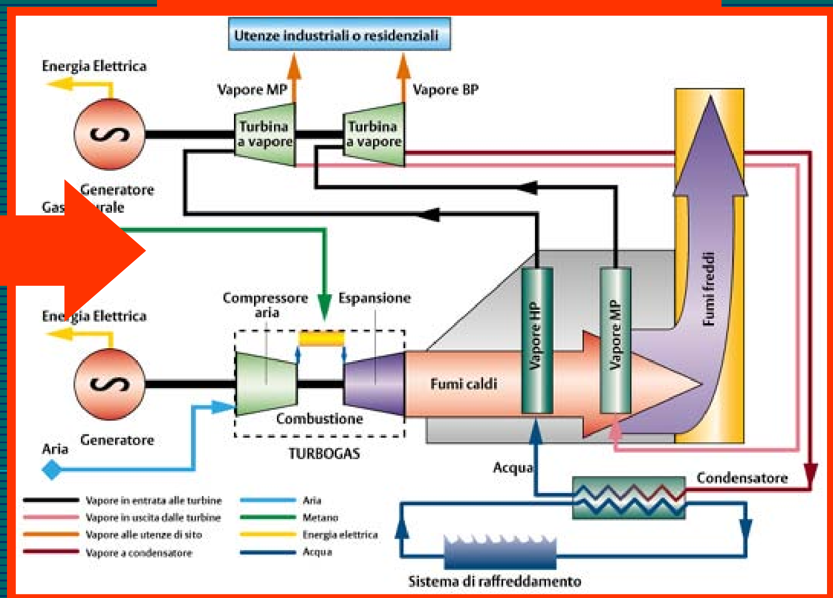
A synthesis gas is produced by oxidising coal or waste products coming from petroleum distillation processes

Layout of an IGCC power plant

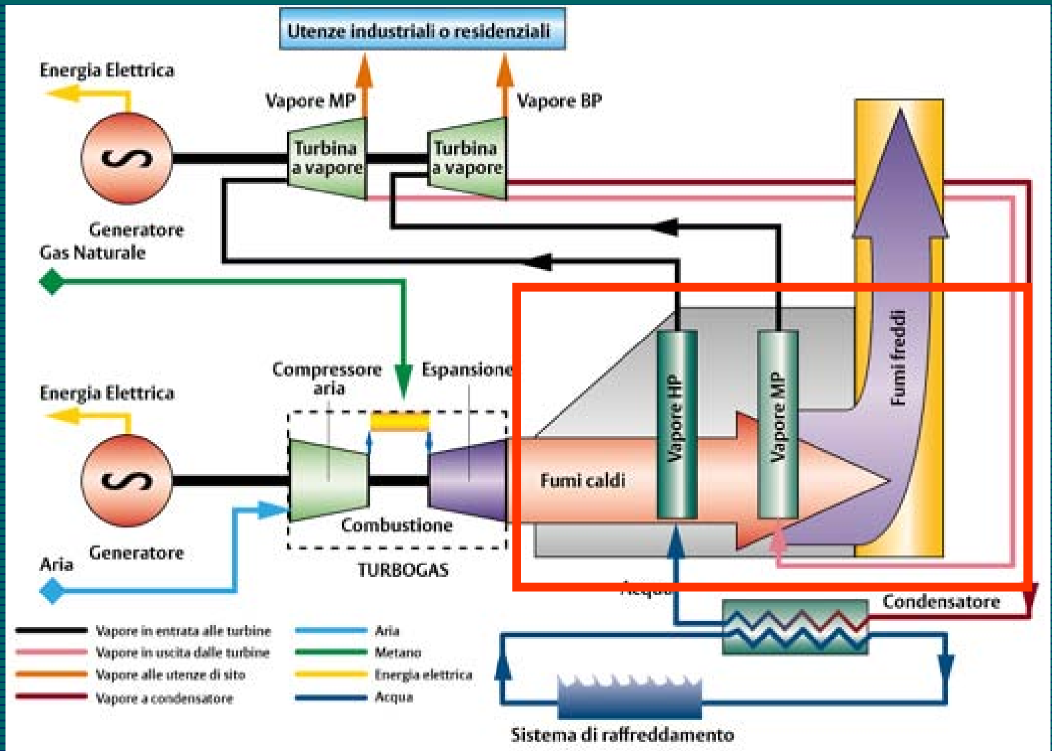


Syngas powers gas turbines that provide hot exhaust gases (Turbine Exhaust Gas, TEG) to a Heat Recovery Steam Generator (HRSG), producing working fluid for steam turbines

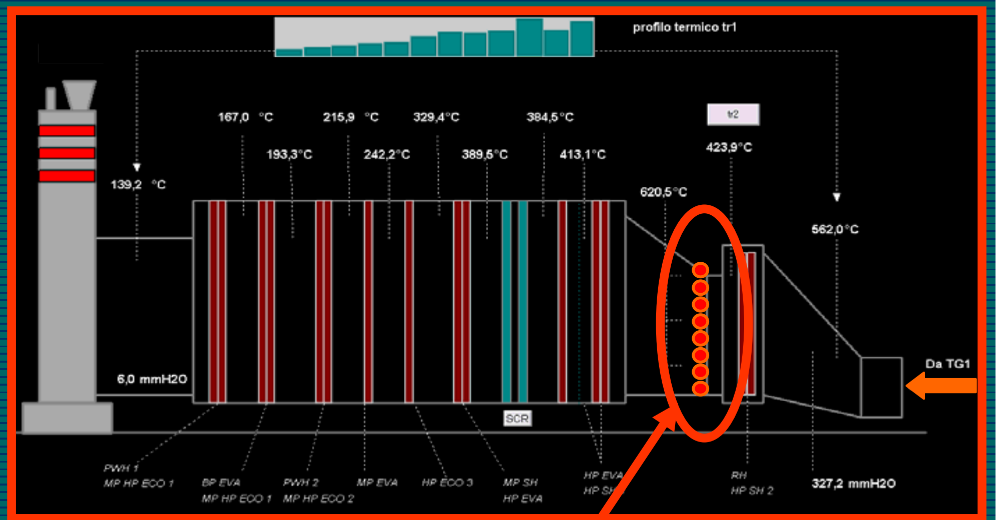
Power Island



The Heat Recovery Steam Generator

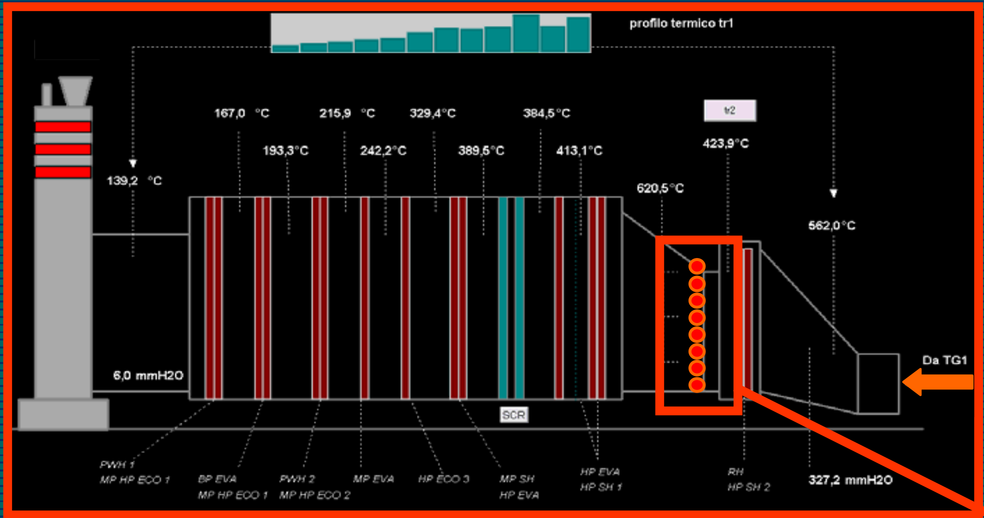


Very often the HRSG is equipped by a post-firing section, in order to balance losses in efficiency of the gas turbines (hotter season)



Post-combustion section

After-burners



The post-firing section consists in arrays of duct-burners, mounted on horizontally arranged pipes providing fuel by transversal nozzles

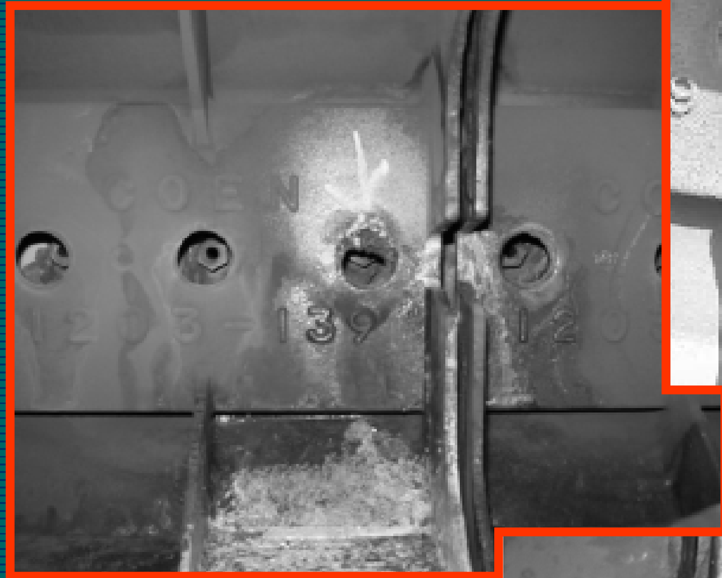
What is the problem ?

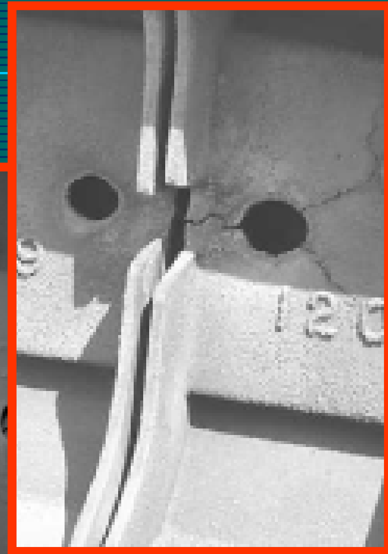
Duct-burners operative conditions are affected by fuel composition: gas impurities (Ni-carbonyl) becomes unstable at temperature above about 700 K, depositing metallic Ni on the burner contour.

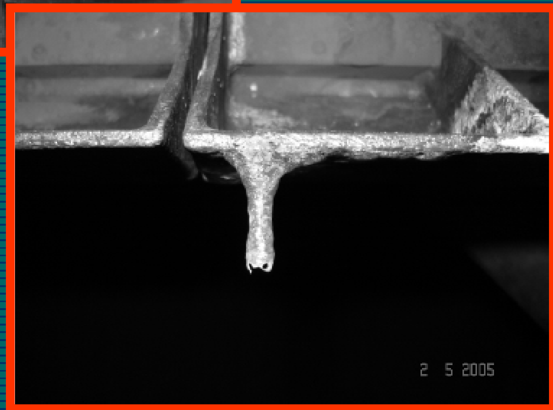
It has been observed as high deposit thickness enables overheating, unusual thermo-mechanical stress and then cracking of the components.

The burners must be periodically cleaned to restore safe operating condition, imposing expensive plant stops.

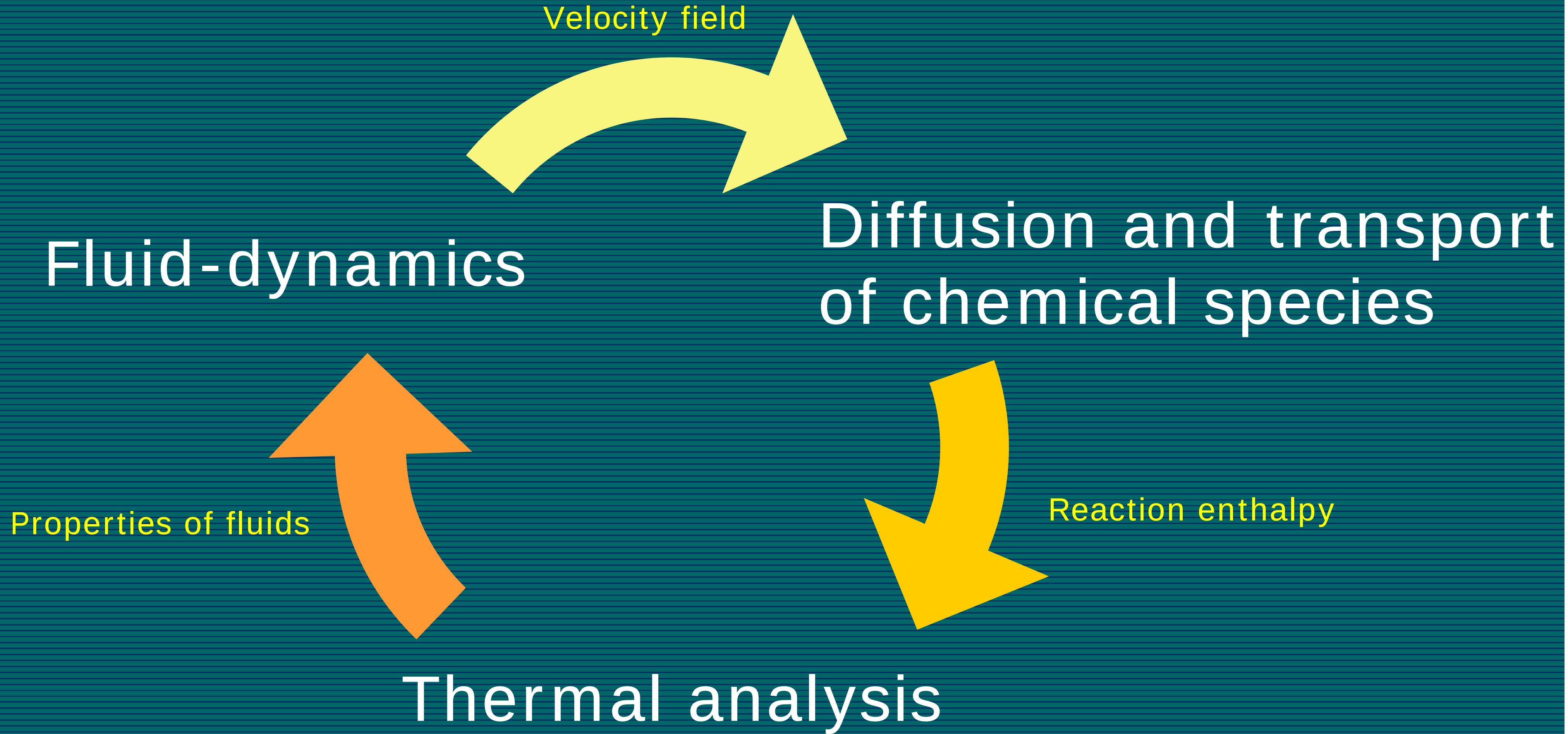
This is a problem !



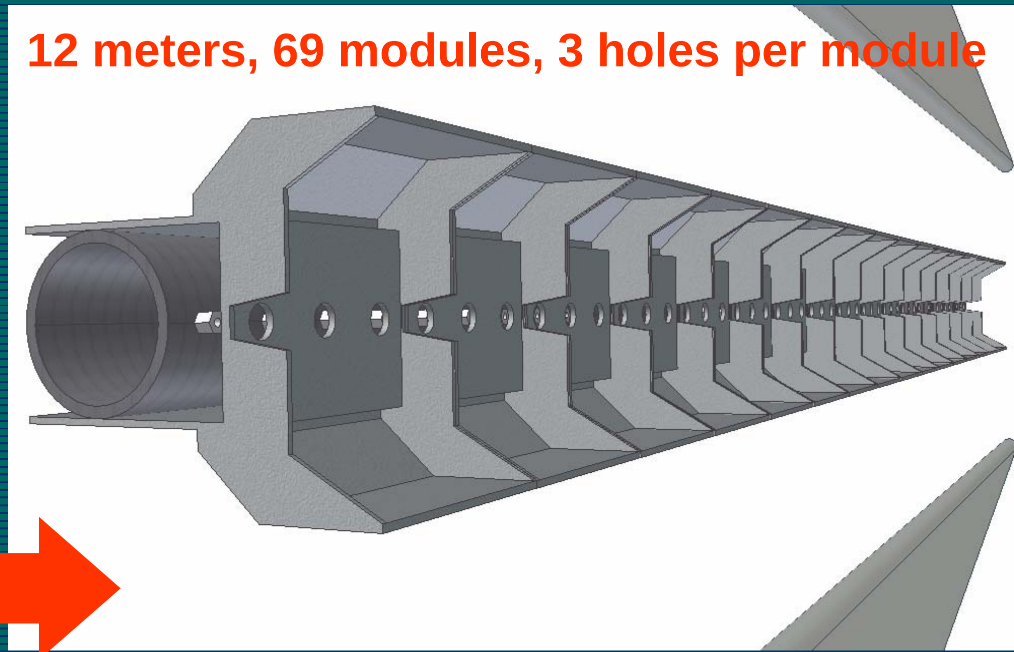




A multi-physical problem ...



Duct-burner array characterization



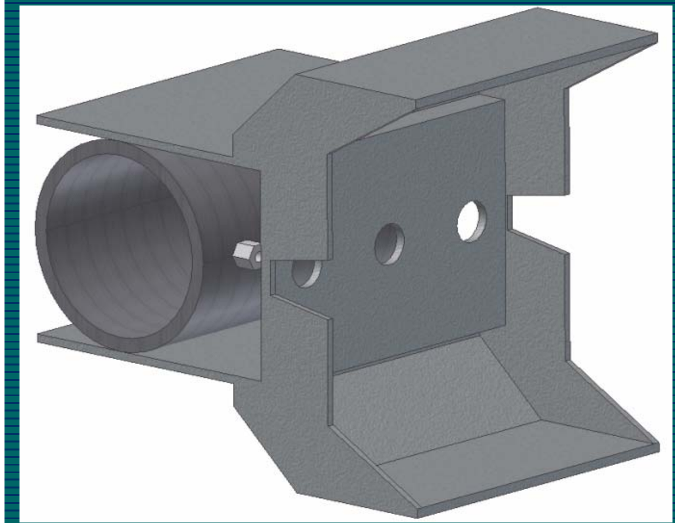
89 MW_{th} - 133 MW_{th}

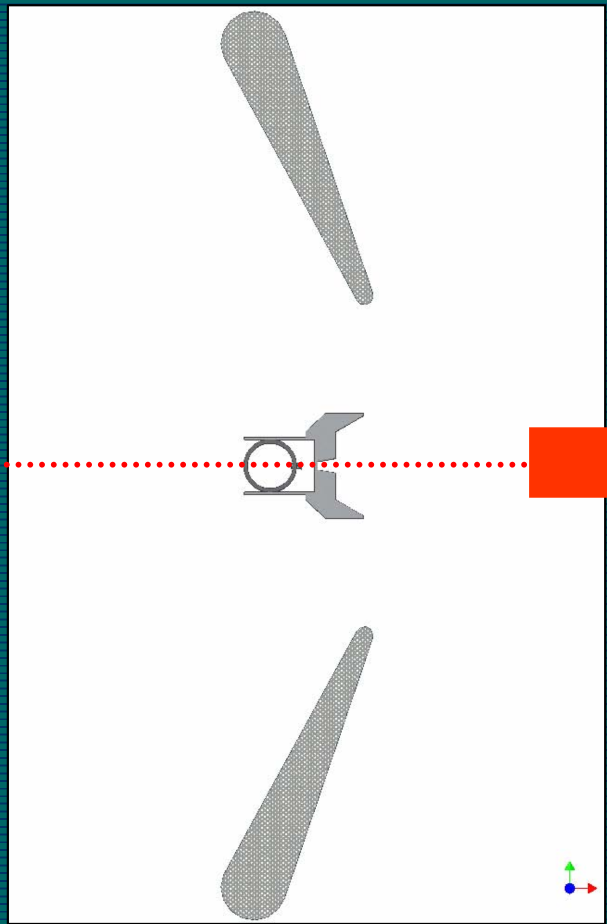
0.8 – 1.2 MW_{th}/m

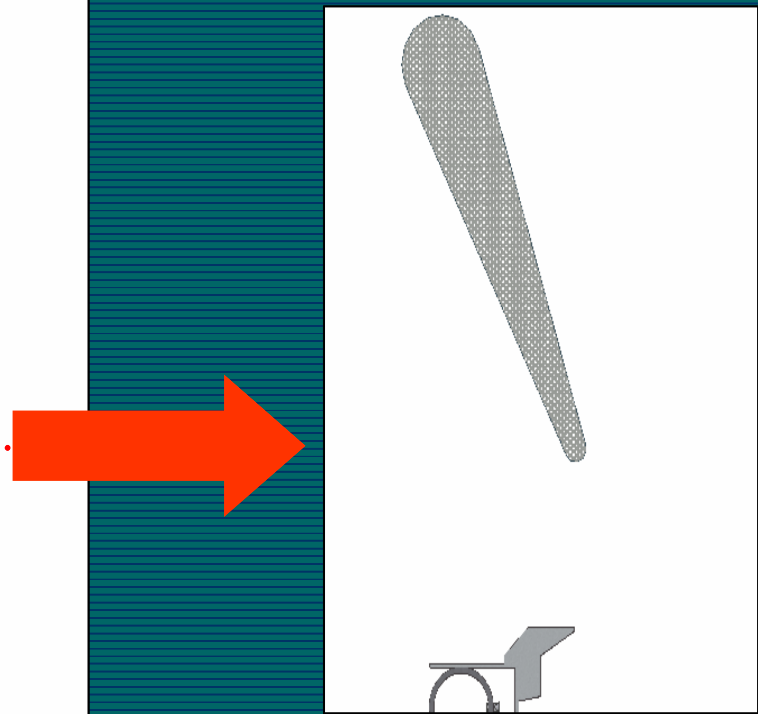
"On design"
(100% thermal power)

"Turn down"
(150% thermal power)

Numerical model

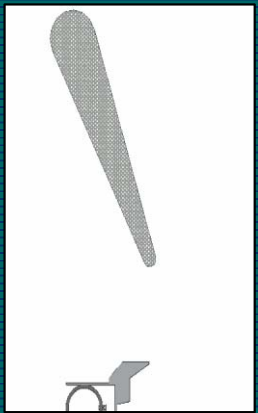


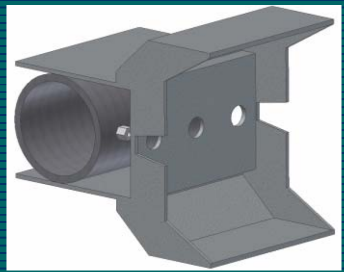


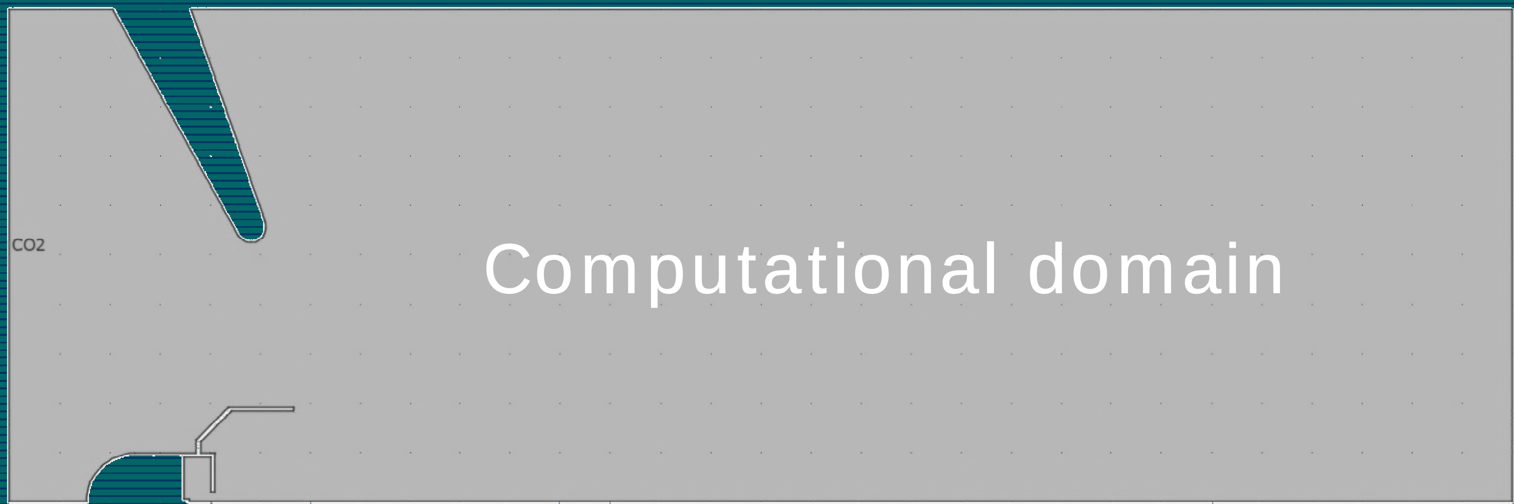


One half section of the burner is considered both in 2D and 3D simulations

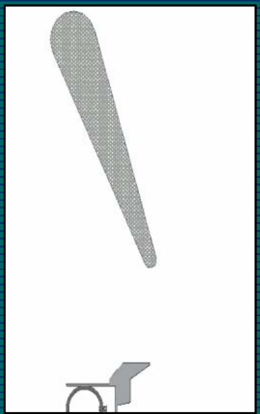
Numerical model

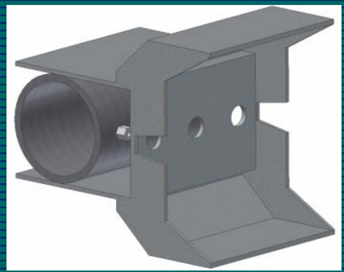


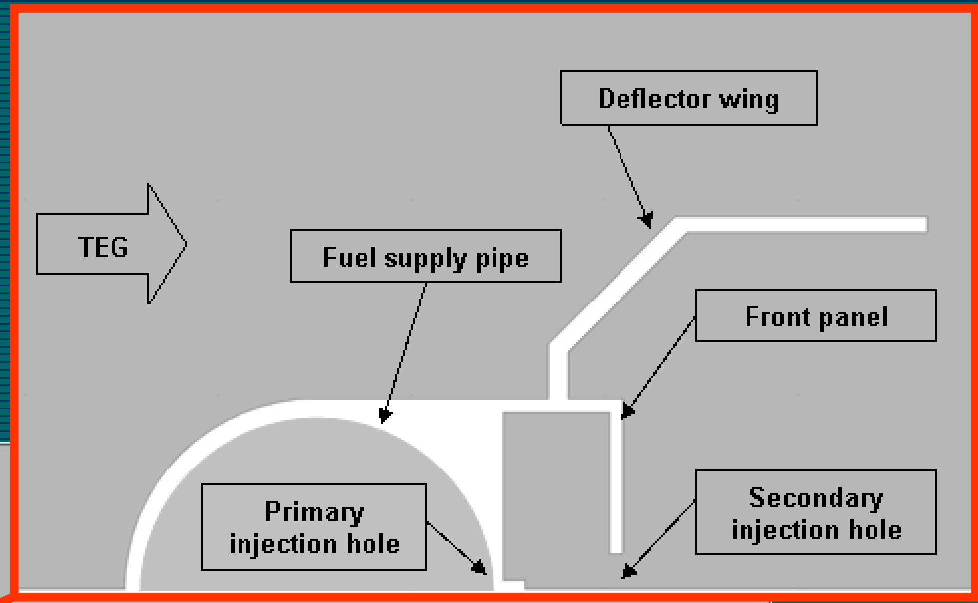


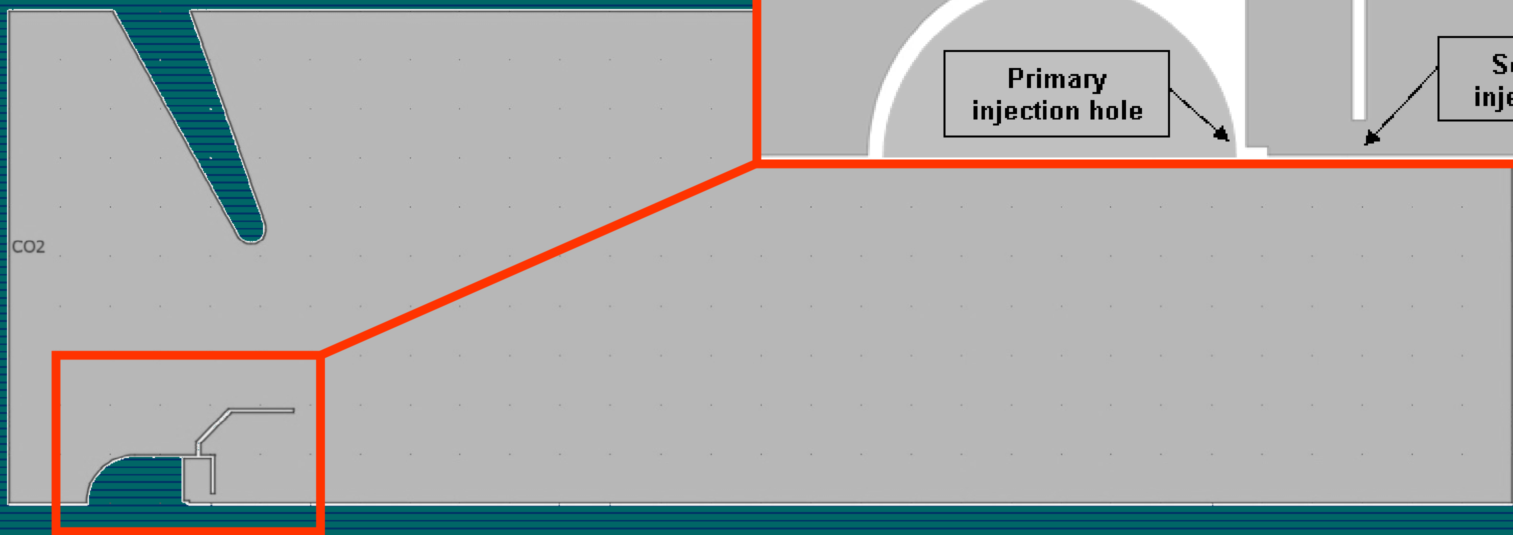


Numerical model

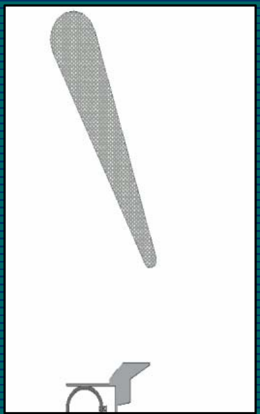


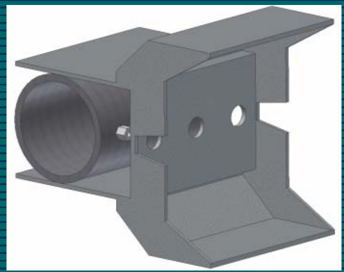


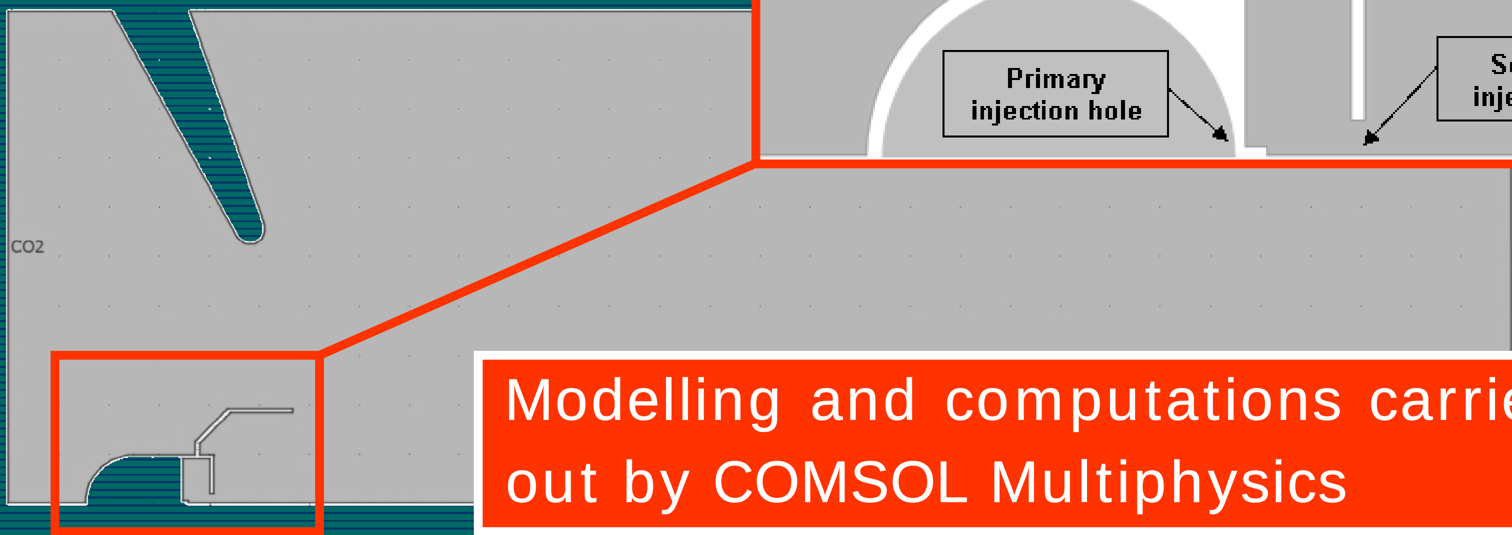


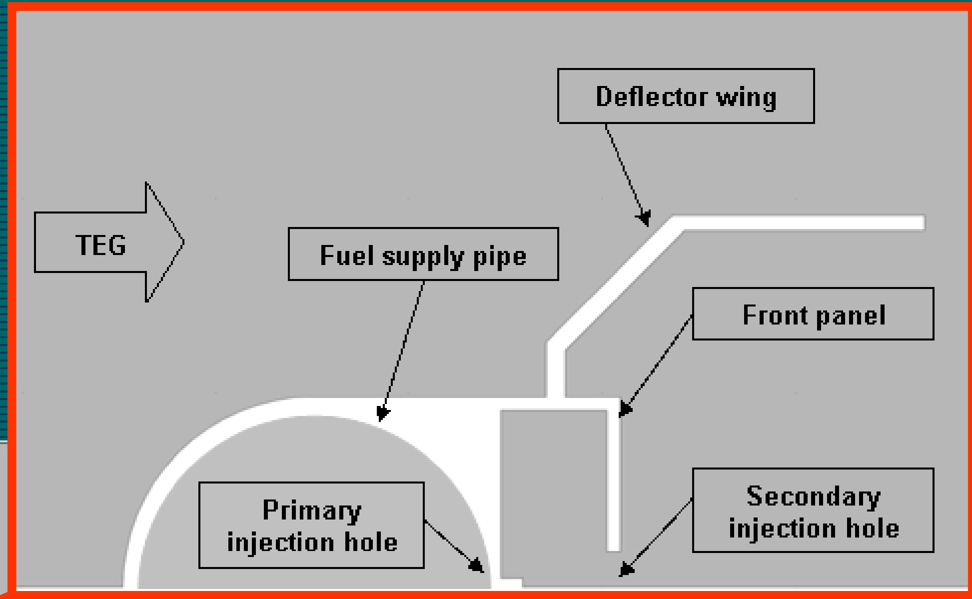


Numerical model









Modelling and computations carried-out by COMSOL Multiphysics

Governing equations

Fluid dynamics: Newtonian fluid - Incompressible, turbulent and steady flow

$$(U\cdot\nabla)U = {}^{-\nabla p}\!/_{\rho} + \nabla\cdot\left[(\nu+\nu_T)\nabla U\right] + {}^{F}\!/_{\rho}$$

Momentum conservation

$$\nabla\cdot U = 0$$

Continuity

$$(U\cdot\nabla)k = \tau_{ij}\frac{\partial u_i}{\partial x_j} - \varepsilon + \nabla\cdot\left[\left(\nu+\frac{\nu_T}{\sigma_k}\right)\nabla k\right]$$

Turbulent kinetic energy

$$(U\cdot\nabla)\varepsilon = c_{\varepsilon 1}\,{}^{\varepsilon}\!/_{k}\cdot\tau_{ij}\frac{\partial u_i}{\partial x_j} - c_{\varepsilon 2}\,{}^{\varepsilon^2}\!/_{k} + \nabla\cdot\left[\left(\nu+\frac{\nu_T}{\sigma_\varepsilon}\right)\nabla\varepsilon\right]$$

Dissipated turbulent energy

Governing equations

Reacting flows and energy conservation

$$CO + H_2 + O_2 \rightarrow H_2O + CO_2$$

Chemical reaction for syngas oxidation (simplified)

$$\nabla \cdot \left(-D_{H_2} \nabla H_2\right) = R - U \cdot \nabla H_2$$

$$\nabla \cdot \left(-D_{CO} \nabla CO\right) = R - U \cdot \nabla CO$$

$$\nabla \cdot \left(-D_{O_2} \nabla O_2\right) = R - U \cdot \nabla O_2$$

$$\nabla \cdot \left(-D_{H_2O} \nabla H_2O\right) = R - U \cdot \nabla H_2O$$

$$\nabla \cdot \left(-D_{CO_2} \nabla CO_2\right) = R - U \cdot \nabla CO_2$$

Transport and diffusion of chemical species (H_2, CO, O_2, CO_2, H_2O)

$$R = \pm\ k_1 \times O_2 \times H_2 \times CO \ \mp\ k_2 \times CO_2 \times H_2O$$

Reaction rate

$$\nabla \cdot \left(-\lambda \nabla T\right) = (R \times H) - \rho C_P U \cdot \nabla T$$

Energy conservation

$$H = H_{CO_2} + H_{H_2O} - (H_{O_2} + H_{H_2} + H_{CO})$$

Net Enthalpy of reaction

Boundary Conditions
Fluid dynamics

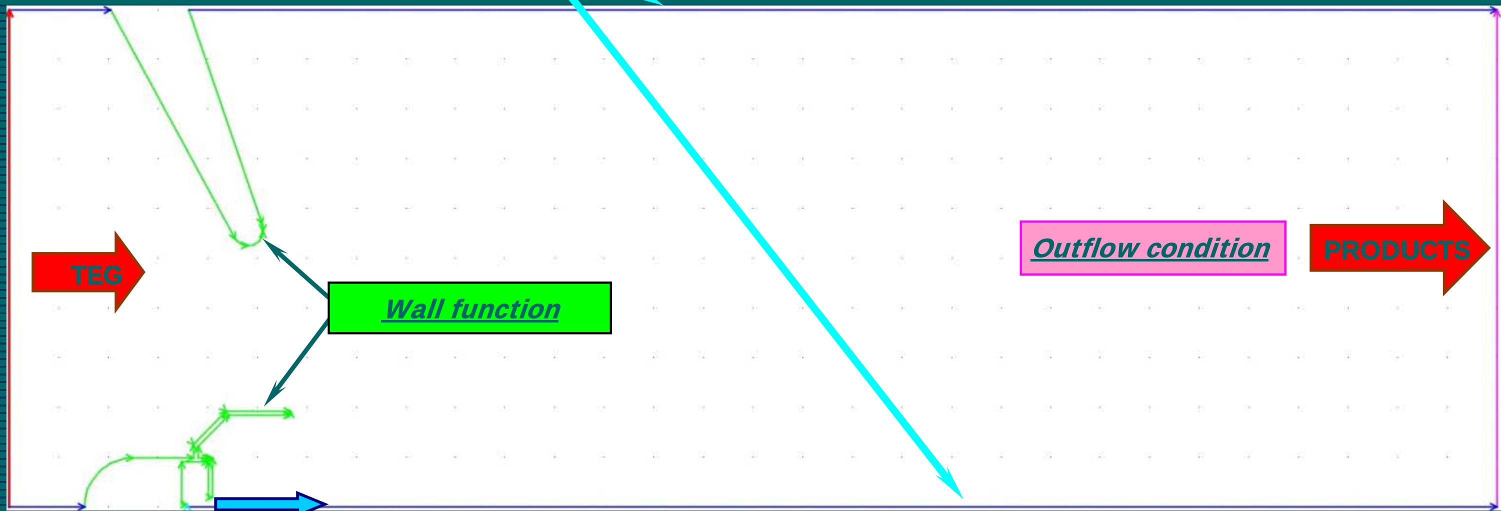
Slip condition

Incoming flow (TEG):

u=***u_teg***

k0=*0.018/4*(u0_chke^2+v0_chke^2)*

*ε**0**=0.1643/0.09*(0.018/4)^(3/2)*sqrt(u0_chke^2+v0_chke^2)^3*



Incoming flow (fuel):

u=*u_syn*

k0=*0.018/4*(u0_chke^2+v0_chke^2)*

*ε**0**=0.1643/0.09*(0.018/4)^(3/2)*sqrt(u0_chke^2+v0_chke^2)^3*

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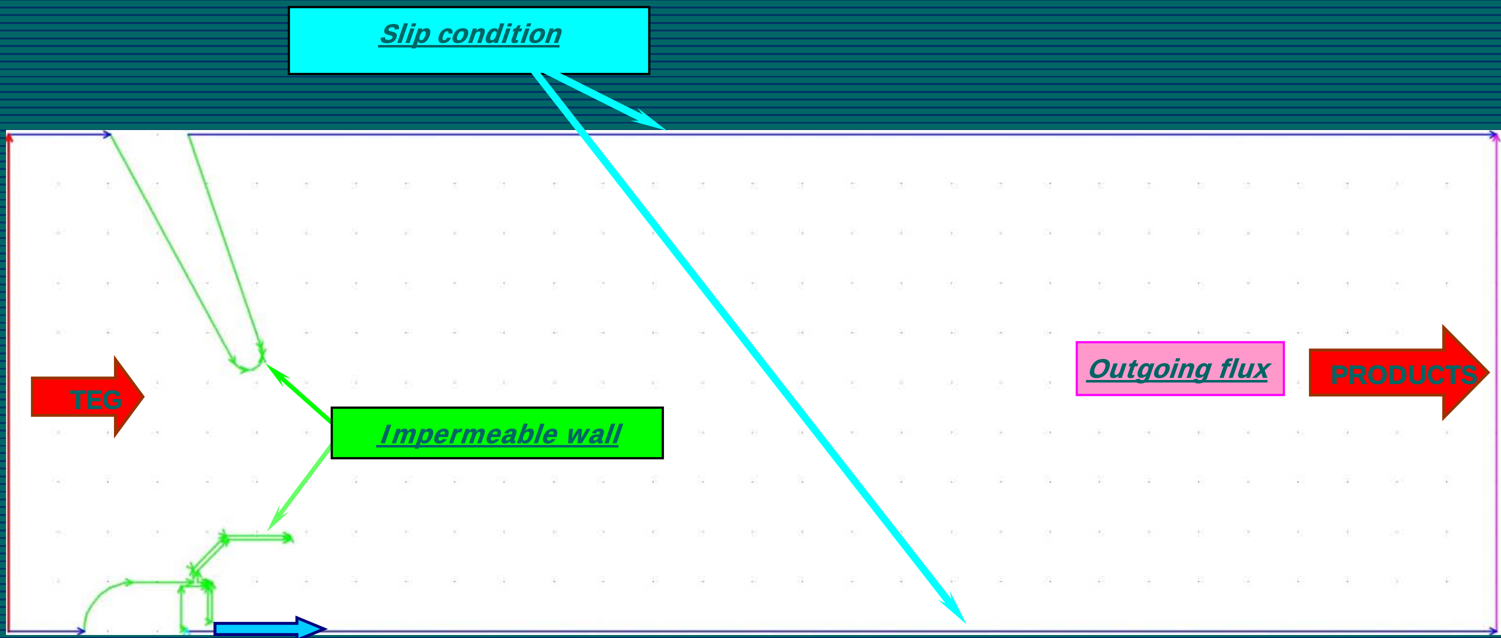
Boundary Conditions
Mass balance of chemical species



***Incoming flux*:**

O2=com_v_O2*rho_teg*u_teg/mm_teg

***Fixed concentration*:**
H2=0
H2O=0
CO=0
CO2=0

***Incoming flux*:**

H2=com_v_H2*rho_teg*u_teg/mm_teg
CO= com_v_CO *rho_teg*u_teg/mm_teg
CO2= com_v_CO2*rho_teg*u_teg/mm_teg

***Fixed concentration*:**
H2O=0
O2=0

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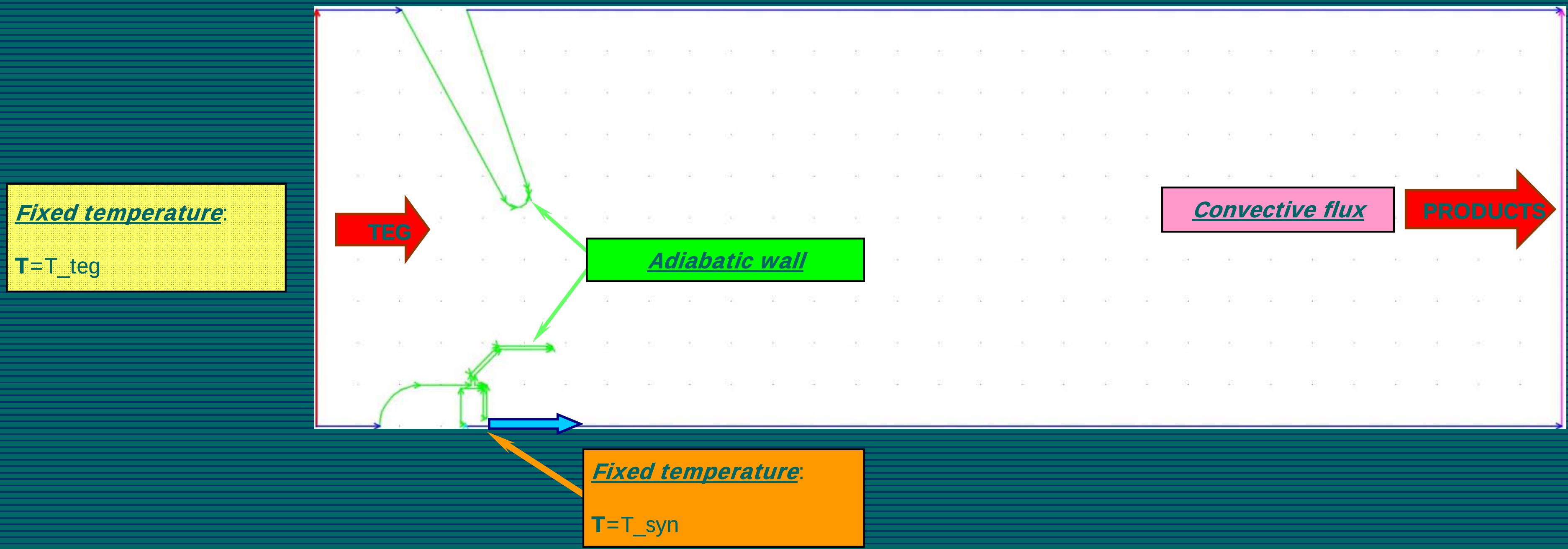
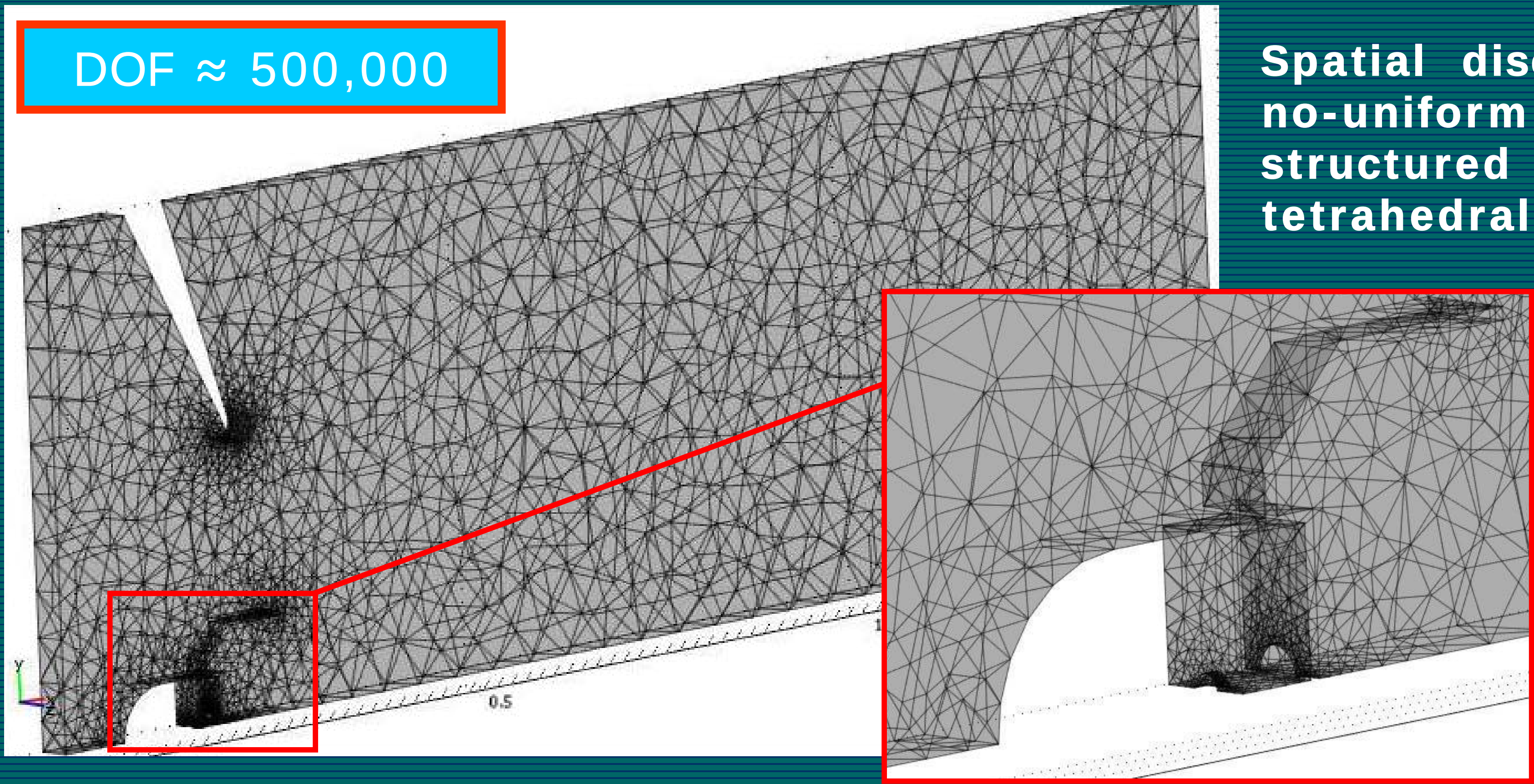
Boundary Conditions
Thermal analysis



Computational grid

DOF ≈ 500,000



Spatial discretization by no-uniform and no-structured triangular or tetrahedral elements

UMF direct method for solving linear systems

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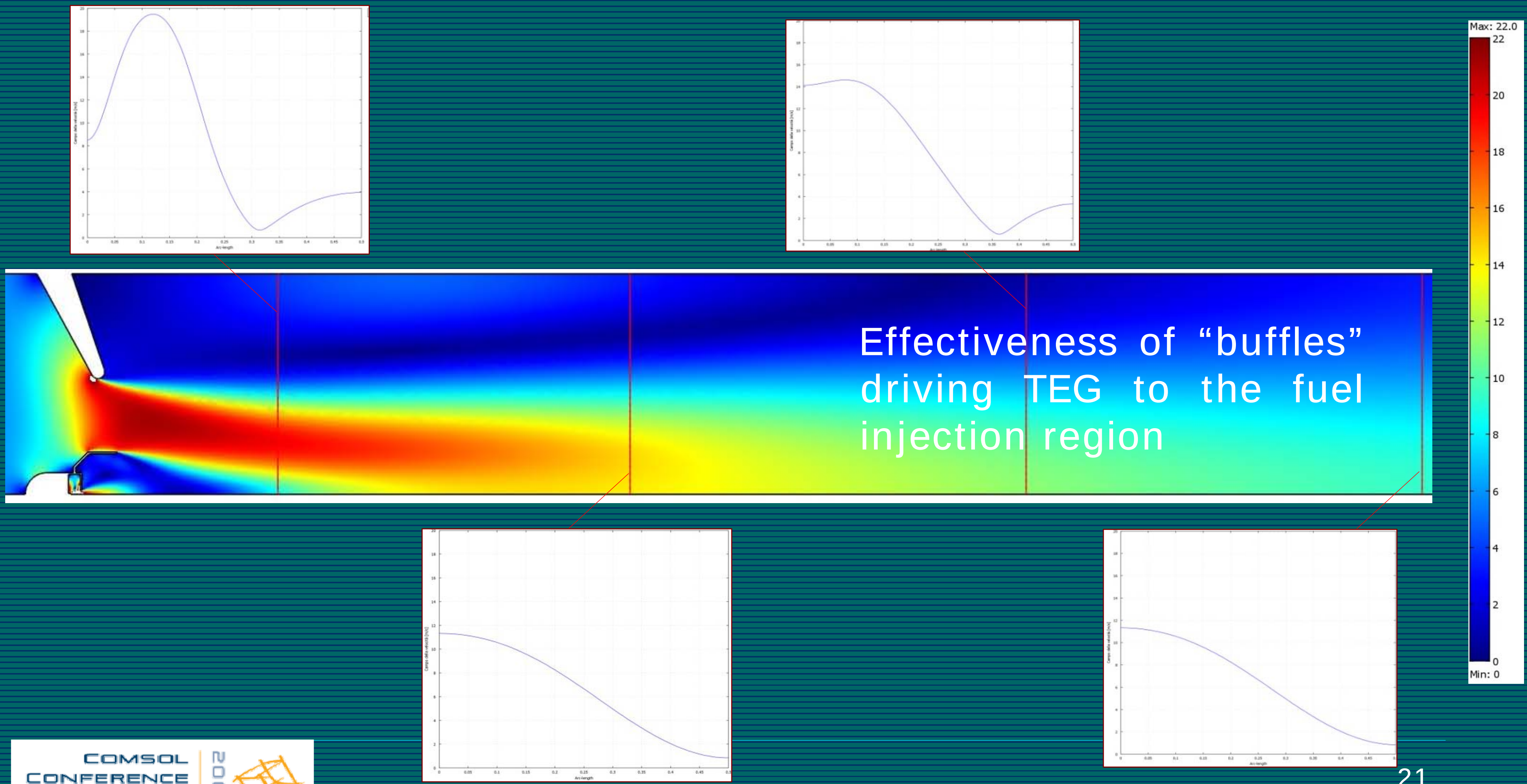
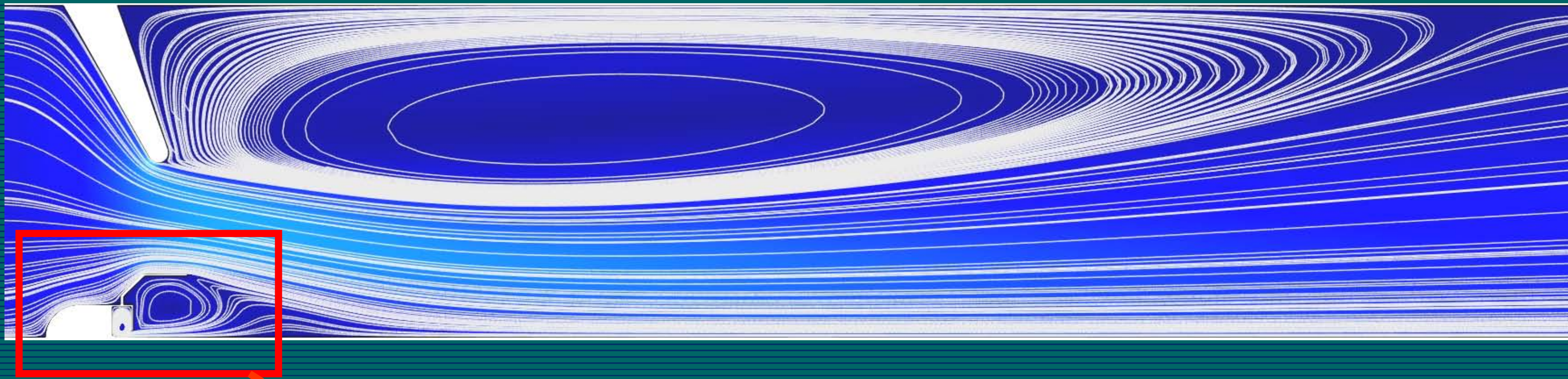
“On design” operative conditions 89 MW_{th} (0.8 MW_{th}/m)

Velocity field

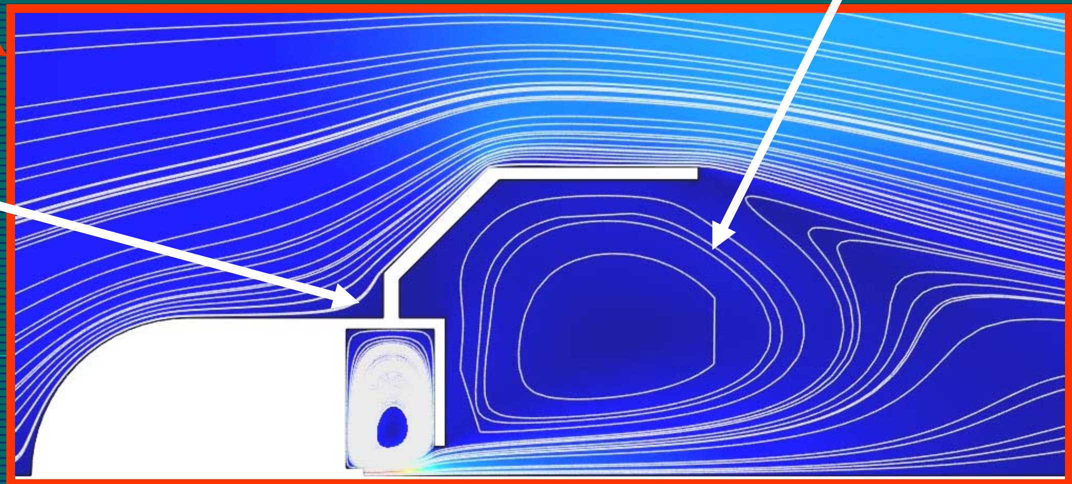


“On design” operative conditions 89 MW_{th} (0.8 MW_{th}/m) Streamlines of flow

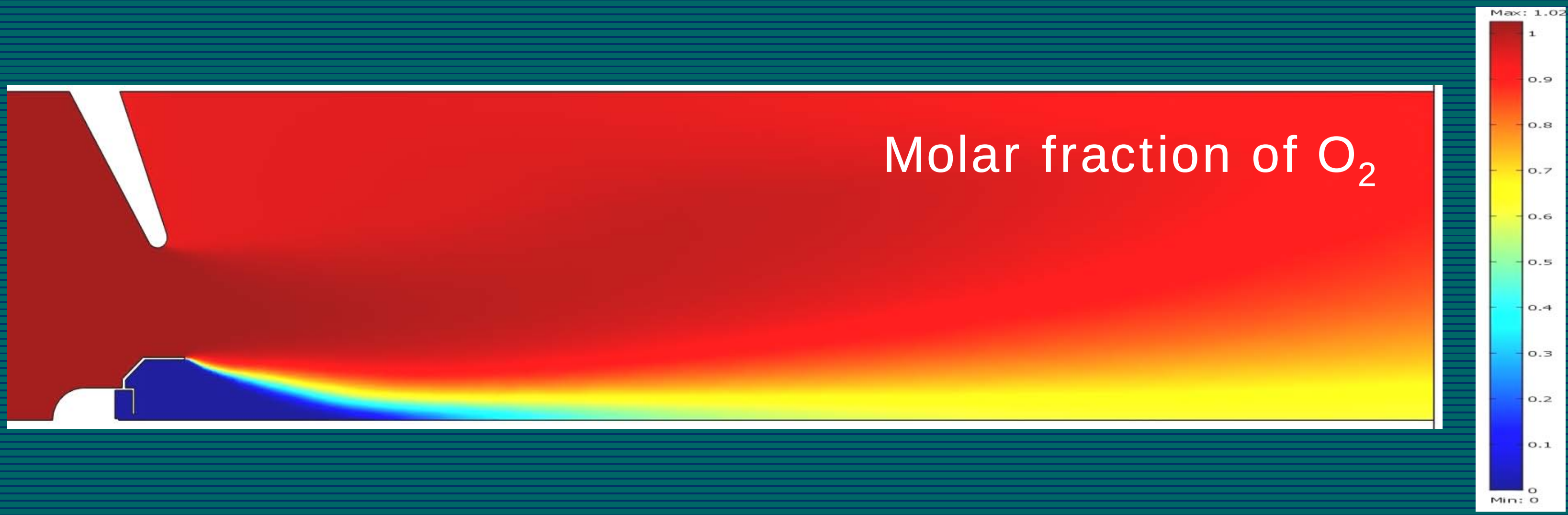


Anticlockwise vortex formation and slight pressure drop caused by the vein contraction

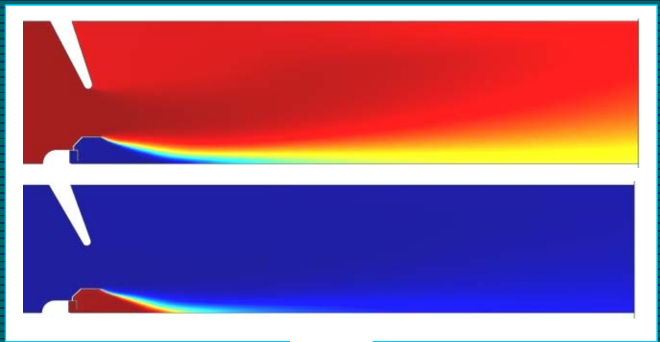
Recirculation chamber: fuel is used as coolant for the burner manifold



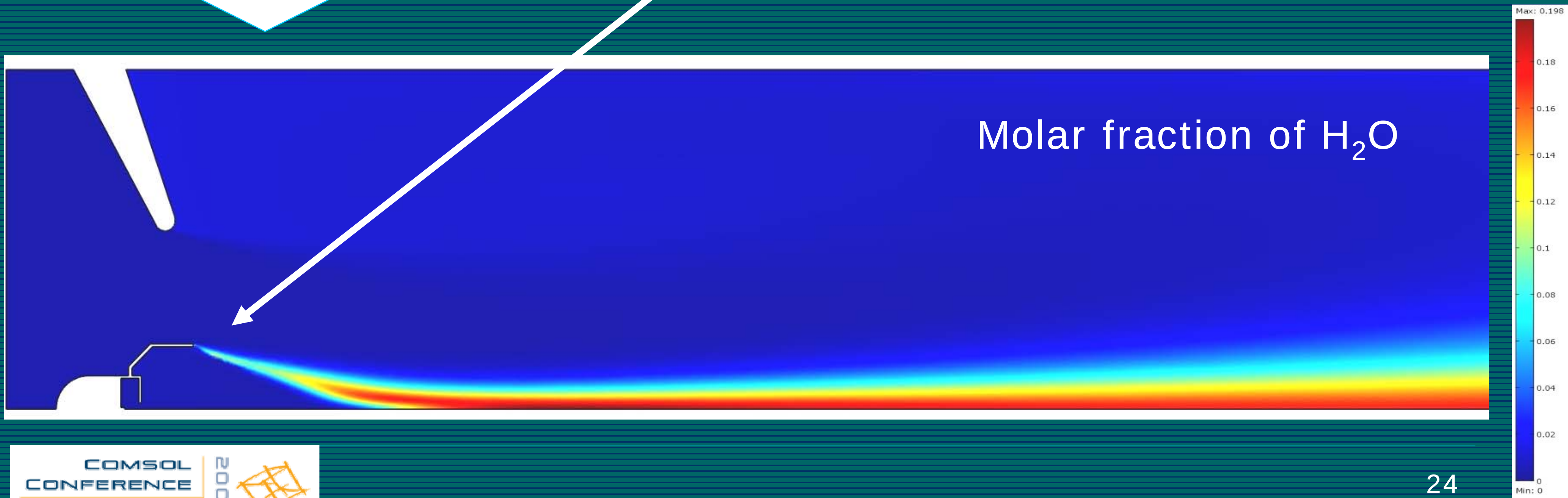
"On design" operative conditions
89 MW_{th} (0.8 MW_{th}/m)
Concentration field of reacting species



"On design" operative conditions
89 MW_{th} (0.8 MW_{th}/m)
Concentration field of product (H_2O)



"Anchorage" assured by the deflector wing with respect to the product formation (mixing and combustion region)



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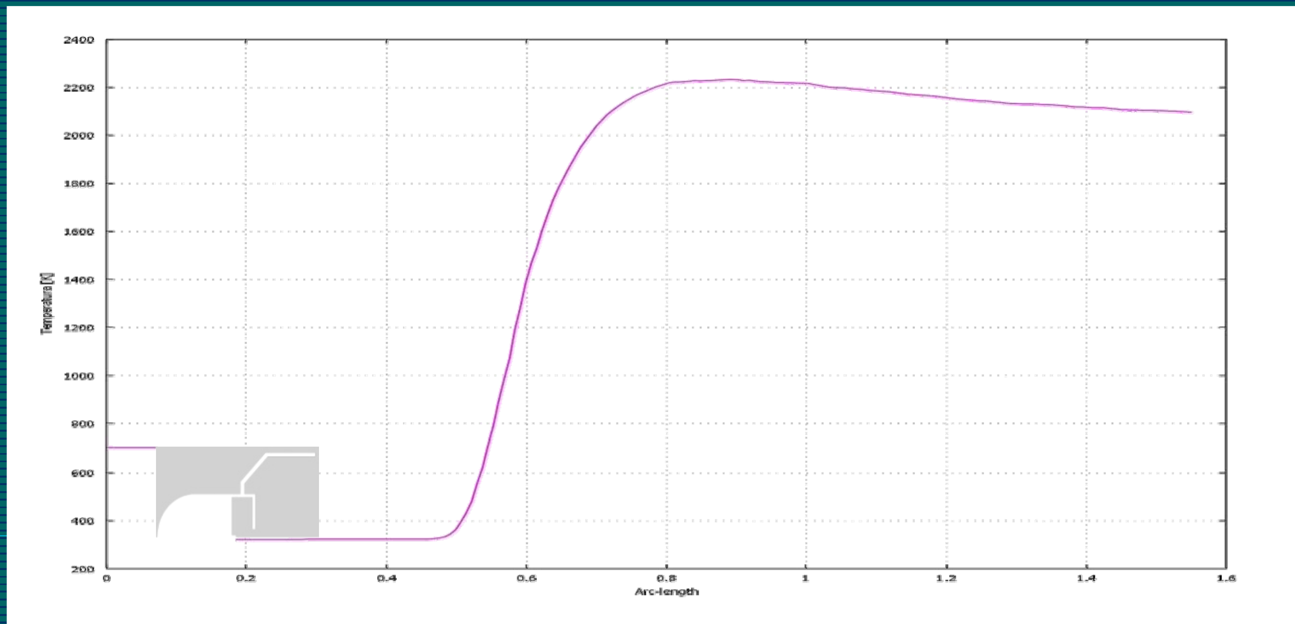
“On design” operative conditions 89 MW_{th} (0.8 MW_{th}/m)

Thermal field

Temperature is lower than the threshold (700 K) causing the Ni deposition



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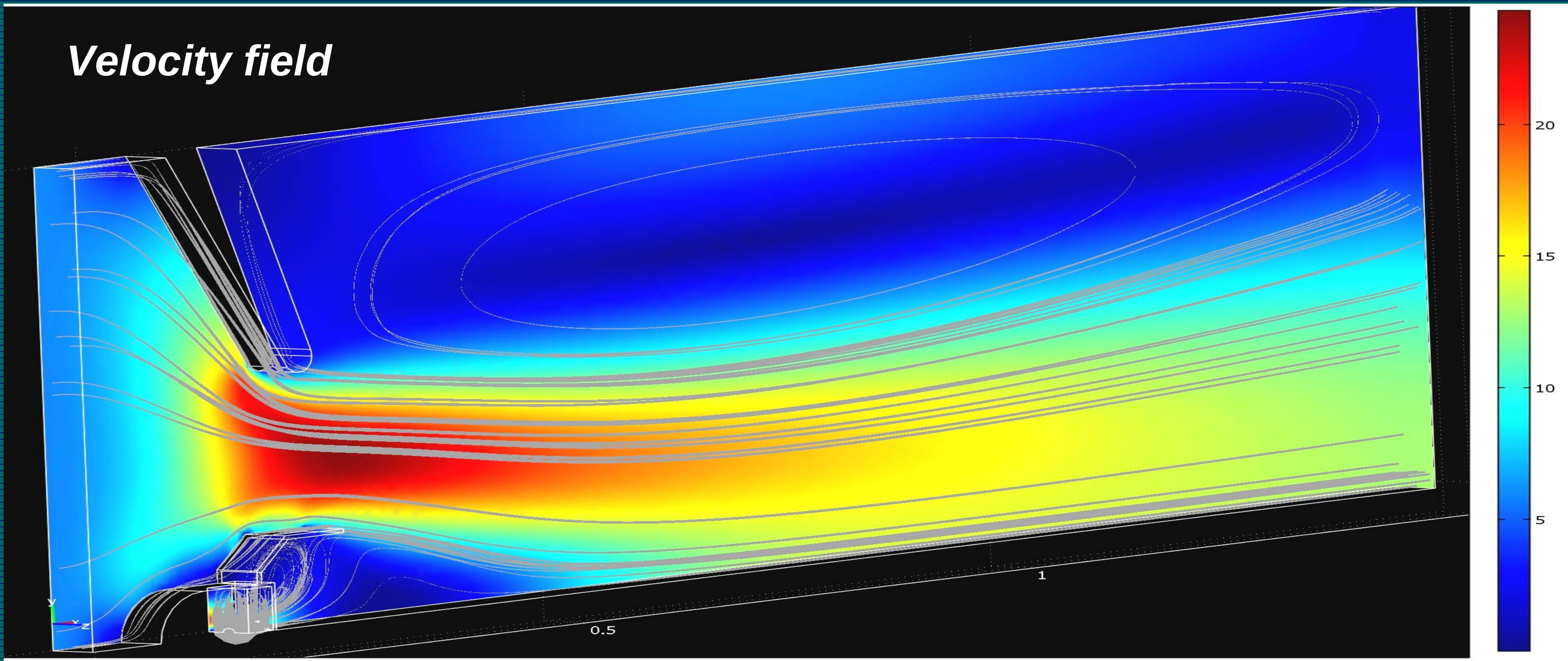
"On design" operative conditions
89 MW_{th} (0.8 MW_{th}/m)
3D results – fluid dynamics



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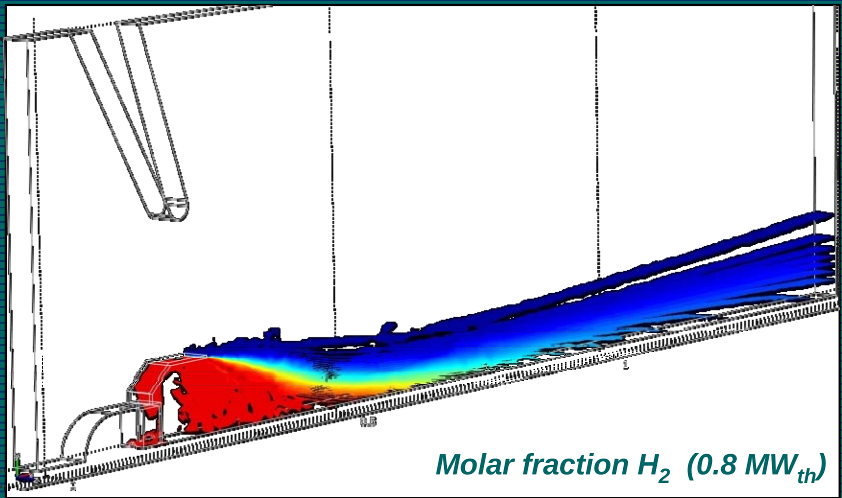
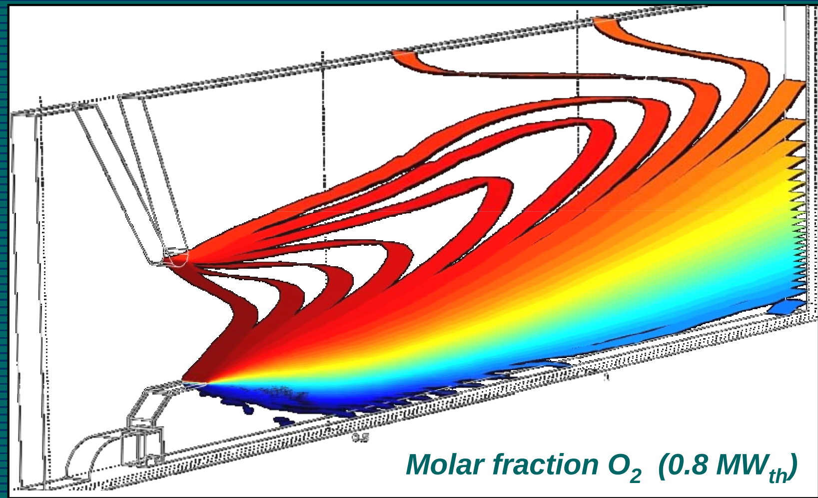
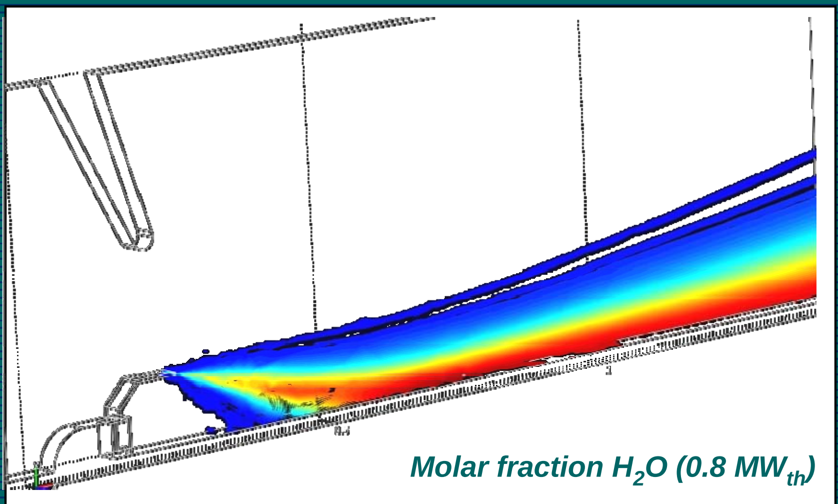
"On design" operative conditions
89 MW_{th} (0.8 MW_{th}/m)
3D results – thermo-chemical



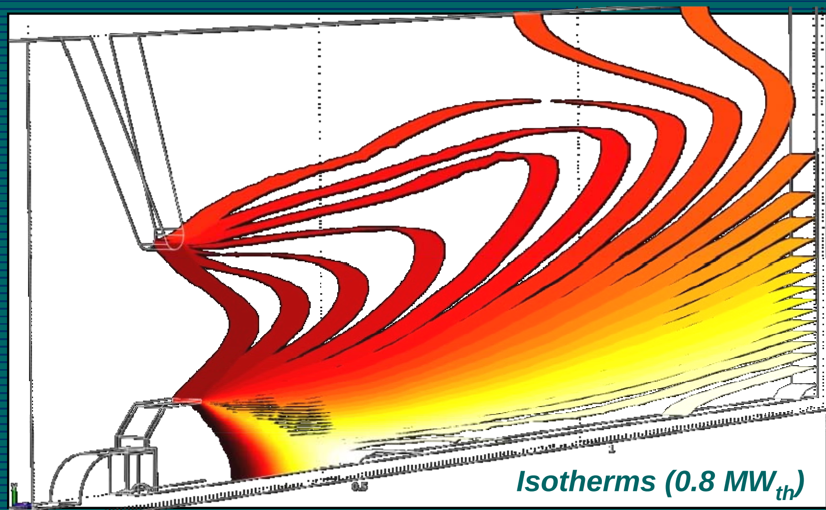
Molar fraction H_2 (0.8 MW_{th})



Molar fraction O_2 (0.8 MW_{th})



Molar fraction H_2O (0.8 MW_{th})



Isotherms (0.8 MW_{th})

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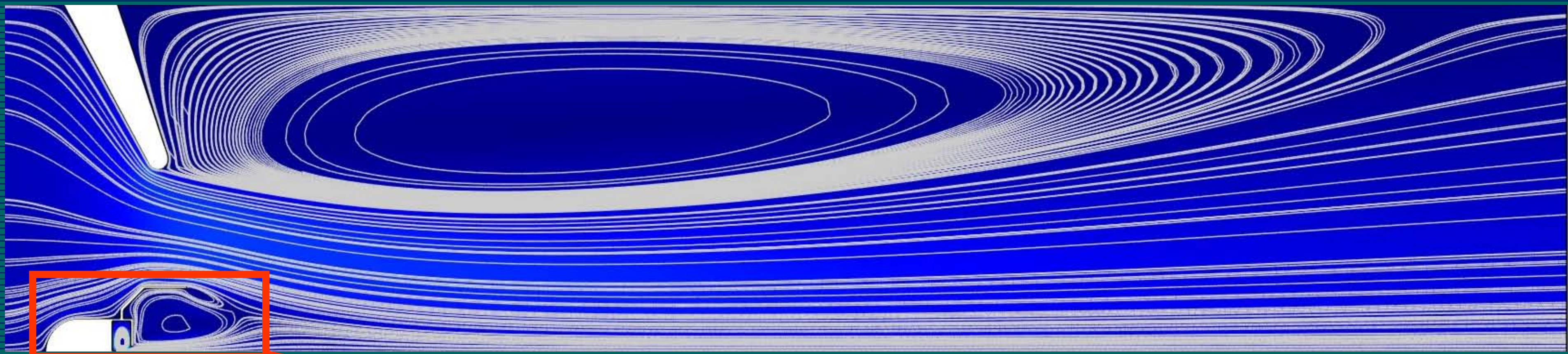
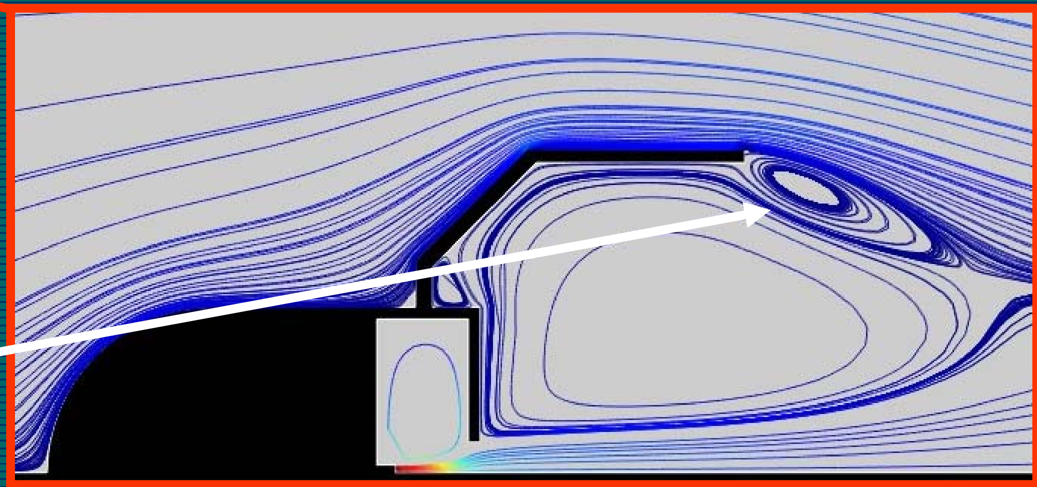
“Turn down” operative conditions (150%) 133 MW_{th} (1.2 MW_{th}/m)

Streamlines of flow

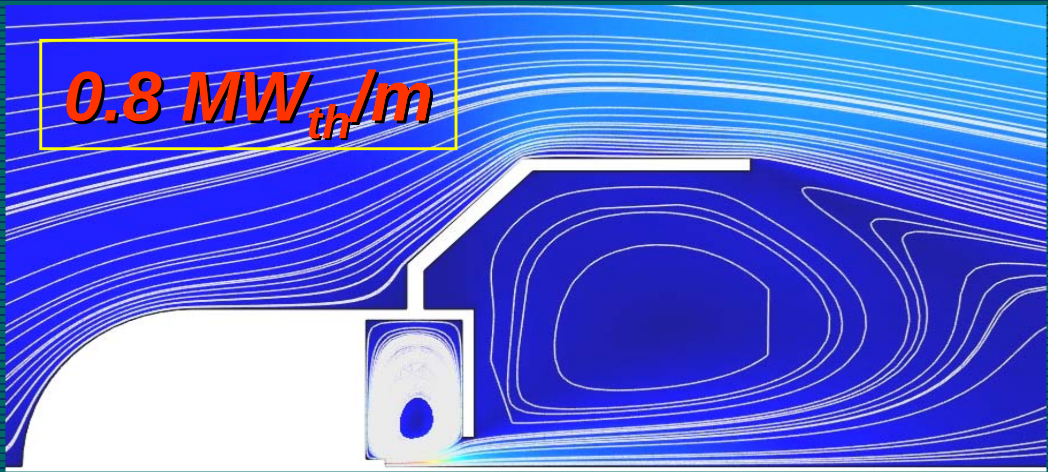


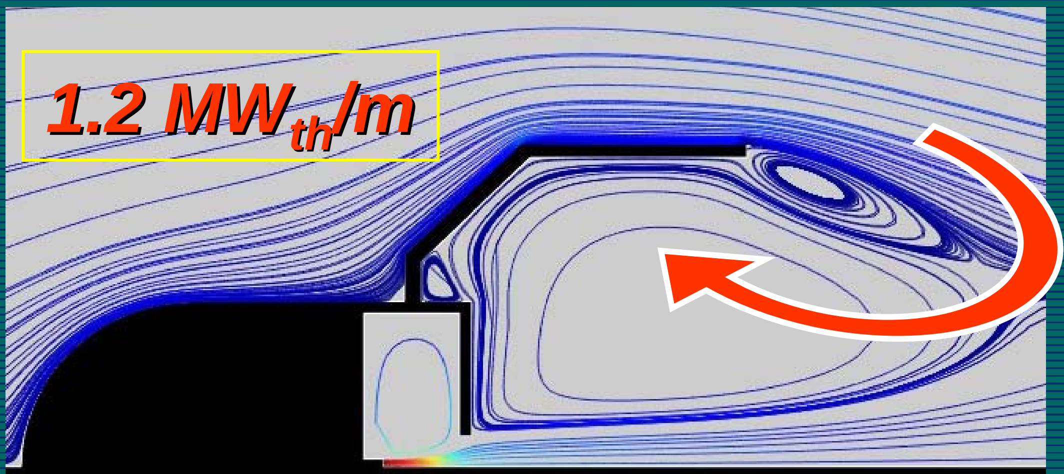
Due to the higher thermal load, flow rates of incoming fluids are increased: fluid-dynamics is modified

A new little clockwise vortex is clearly observable close to the end of the deflector wing



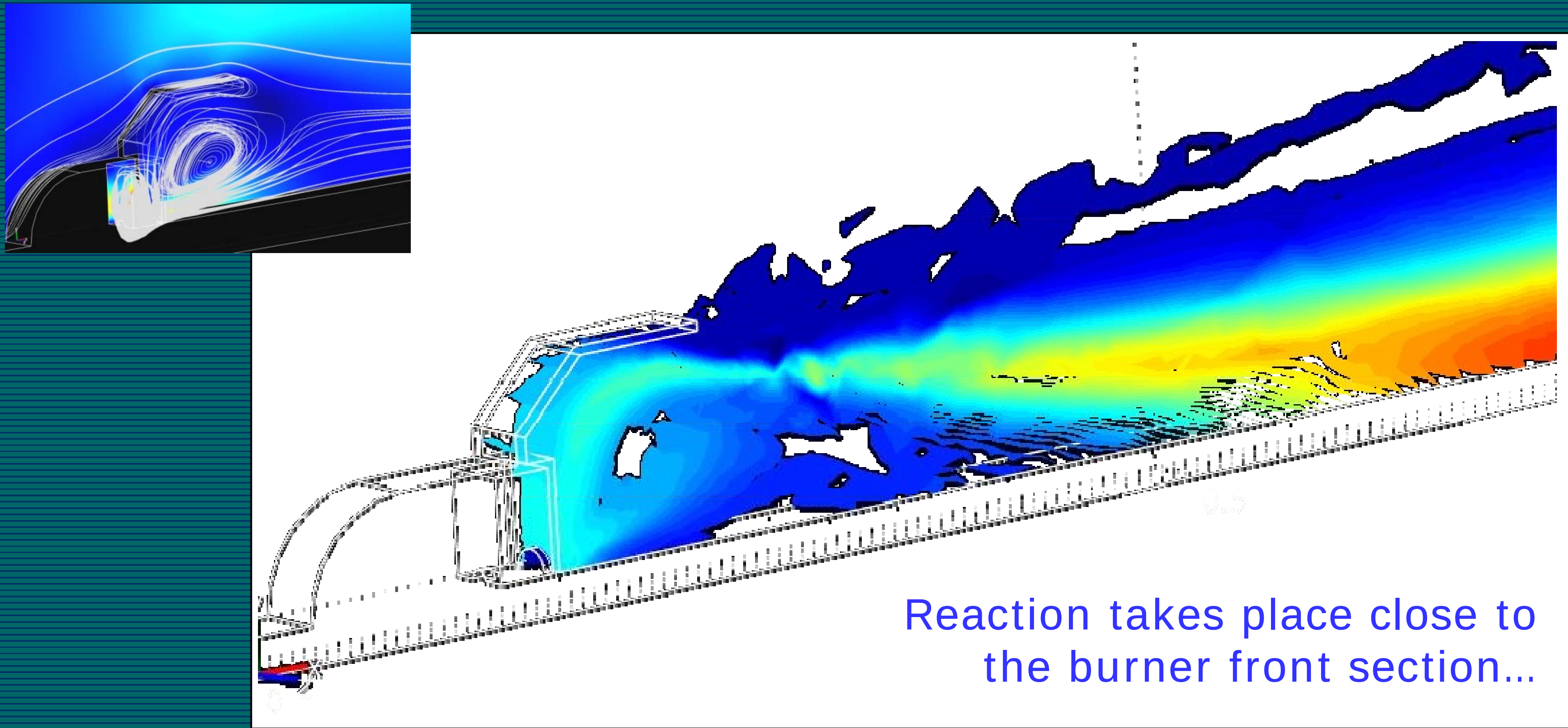
"On design" Vs "Turn down"
Comparison of fluid dynamical fields





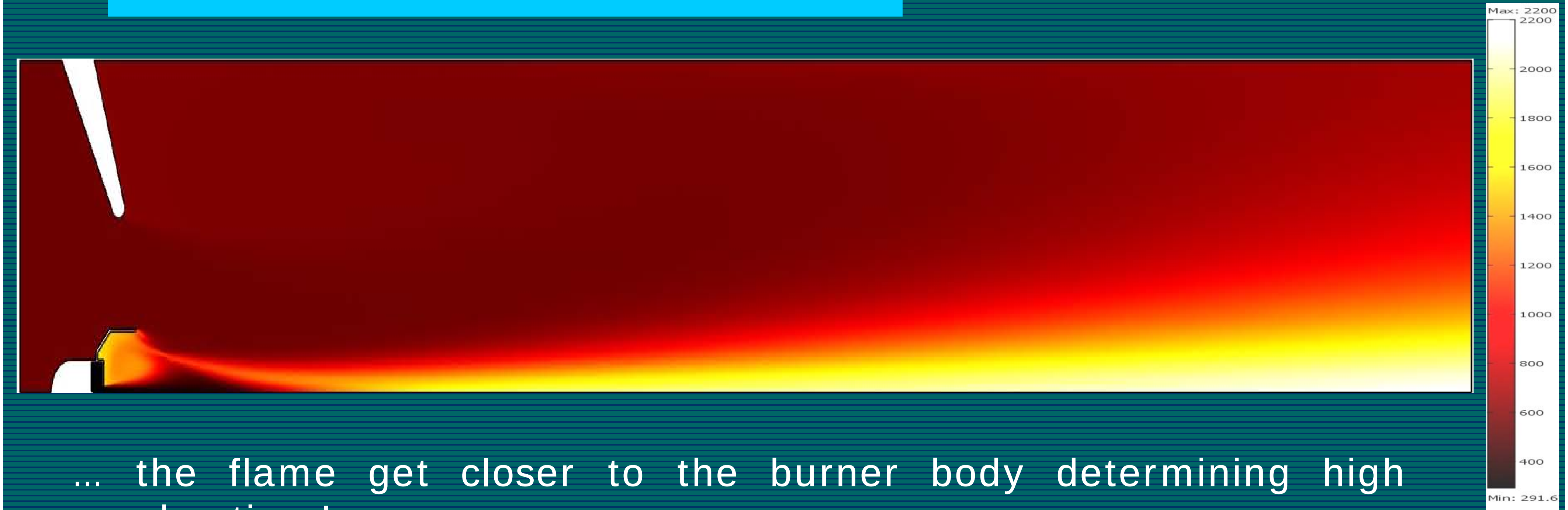
The highlighted new fluid structure allows TEG to come closer to the fuel injection hole improving mixing between oxidising and combustive

“Turn down” operative conditions
133 MW_{th} (1.2 MW_{th}/m)
Concentration field of product (H_2O)



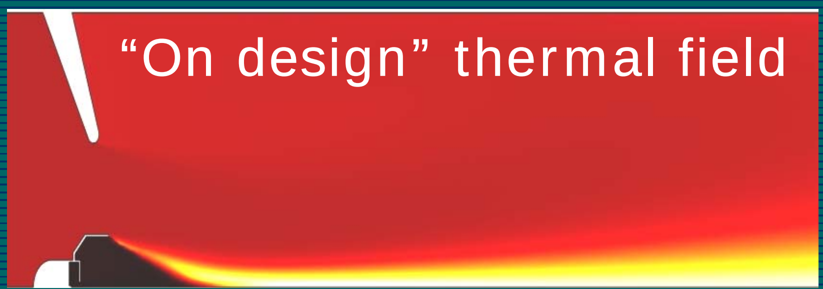
“Turn down” operative conditions 133 MW_{th} (1.2 MW_{th}/m)

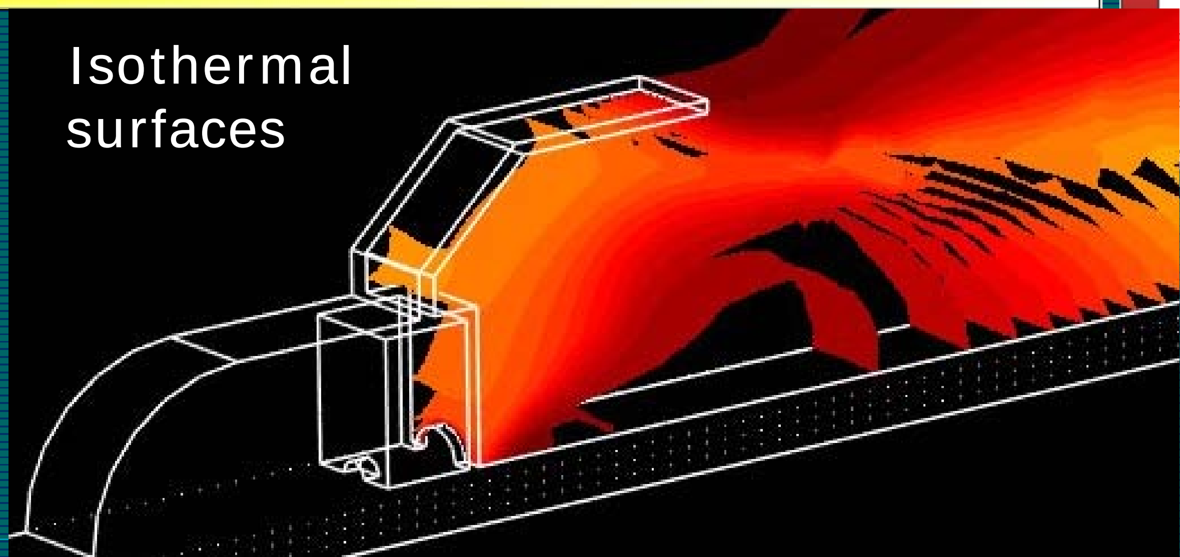
Thermal field



… the flame get closer to the burner body determining high overheating !

“Turn down” operative conditions
133 MW_{th} (1.2 MW_{th}/m)
Thermal field





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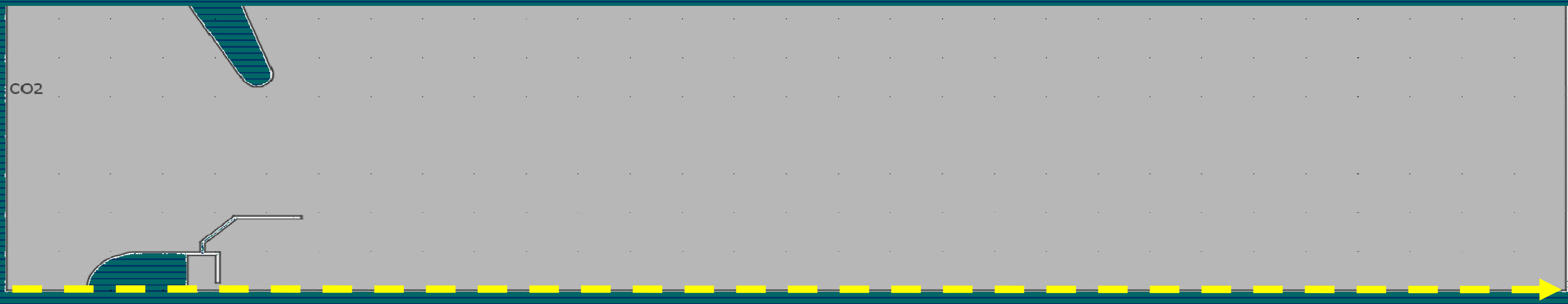
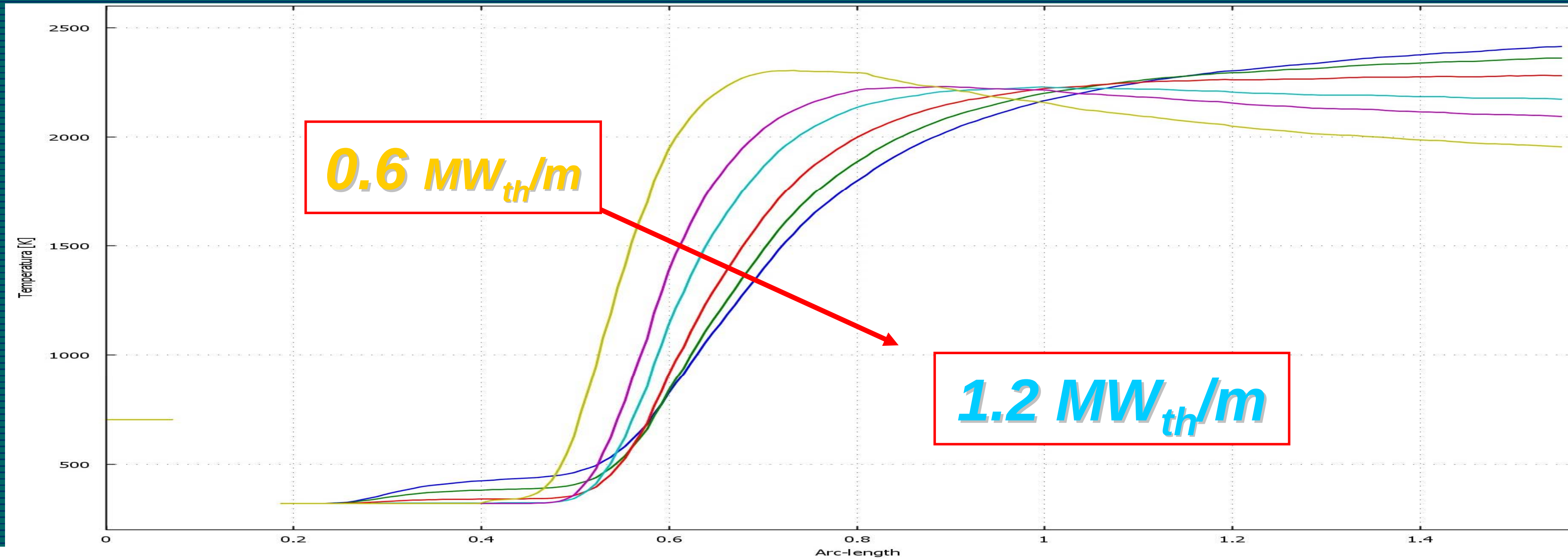
“Turn down” operative conditions 133 MW_{th} (1.2 MW_{th}/m)

Temperature along symmetry axis





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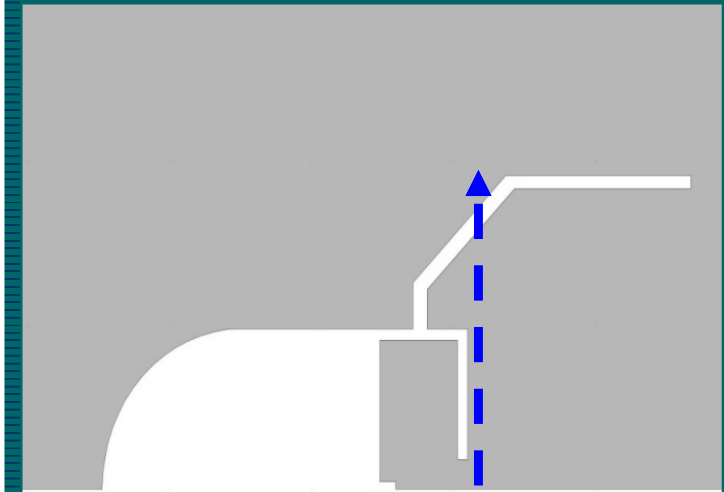
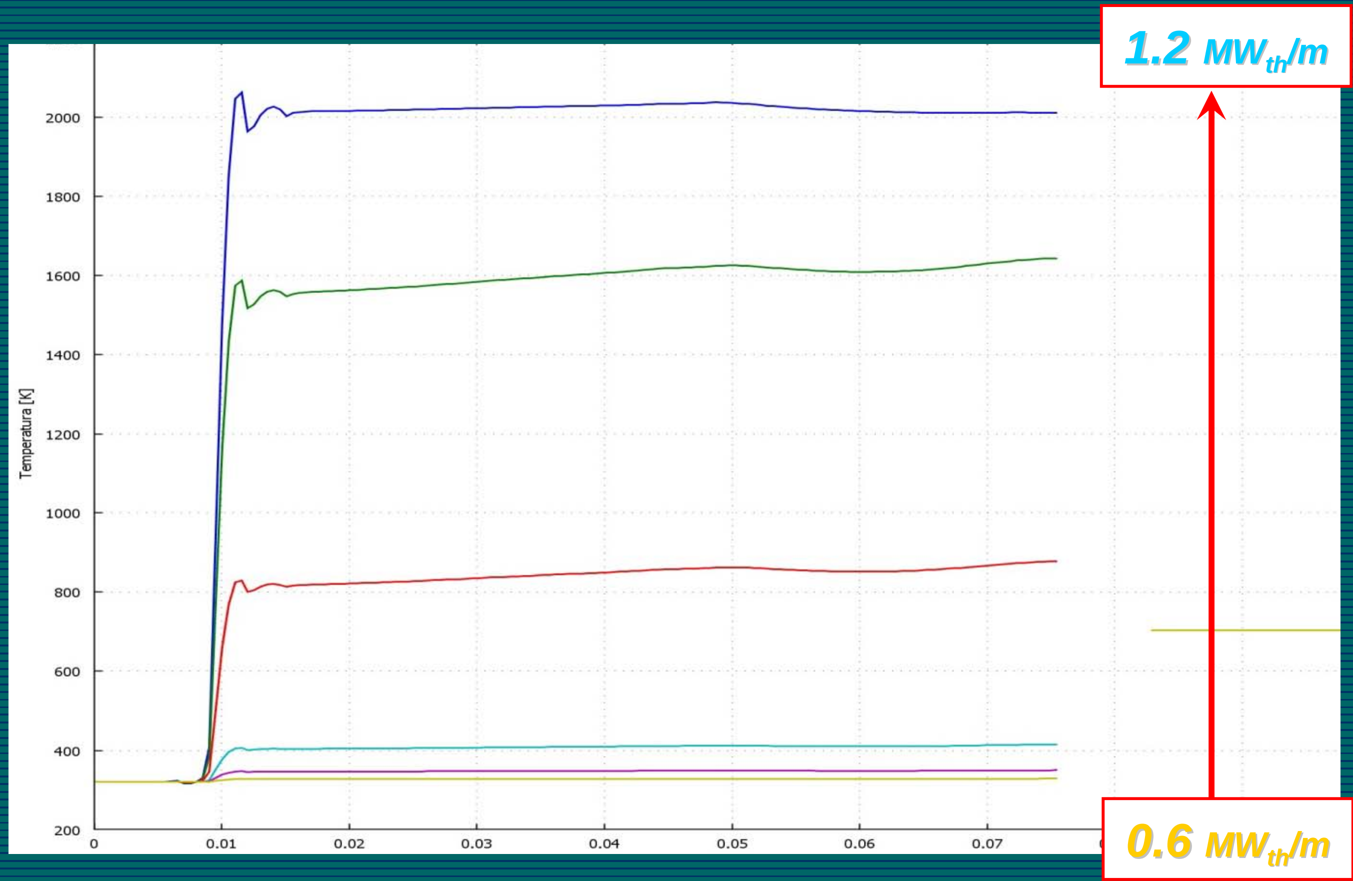
"Turn down" operative conditions 133 MW_{th} (1.2 MW_{th}/m)

Temperature along the front panel





Nickel-carbonyl deposition becomes "possible" due to the high temperature of the burner manifold

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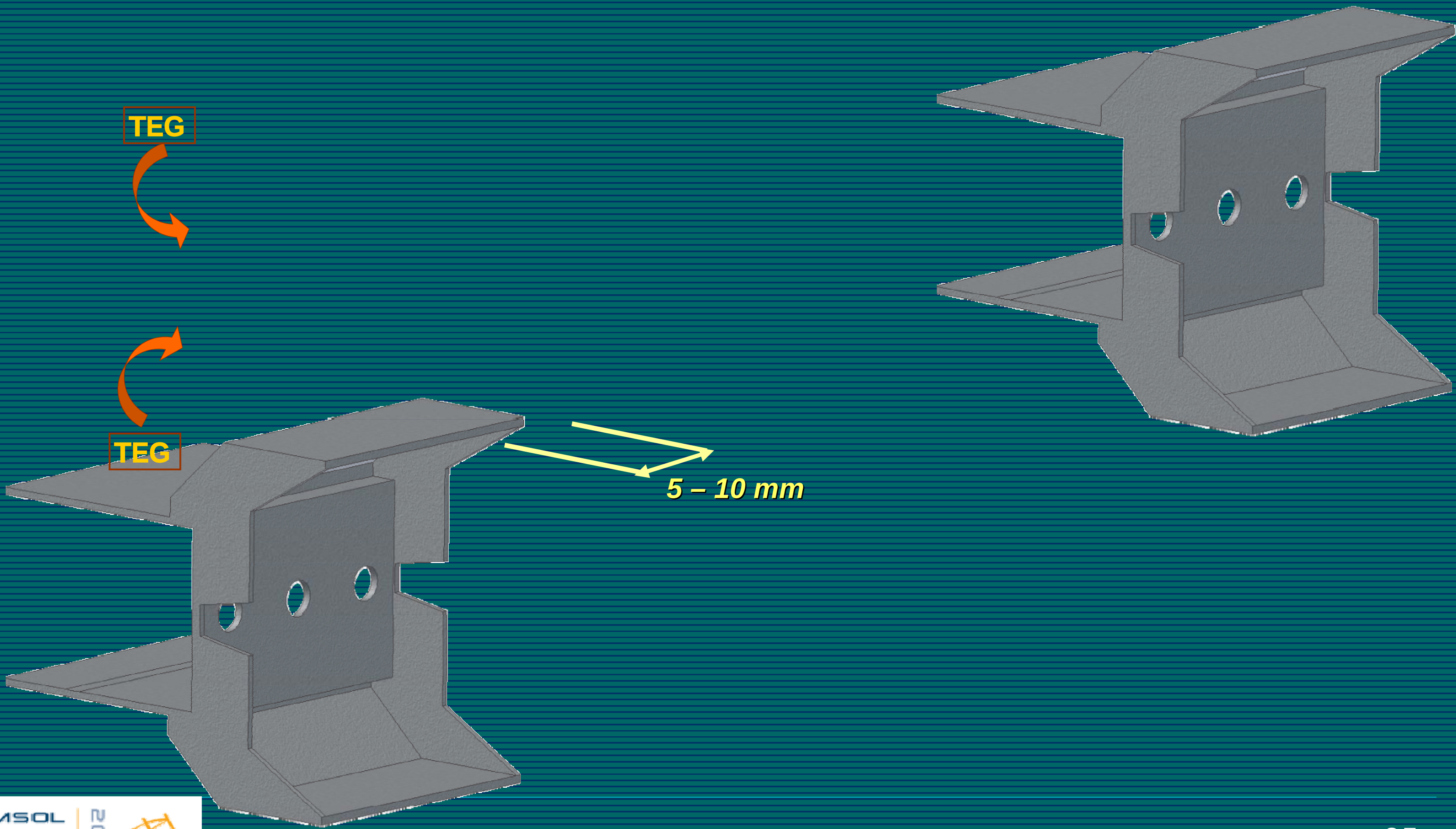
Other condition potentially responsible of brisk combustion:
Slight gap between modules



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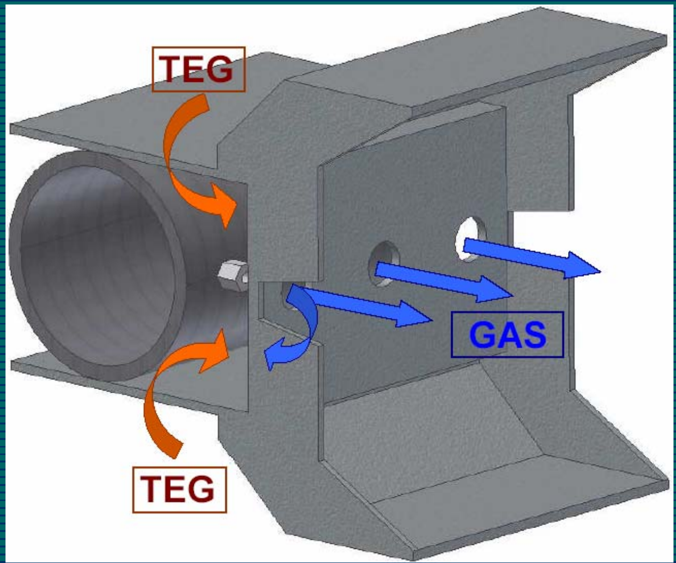
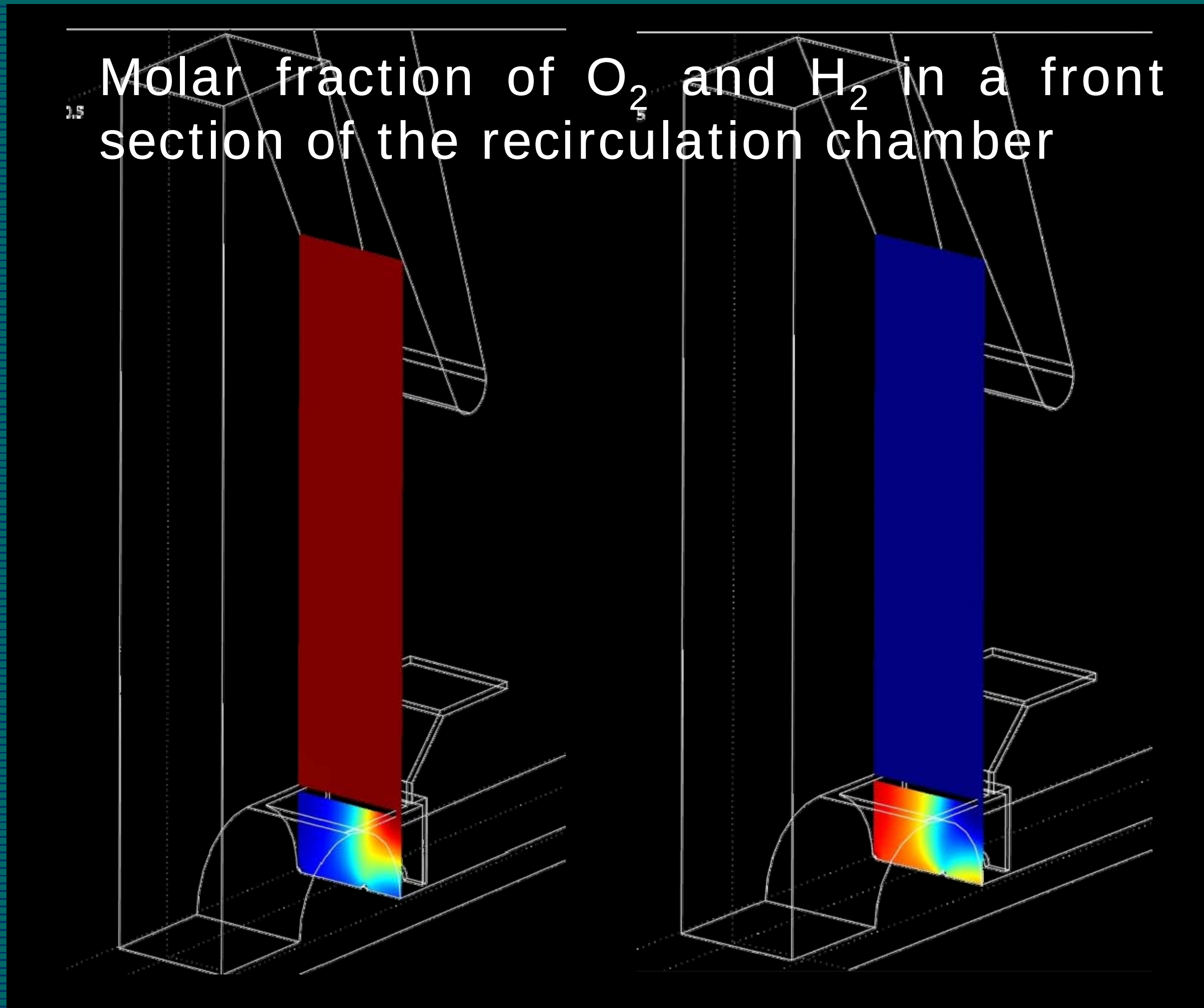
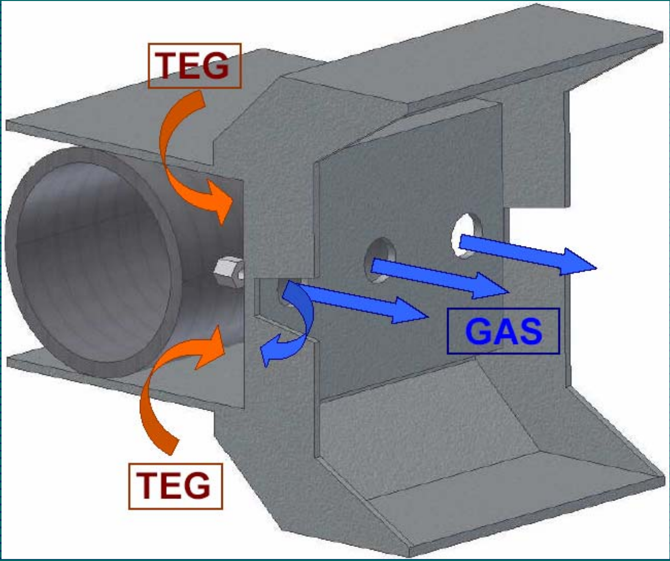
Slight gap between modules

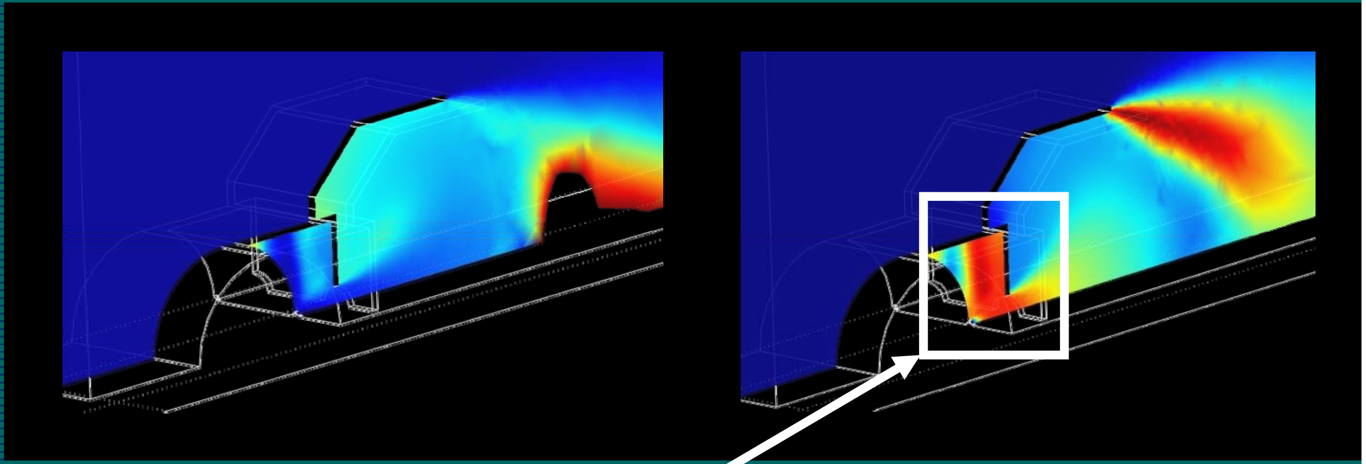




Other condition potentially responsible of brisk combustion:
Slight gap between modules

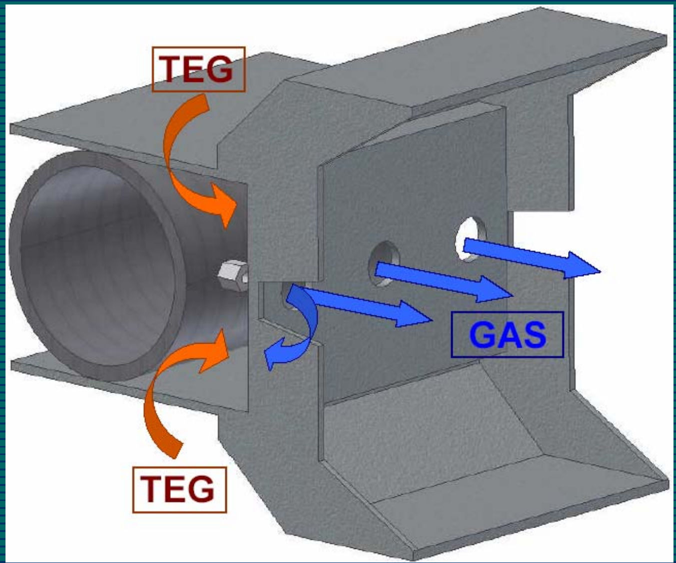


Molar fraction of H_2O in longitudinal sections of the burner

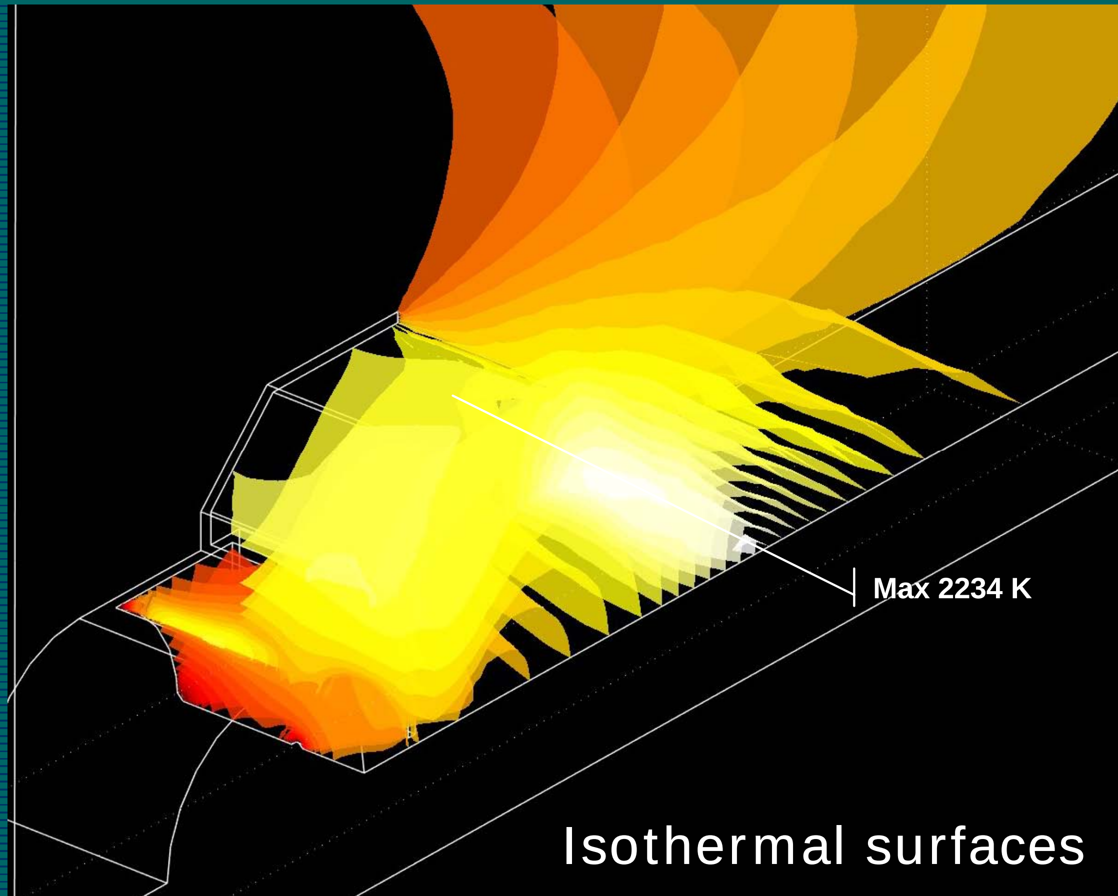


H_2O production

Other condition potentially responsible of brisk combustion: Slight gap between modules



TEG leakage to the recirculation chamber lead to a brisk combustion close to the burner body



Conclusions

A multi-physical numerical analysis concerning fluid-dynamical, chemical and thermal behaviour of an industrial duct-burner has been performed:

✓ The present study underlines the needed of simulating simultaneously several interconnected aspects of physics for technological systems, in order to completely describe their operative conditions.

✓ Simulations well highlight as modification in fluid-dynamics, related to increasing in mass flow rate of reactants, seriously compromise flame stability. Flame triggering during "turn-down" conditions results too close to after-burners manifold, so that metal deposition and high thermal stresses could be produced.

✓ The onset of a dangerous brisk combustion, related to TEG leakages through out the assembled array of duct-burners, has been also detected by 3D simulations.

THANK YOU!

This research work has been developed at:

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