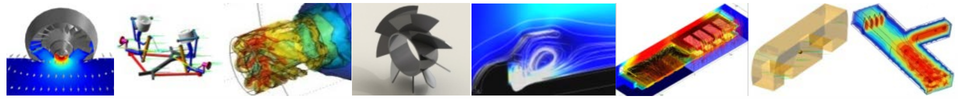
An Integrated Numerical-Experimental Approach for Heat Transfer Analysis of Industrial Furnaces

Adorisio A.[1], Adorisio S.[1], Calderisi M.[2], Cecchi A.[2], Petrone G.[3], Scionti M.[3], Turchi F.[2]

[1] Gadda Industrie, Viale A. Olivetti - 10010 Colleretto Giacosa-Ivrea (TO), ITALY
[2] Laboratori Archa, Via di Tegulaia 10/A - 56121 Ospedaletto (PI), ITALY
[3] BE CAE & Test, Viale Africa, 44 – 95129 Catania, ITALY

COMSOL Conference - EUROPE 2012
October 10-12 2012, Milan (Italy)



Background

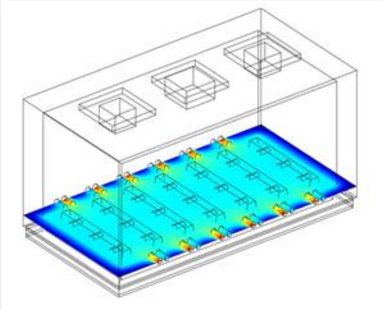
research project supported by the Italian Ministry of Education, University and Research (MIUR), grant from “art.14 letter C - DM. 593/00”

Discrete input data

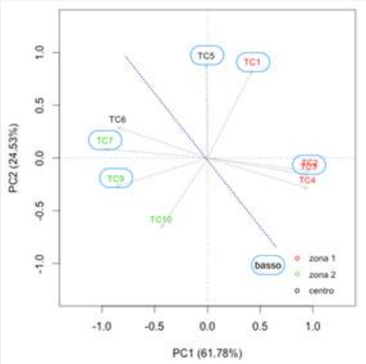
Model validation

Distributed input data

Experimental measurements

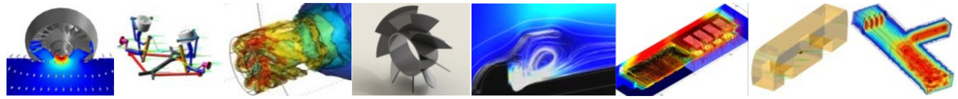


numerical models



Multivariate analyses

design & process improvement

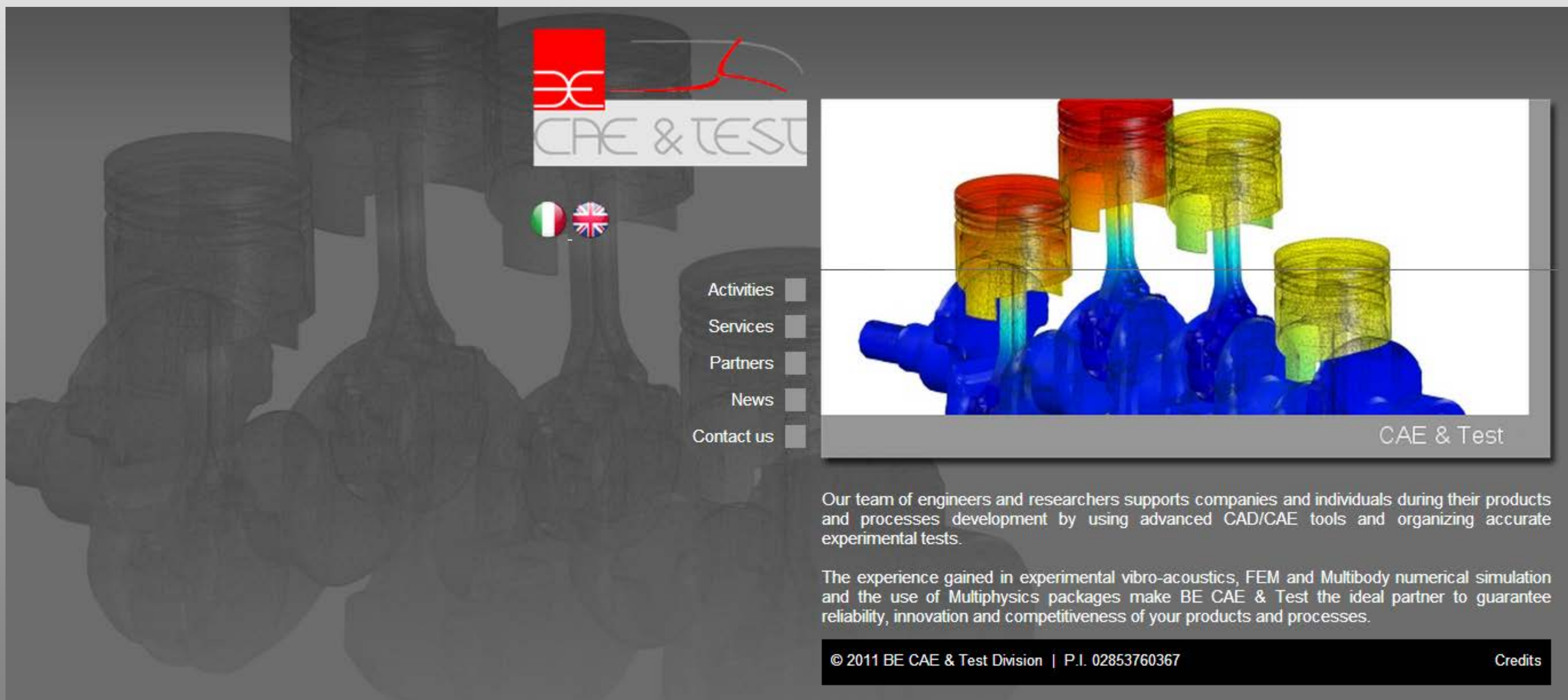


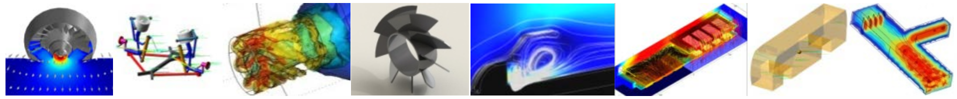
BE CAE & Test

Company profile

- ✓ **BE CAE & Test** (http://www.be-caetest.it) provides consultancy services in several industrial sectors by using innovative **CAD/CAE modelling tools** and carrying out **experimental campaigns**
- ✓ The company collaborates with **industrial partners** and **research centers** in several technologic fields

http://www.be-caetest.it/

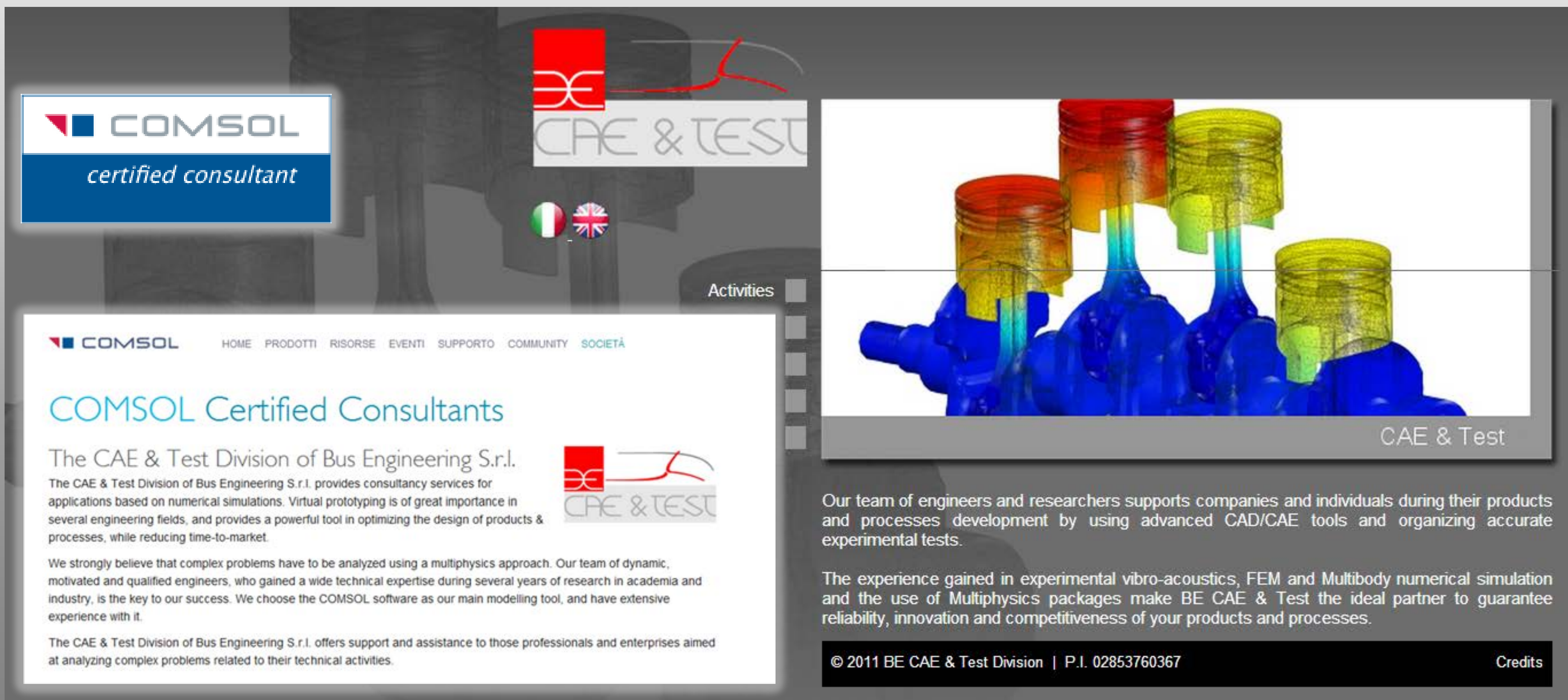


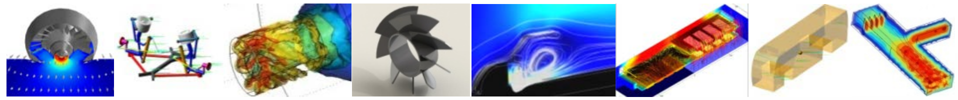


BE CAE & Test

Partnership

http://www.comsol.it/company/consultants/bus/





BE CAE & Test

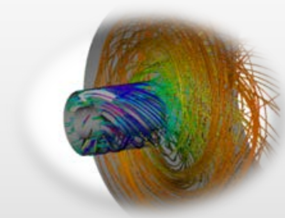
Fields of activity

multiphysics

- **Fluid dynamics and thermal analyses**

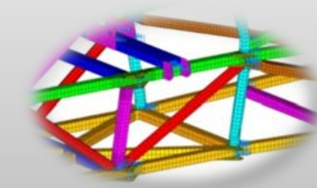
  - Environmental energetics (HVAC, thermal comfort, IAQ)

  - Industrial energetics (Thermal design, energy conversion, reacting flows)



- **Structural analyses**

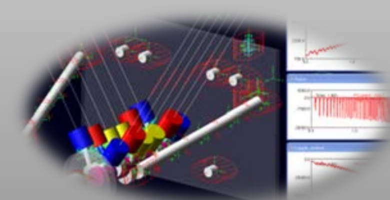
  - Linear and non-linear statics, dynamic and vibro-acustics analyses in industrial and civil applications



- **System dynamics and Multi-body analyses**

  - Vehicle and rail dynamics (handling, ride comfort)

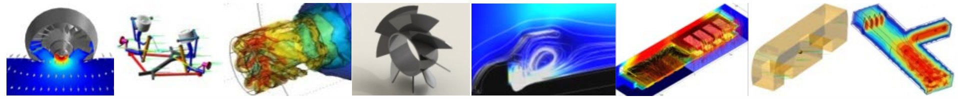
  - Kinematics, dynamics, rigid and flexible bodies analyses of mechanisms



- **Experimental testing**

  - Ride comfort (NVH), modal analyses

  - Human body vibrations (ISO standard)



INTRODUCTION

Technical framework and research target

Heat treatments are used to alter the physical, and sometimes chemical, properties of a material. They **involve the use of heating** or chilling, normally to extreme temperatures, **to achieve** a desired result such as **hardening or softening of a material**

Proper heat treating requires very precise control over temperature, time held at a certain temperature and cooling rate. During the heat treatment **it is** in fact **essential that an uniform thermal load is applied to pieces located inside the furnace** at each time step of the process.

As a consequence, **furnaces need to be designed in order to avoid undesired spatial gradients of temperature** when working.

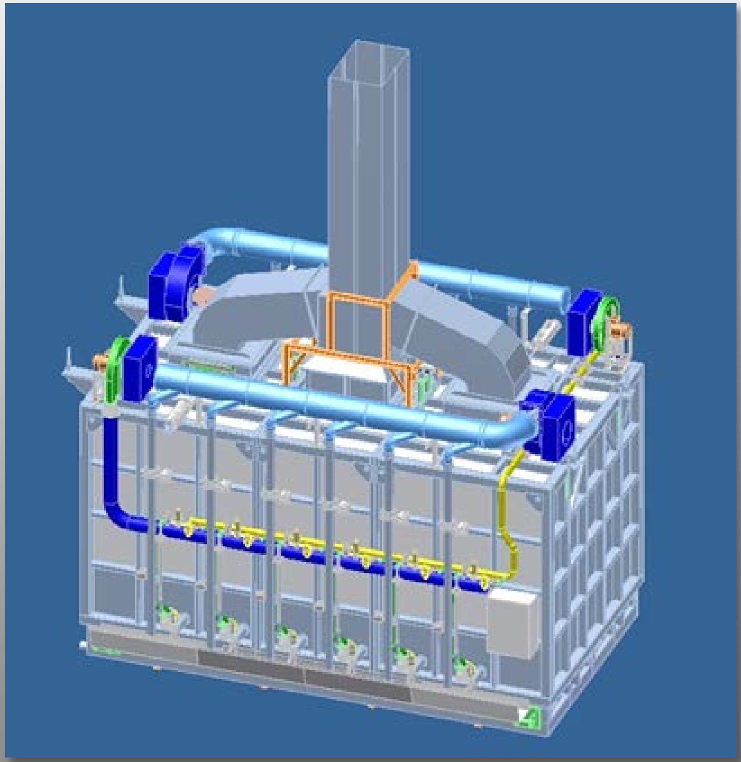
- The present study deals with an **integrated numerical and experimental** analysis aiming at the **investigation of thermal distribution inside an industrial furnace** built for metal materials treatments.
- **The main goal** of the research **is to analyze the influence of geometrical and functional parameters on the thermal distribution** inside the internal volume of the furnace.

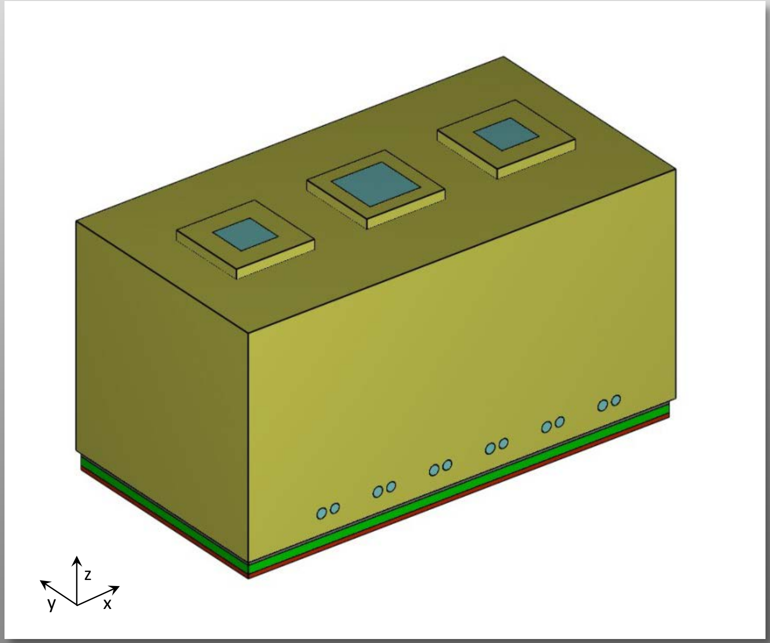


NUMERICAL MODEL

Geometry

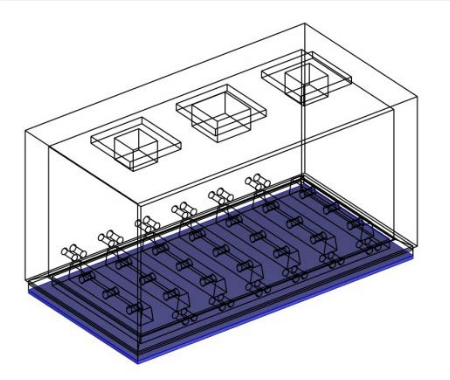
Geometry used for computations is derived by the original CAD of the furnace, **depurated by** all **details not** strictly **needed for fluid-dynamical and thermal simulation**



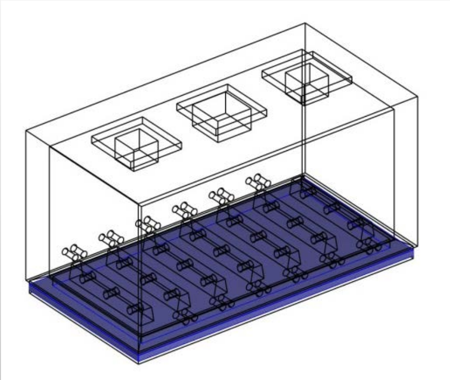


NUMERICAL MODEL

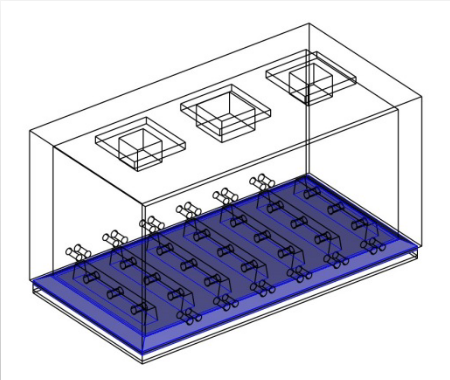
Geometry



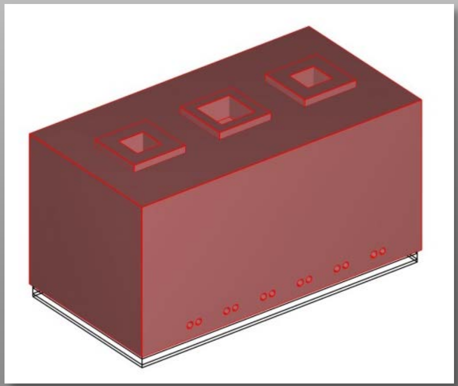
MOSCONI ISO-450
Refractory basement #1



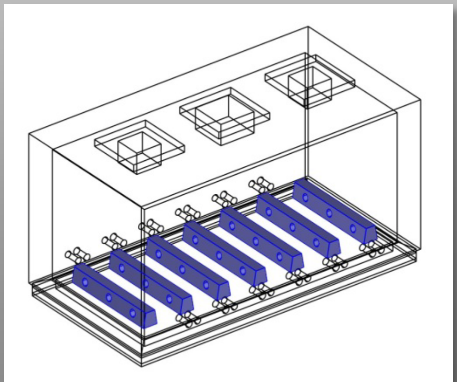
FIR 23 - 0,8 HT
Refractory basement #2



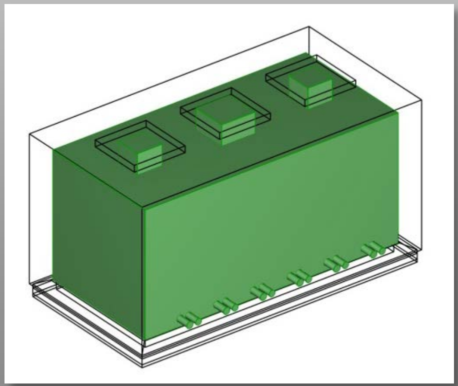
CALDECAST 1560
Refractory basement #3



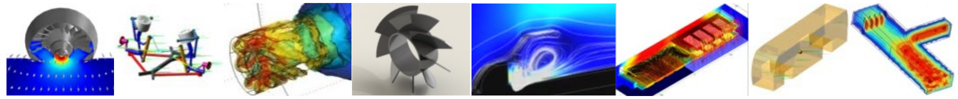
FIBERFRAX
Insultaing layer



Support for pieces
Steel



Air volume
Ideal gas



NUMERICAL MODEL

Equations and boundary conditions

<u>Fluid dynamics</u>

Newtonian fluid and uncompressible turbulent flow (k-ε model)

$$\rho \frac{\partial \mathbf{U}}{\partial t} + \rho \left(\mathbf{U}\cdot\nabla\right)\mathbf{U} = \nabla \cdot \left[-p\mathbf{I} + \left(\mu+\mu_T\right)\left(\nabla\mathbf{U}+\left(\nabla\mathbf{U}\right)^{\mathrm{T}}\right)\right] + F$$

$$\nabla \cdot \mathbf{U} = 0$$

$$\rho \frac{\partial k}{\partial t} + \rho\mathbf{U}\cdot\nabla k = \nabla \cdot \left[\left(\mu+\frac{\mu_T}{\sigma_k}\right)\nabla k\right] + \frac{1}{2}\mu_T\left[\nabla\mathbf{U}+\left(\nabla\mathbf{U}\right)^{\mathrm{T}}\right]^2 - \rho\varepsilon$$

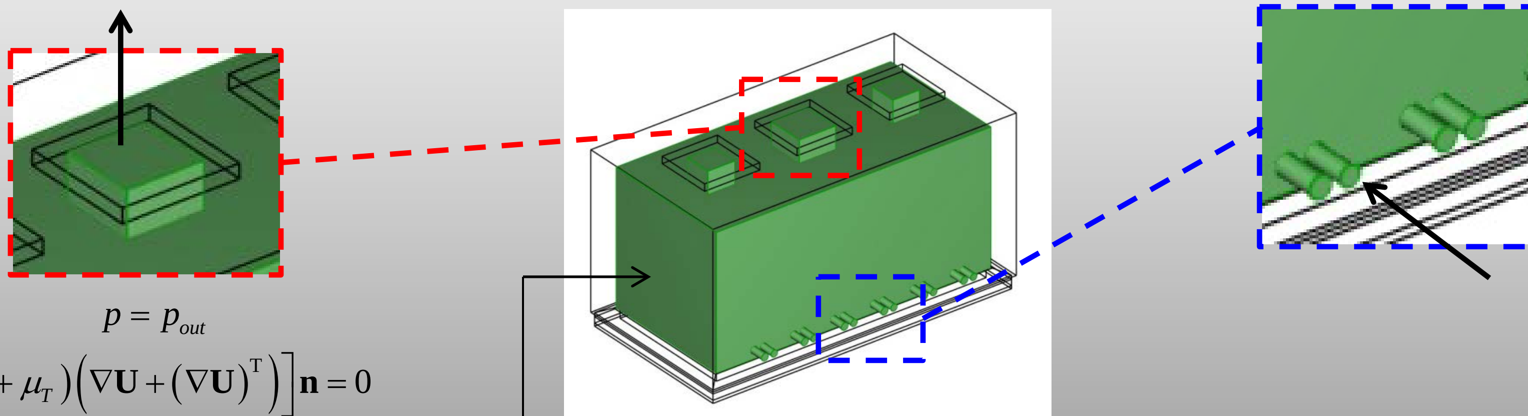
$$\rho \frac{\partial \varepsilon}{\partial t} + \rho\mathbf{U}\cdot\nabla\varepsilon = \nabla \cdot \left[\left(\mu+\frac{\mu_T}{\sigma_\varepsilon}\right)\nabla\varepsilon\right] + \frac{1}{2}C_{\varepsilon 1}\frac{\varepsilon}{k}\mu_T\left[\nabla\mathbf{U}+\left(\nabla\mathbf{U}\right)^{\mathrm{T}}\right]^2 - \rho C_{\varepsilon 2}\frac{\varepsilon^2}{k}$$

NUMERICAL MODEL

Equations and boundary conditions

Fluid dynamics

Boundary conditions



$$p = p_{out}$$

$$\left[(\mu+\mu_T)\left(\nabla\mathbf{U}+(\nabla\mathbf{U})^{\mathrm{T}}\right)\right]\mathbf{n}=0$$

$$\mathbf{U} = -U_{in}\mathbf{n}$$

$$\mathbf{n}\cdot\mathbf{U}=0$$

$$\left[(\mu+\mu_T)\left(\nabla\mathbf{U}+(\nabla\mathbf{U})^{\mathrm{T}}\right)\right]\mathbf{n}=\left[\rho C_\mu^{0.25}k^{0.5}/\left(\ln\left(\delta_w^+\right)/\kappa+C^+\right)\right]\mathbf{U}$$

NUMERICAL MODEL

Equations and boundary conditions

Thermal analysis

Rosseland approximation in order to express the radiating term in the energy equation

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{U} \cdot \nabla T = \nabla \cdot \left(\lambda \nabla T\right) + Q + \boxed{\nabla q_r}$$

$$\boxed{\nabla q_r} = \nabla \cdot \left(\frac{4}{3\kappa_R} \nabla E_b\right) = \nabla \cdot \left(\frac{4}{3\kappa_R} \nabla\left(\sigma T^4\right)\right) = \nabla \cdot \left(\frac{16\sigma T^3}{3\kappa_R} \nabla T\right) = \boxed{\nabla \cdot \left(\lambda_R \nabla T\right)}$$

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{U} \cdot \nabla T = \underline{\nabla \cdot \left((\lambda + \lambda_R) \nabla T\right)} + Q$$

NUMERICAL MODEL

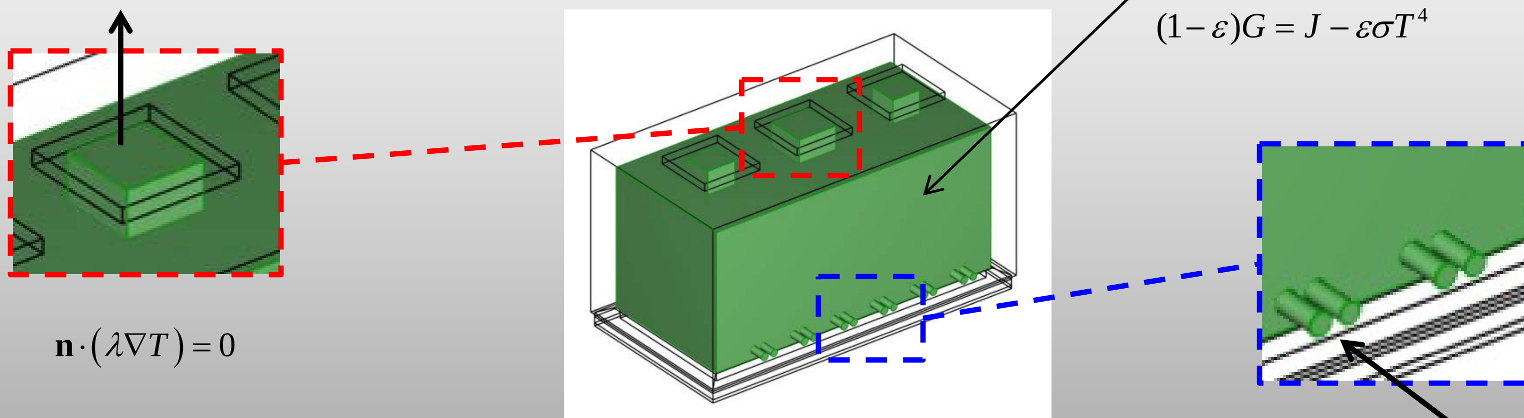
Equations and boundary conditions

Thermal analysis

Boundary conditions

$$\mathbf{n}\cdot\left(\lambda\nabla T\right)=\varepsilon(G-\sigma T^4)$$

$$(1-\varepsilon)G = J-\varepsilon\sigma T^4$$



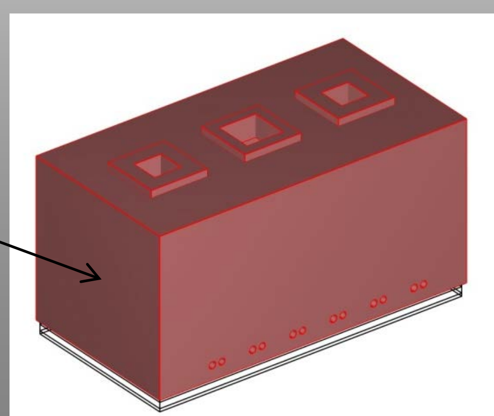
$$\mathbf{n}\cdot\left(\lambda\nabla T\right)=0$$

$$T = T_{in}$$

or

$$-n\cdot\left(-\lambda\nabla T\right)=q_0$$

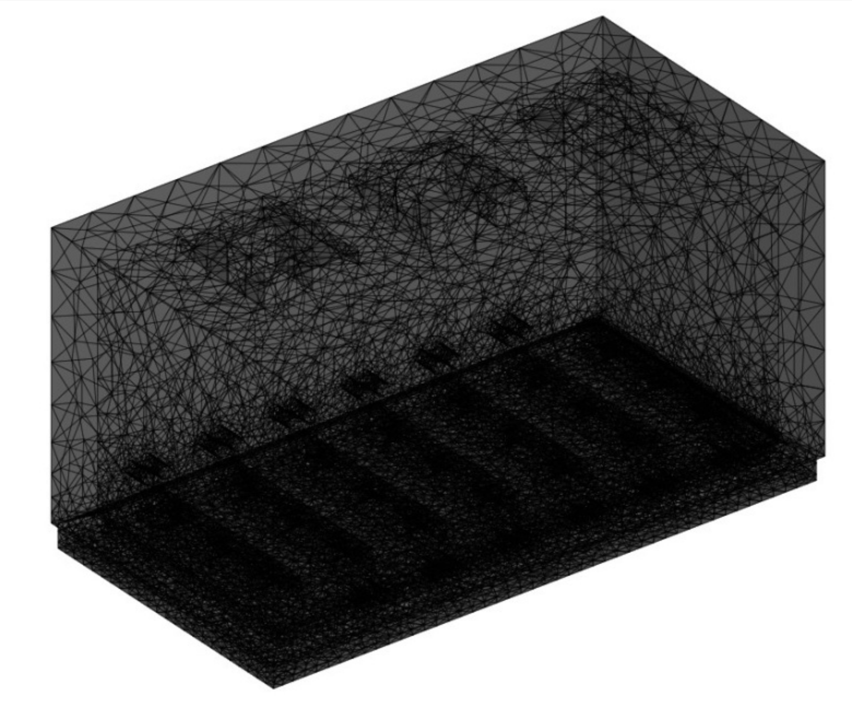
$$\mathbf{n}\cdot\left(\lambda\nabla T\right)=h(T_{amb}-T)+\varepsilon(T_{amb}^4-T^4)$$



NUMERICAL MODEL

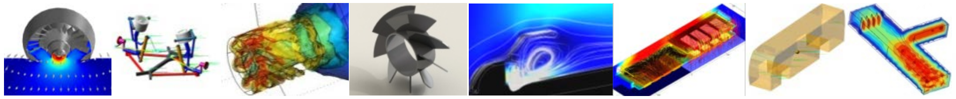
Solving

- Continuous equations discretized on **no-structured** and **no-uniform mesh** made of tetrahedral **Lagrange elements of order 2**
- **Time-marching** performed by an **Implicit Differential-Algebraic** (IDA) solver based on a variable-order and variable-step-size **Backward Differentiation Formulas** (BDF)
- **Steady solutions** achieved by applying an iterative **Newton-Raphson algorithm**
- **Linear system** solved by a **PARDISO package**



Mesh study

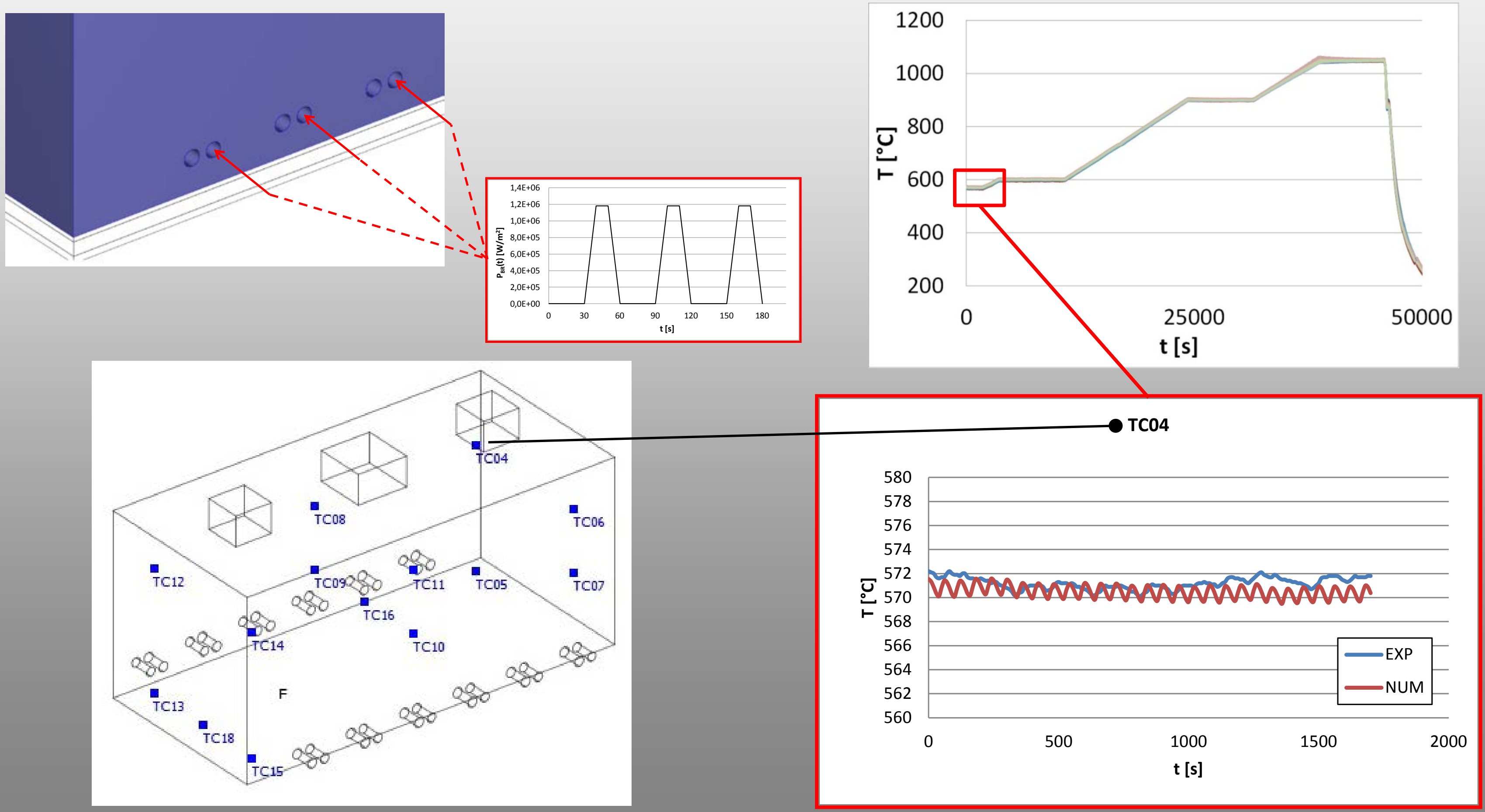
Mesh	Mesh #1	Mesh #2	Mesh #3	Mesh #4	Mesh #5
Degree of freedom	61397	87123	108784	151626	228341
Mesh refinement (%)		29.53%	19.91%	28.26%	33.60%
Temperature in (0; 0; 1,5) [°C]	821.3	829.4	835.5	837.4	838.6
Relative gap	2.07%	1.10%	0.37%	0.14%	0.00%

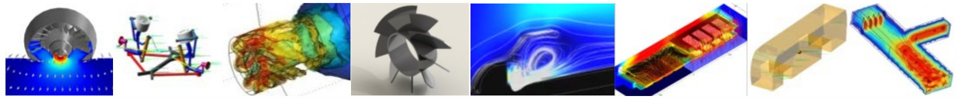


NUMERICAL MODEL

Validation with experimental data (Plateau zone @570 °C)

Computations are carried-out by applying a **periodic thermal flux as thermal input** to the furnace chamber in the FE model, **that simulates** the controlled **ON/OFF** working conditions **for burners**

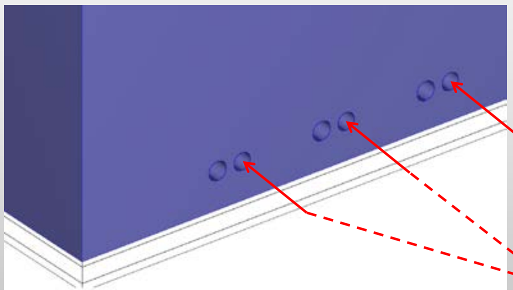


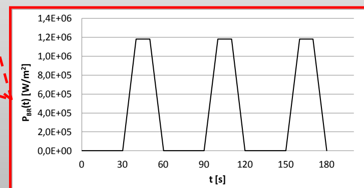


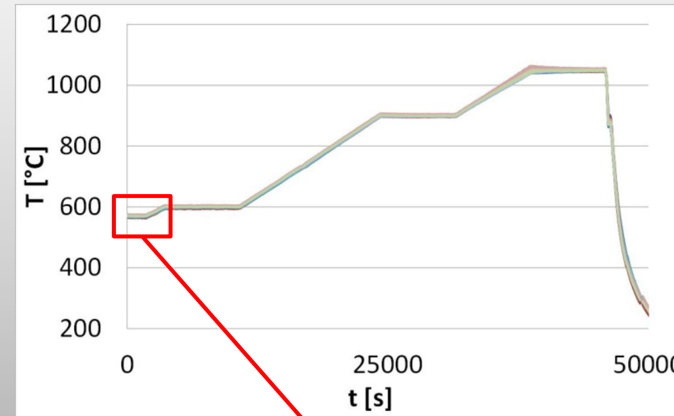
NUMERICAL MODEL

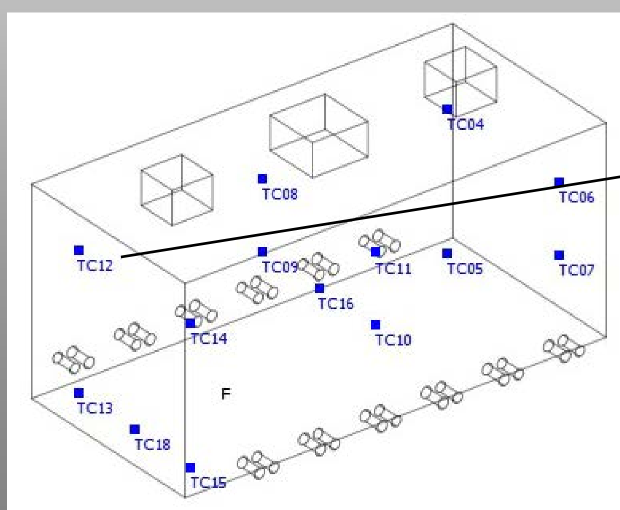
Validation with experimental data (Plateau zone @570 °C)

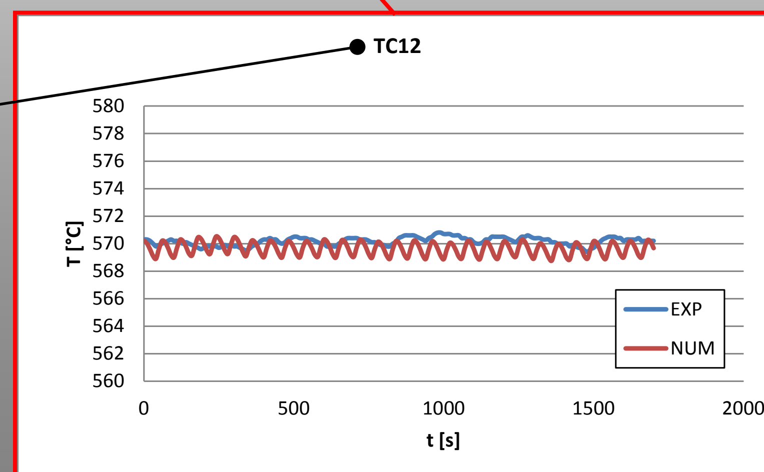
Computations are carried-out by applying a **periodic thermal flux as thermal input** to the furnace chamber in the FE model, **that simulates** the controlled **ON/OFF** working conditions **for burners**







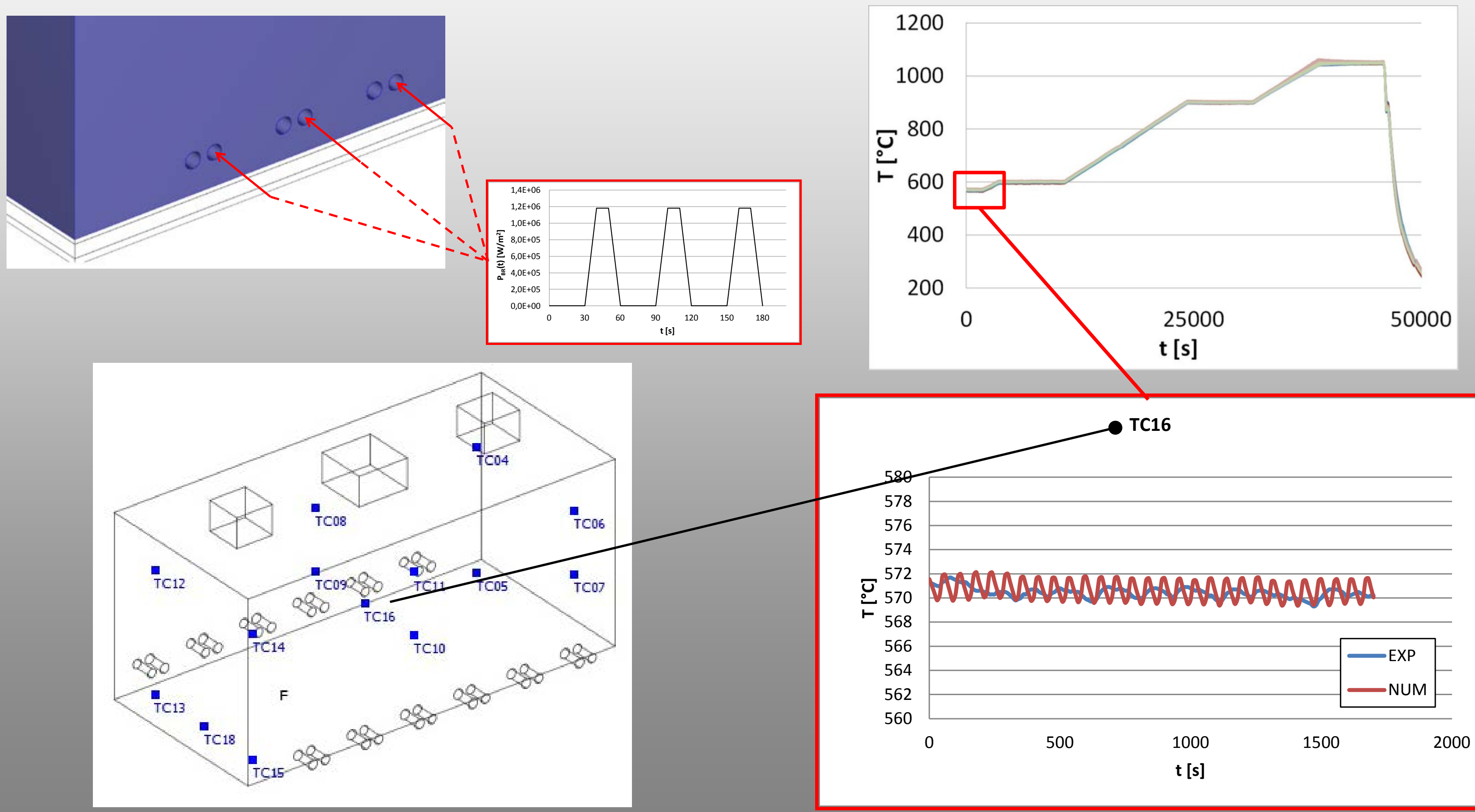




NUMERICAL MODEL

Validation with experimental data (Plateau zone @570 °C)

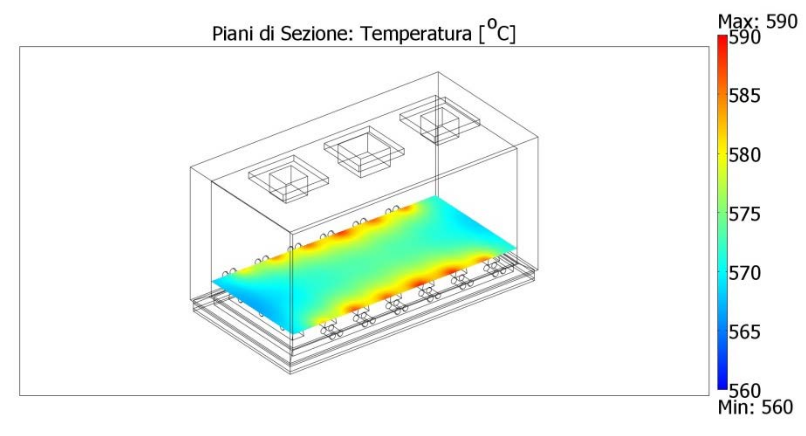
Computations are carried-out by applying a **periodic thermal flux as thermal input** to the furnace chamber in the FE model, **that simulates** the controlled **ON/OFF** working conditions **for burners**

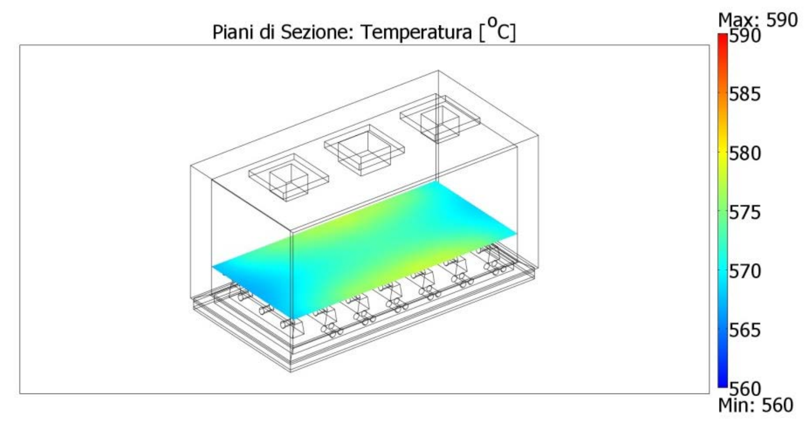


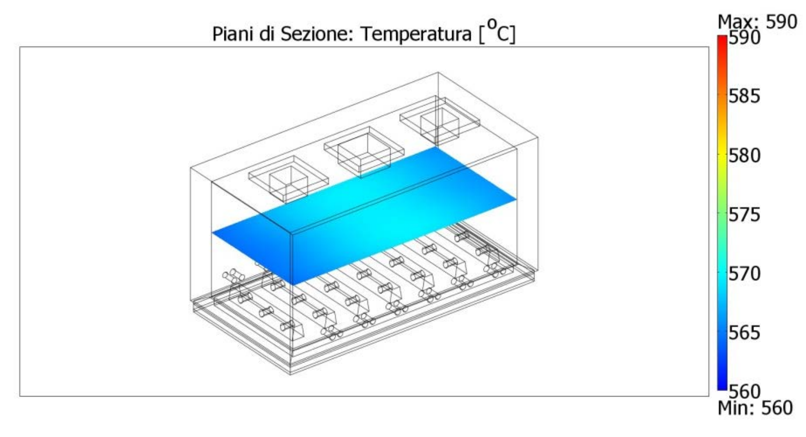
RESULTS

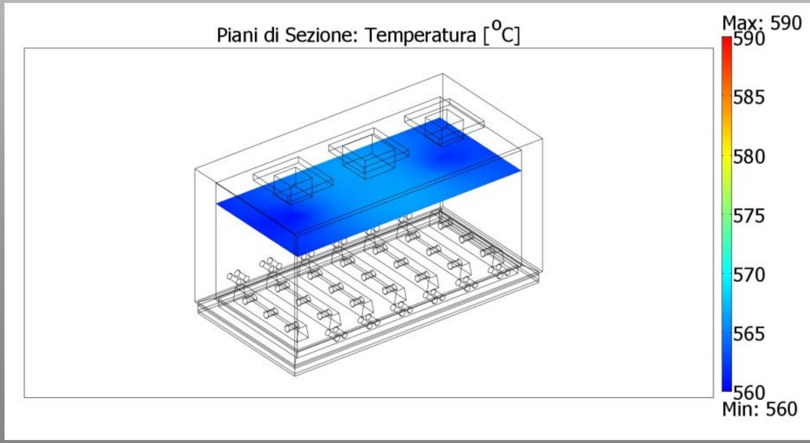
“Base configuration”

✓ **Thermal distribution** in **horizontal** sections of the chamber





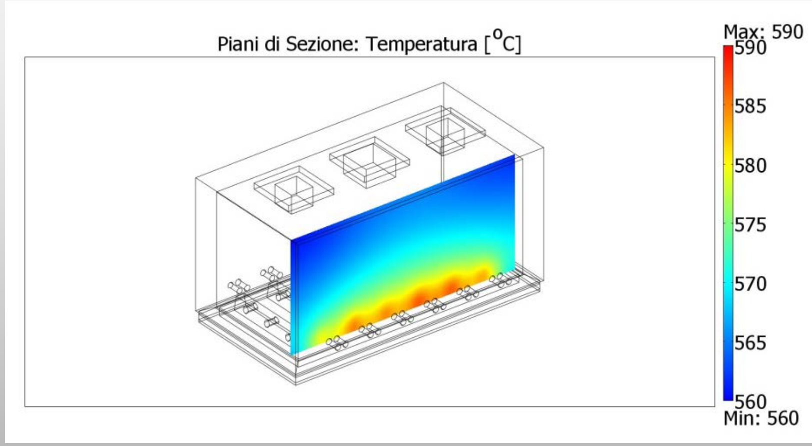


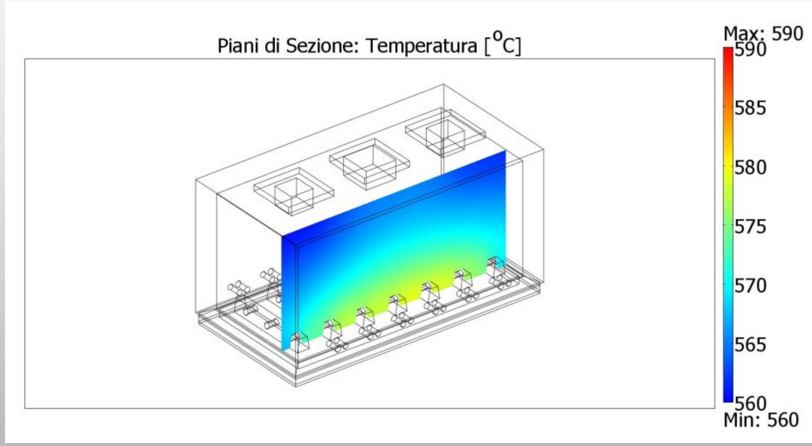


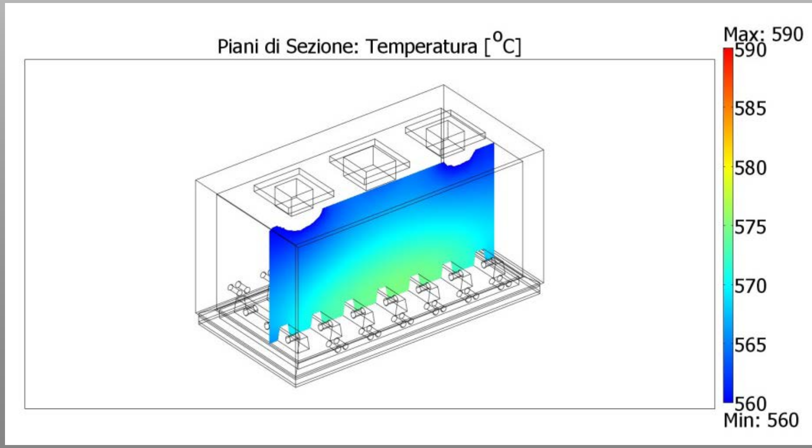
RESULTS

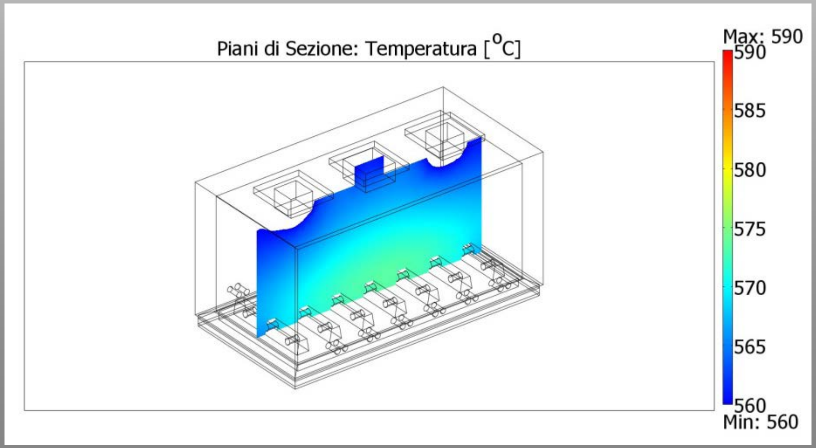
“Base configuration”

✓ **Thermal distribution** in **vertical** sections of the chamber





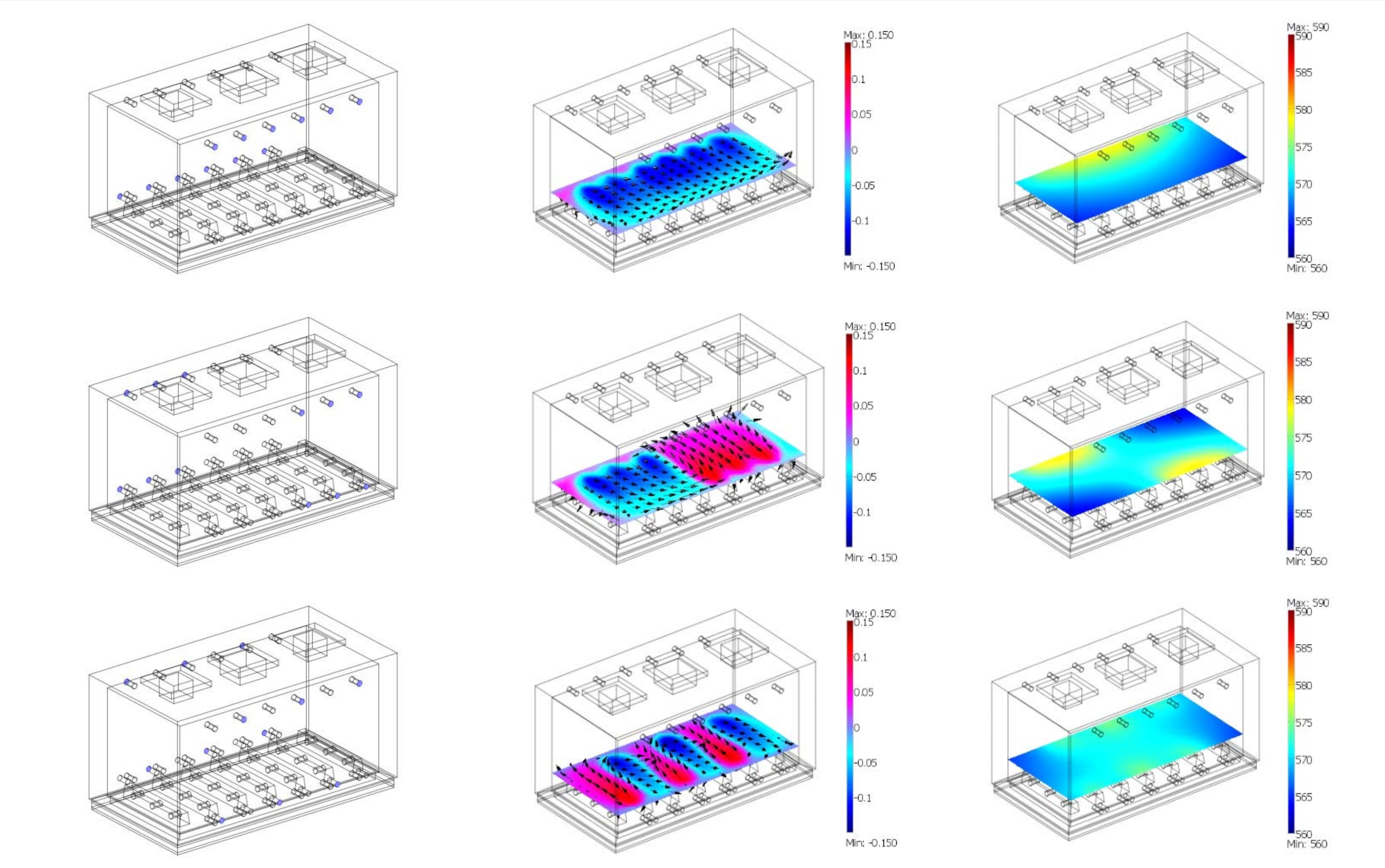




RESULTS

Influence of active burners location

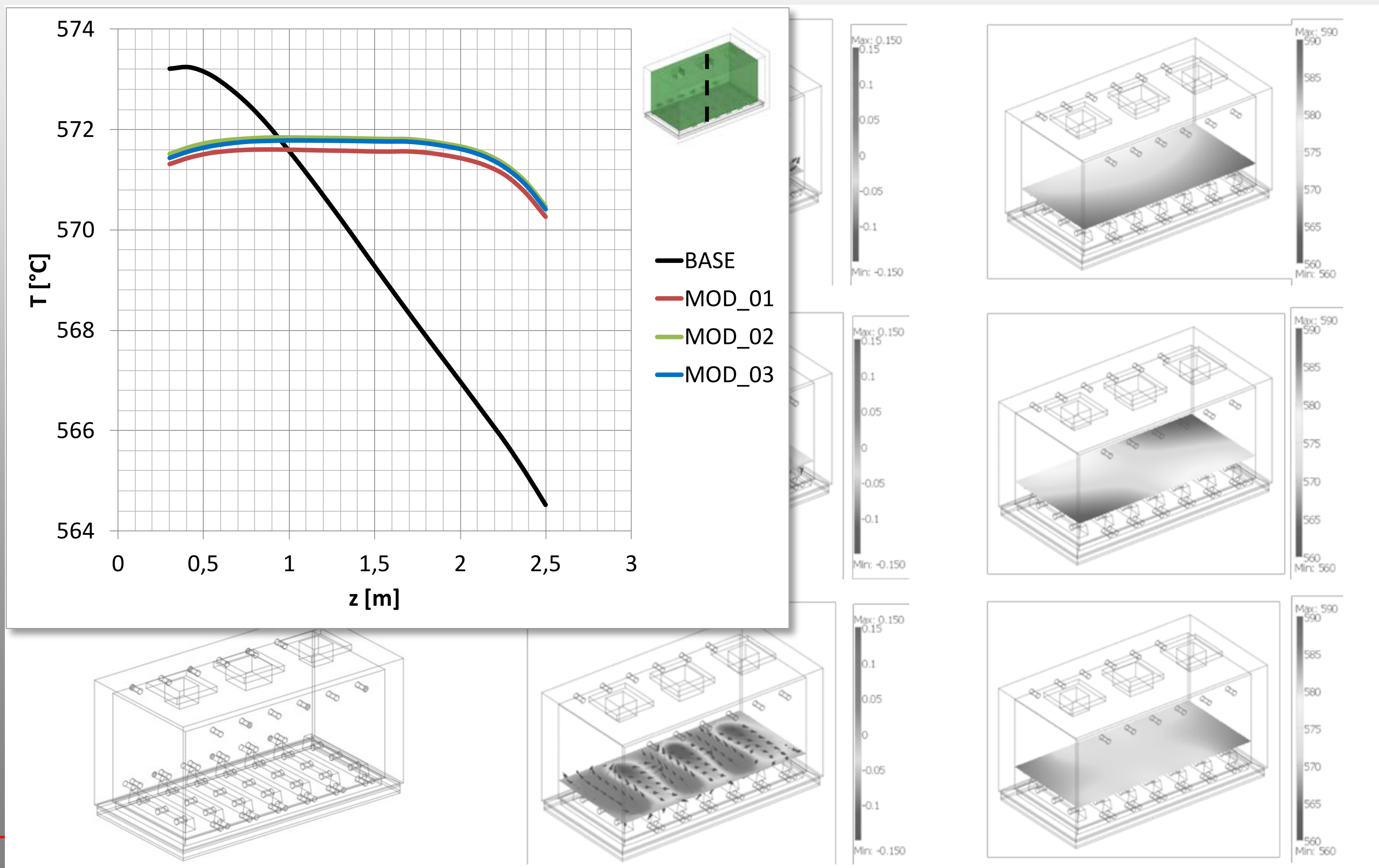
✓ **Fluid dynamical** and **thermal** distribution in **horizontal** sections of the chamber



RESULTS

Influence of active burners location

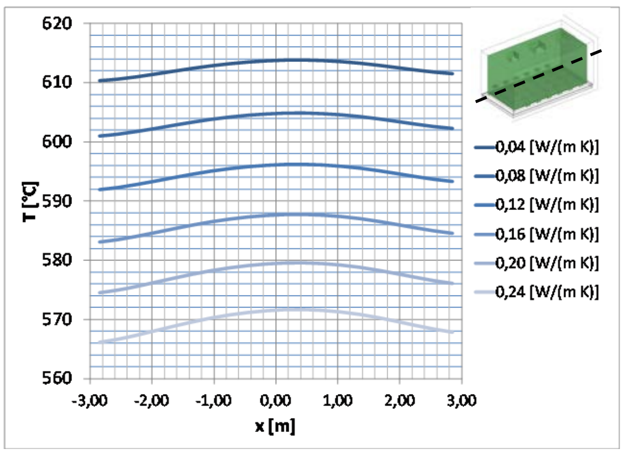
✓ **Thermal** profile along the z-direction of the chamber for the studied configurations

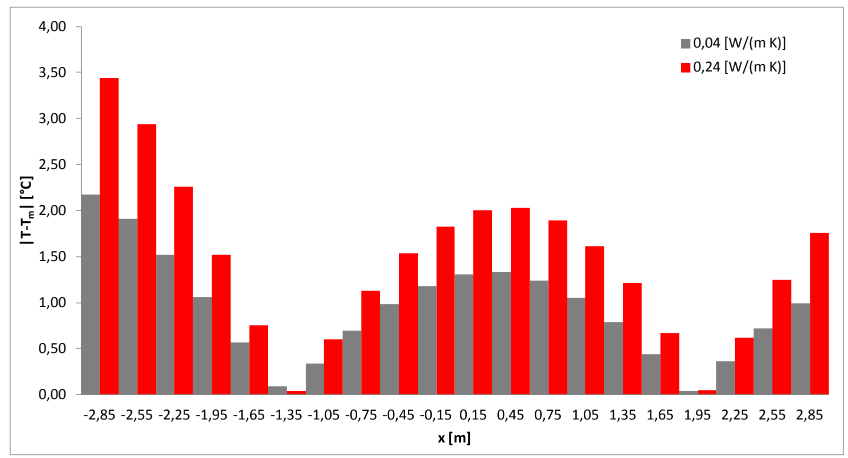


RESULTS

Influence of envelope thermal resistance

- ✓ **Temperature** profile along the x-direction as a function of the **thermal conductivity** of the insulating layer
- ✓ **Gap between local and average temperature** along the x-direction for chosen thermal conductivity values

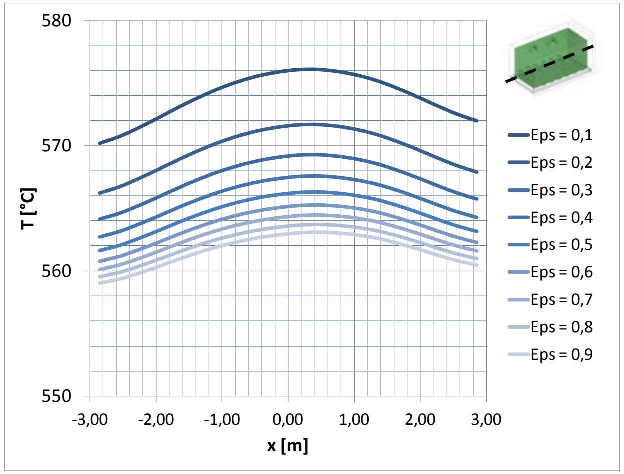


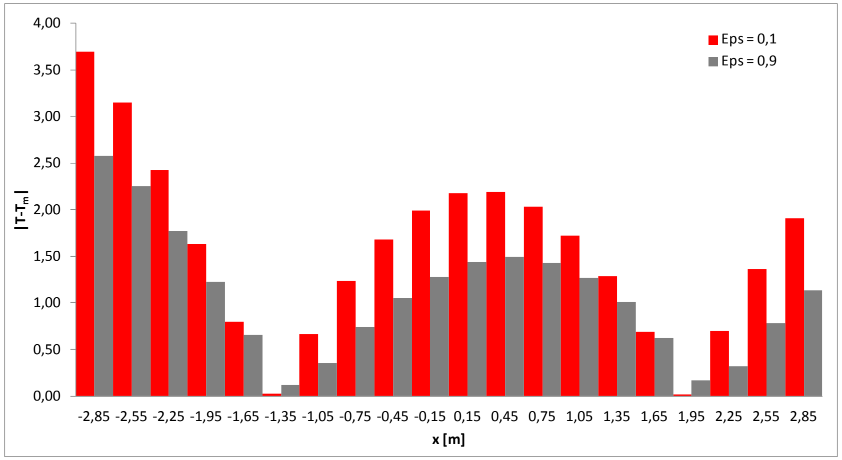


RESULTS

Influence of the internal surface thermal emissivity

- ✓ **Temperature profile** along the x-direction as a function of the **thermal emissivity** of the chamber surface
- ✓ **Gap between local and average temperature** along the x-direction for chosen thermal emissivity values

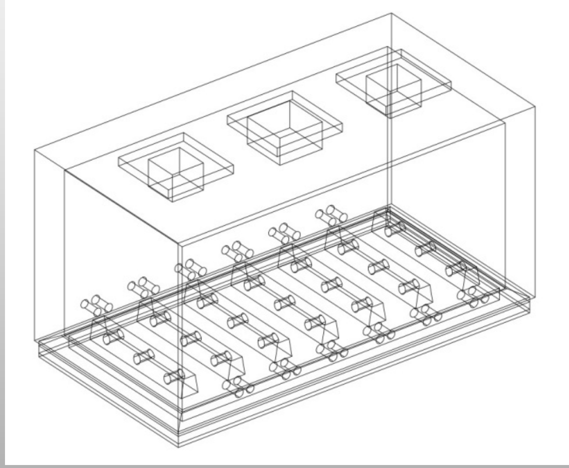


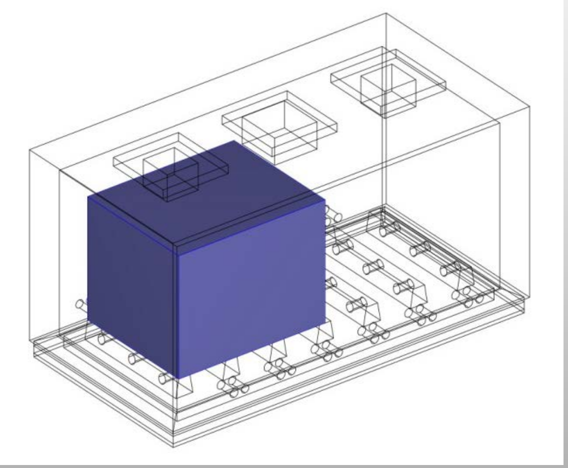


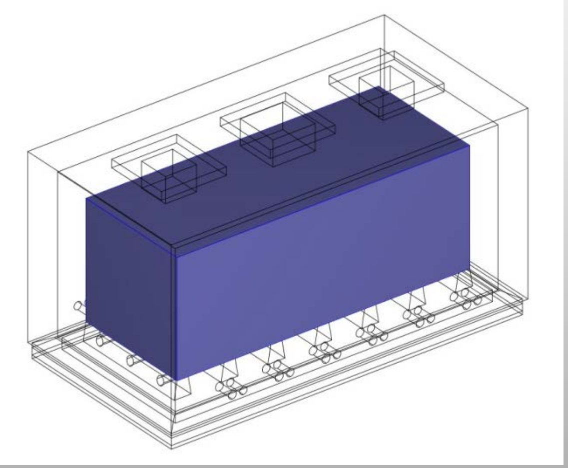
RESULTS

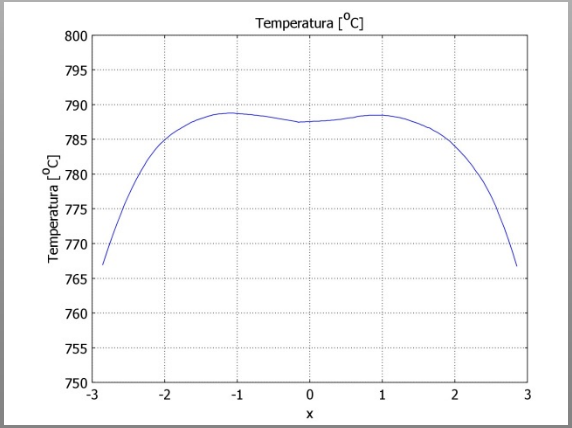
Influence of load

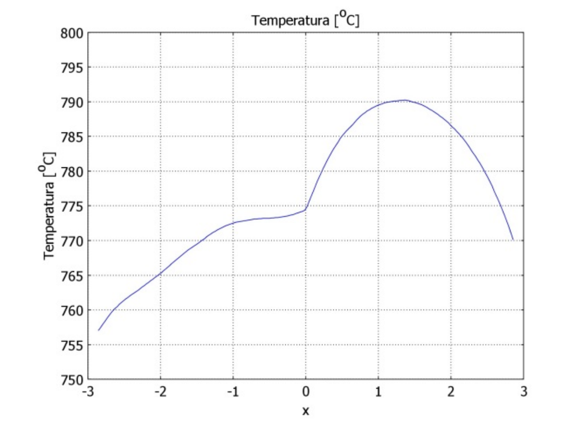
✓ Thermal profile along the x-direction for load-less, half-load and full-load conditions at time instant t=10800 [s] (after 3 hours of heating)

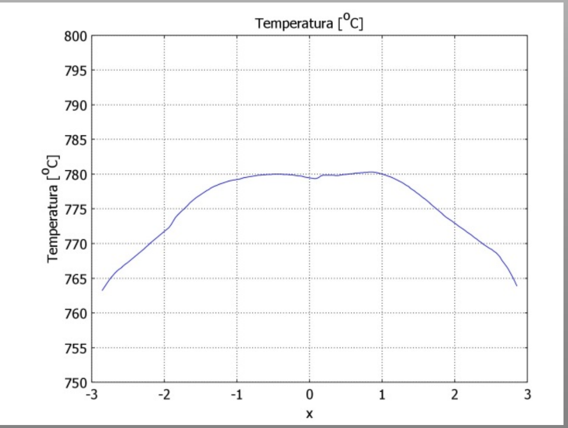


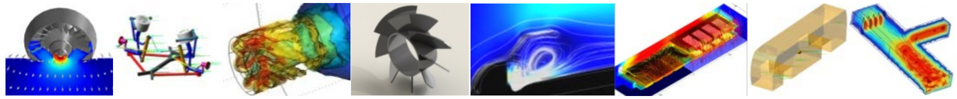










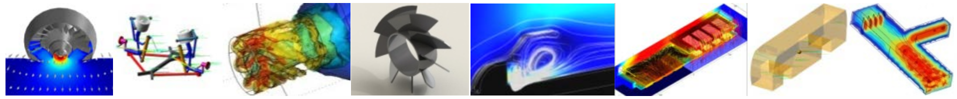


CONCLUSIONS

- An **integrated experimental** and **numerical approach** has been exploited in order **to assess influence** of several **geometrical** and **functional parameters on the internal thermal distribution** inside an **industrial furnace**

- **Experimental acquisitions have been used in order to validate FE models as well as input data for statistical analyses** based on multivariate regression and unsupervised methods

- **Parametrical analyses simulating several working configurations** of the device have been **carried-out, highlighting optimization criteria** related to some design parameters in order **to obtain the most homogeneous thermal distribution inside the furnace**



BE CAE & TEST

VIALE AFRICA, 44 – 95129 CATANIA (CT)

TEL: +39 095 286 4040

URL: http://www.be-caetest.it
E-mail: info@be-caetest.it

C.F., P.IVA 02853760367 - REA: 303591

http://www.comsol.it/company/consultants/bus/