A model of heat transfer in metal foaming

B. Chinè[1,2], V. Mussi[2], M. Monno[3], A Rossi[2]

[1]Instituto Tecnológico de Costa Rica, Costa Rica;
[2] Laboratorio MUSP, Macchine Utensili e Sistemi di Produzione, Piacenza, Italy;
[3]Politecnico di Milano, Italy.

bchine@itcr.ac.cr

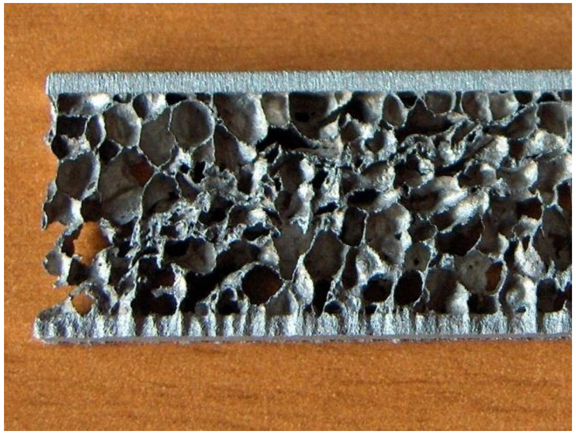
TEC Tecnológico de Costa Rica

MUSP
Macchine Utensili e Sistemi di Produzione

COMSOL
CONFERENCE
2015 GRENOBLE

October 14-16, 2015

Presentation overview



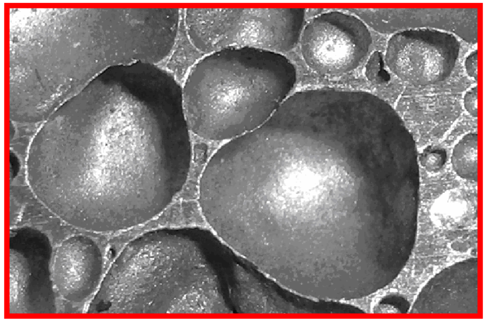
- Introduction
- Foaming process of a metal foam
- Modeling the heat transfer
- Mathematical model
- Numerical results
- Conclusions

Foaming process of a metal foam

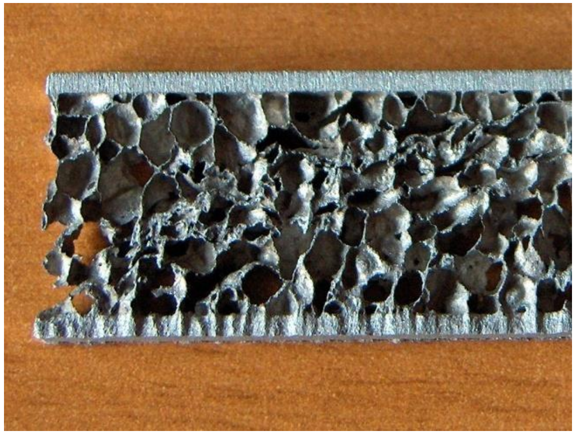
Metal foaming [1,2] is a complex phenomenon:

- simultaneous mass, momentum and energy transfer mechanisms between solid, liquid and gas phases
- **thermal gradient** control the heating, the expanding process of the melted phase and the final solidification of the metal foam
- several physical phenomena on interfaces, interface motion bubble expansion, dynamics, coarsening, rupture, etc.

melted Al and H_2 gas



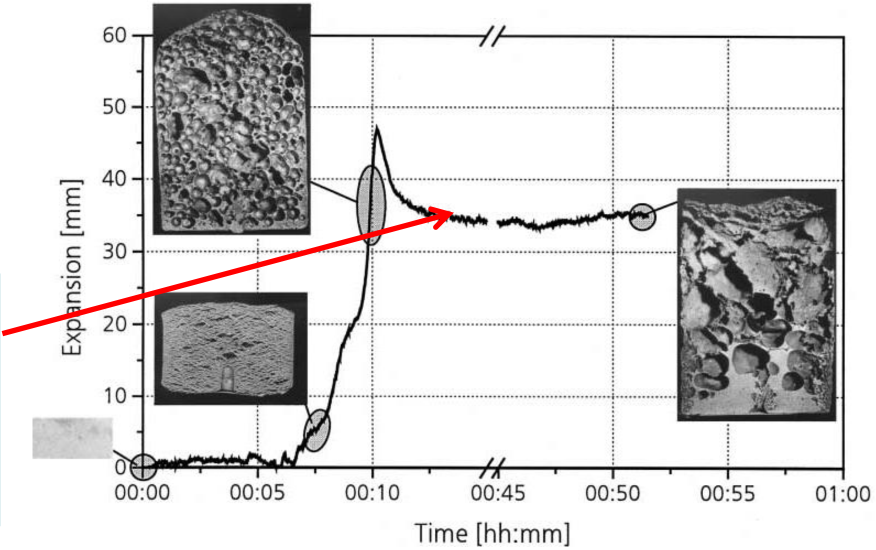
solidified metal foam



Foaming process of a metal foam

Heat treatment at temperatures near the melting point of the matrix material is a fundamental step.

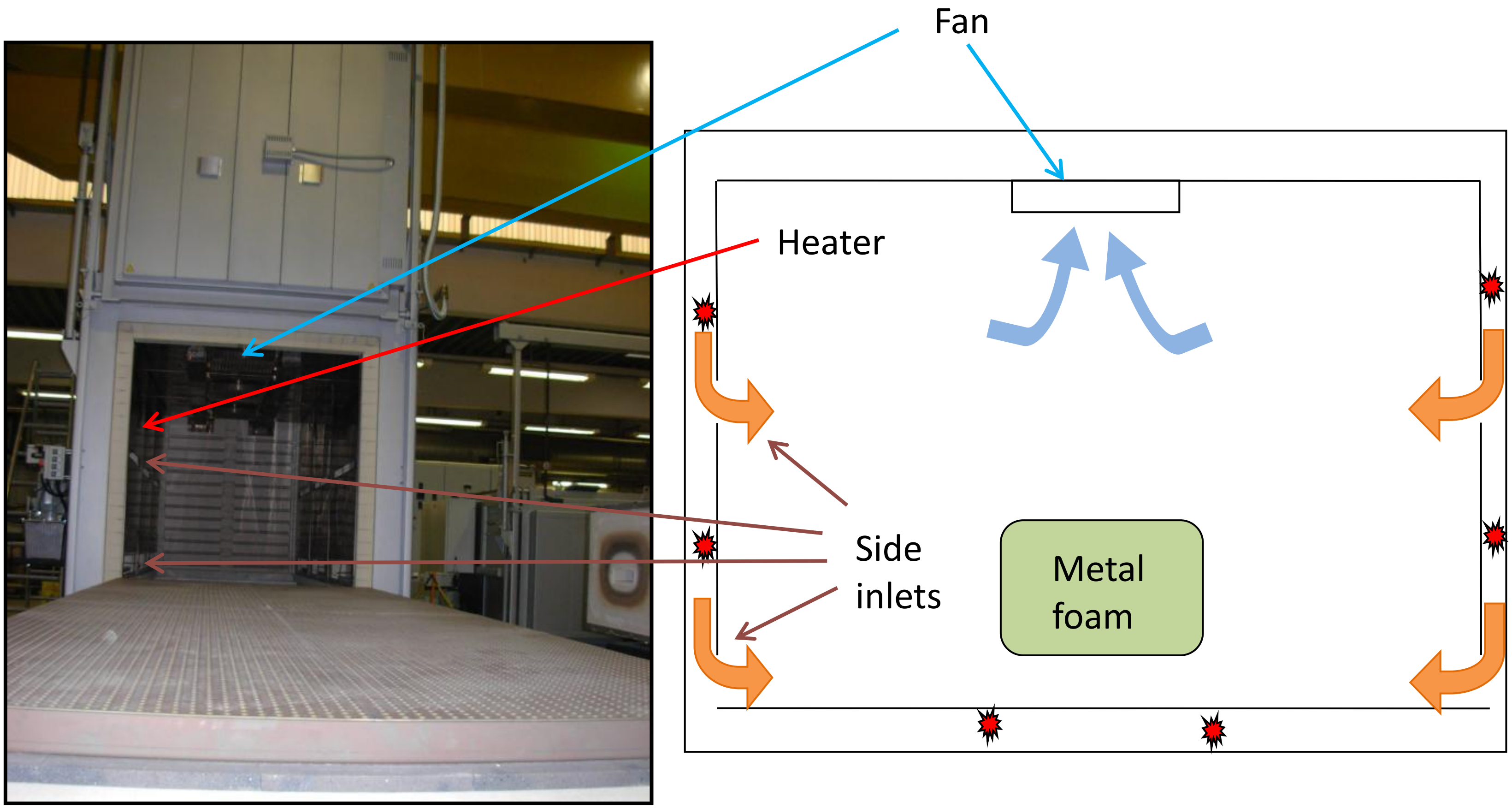
The blowing agent, decompose within the dense metallic matrix. The released gas forces the compacted precursor material to expand, thus forming its highly porous structure.



The time needed for full expansion depends on **temperature** and the size of the precursor and ranges from a few seconds to several minutes.

Metal foaming in a furnace

- The heating process (convective heating process) is carried out in a furnace of dimension 3600x1400x1400 mm^3.
- Air is moved by three fans set on the roof (each one of 2000 W and with a diameter of 400 mm).
- Side inlets convey the air, heated by electric resistive elements, into the furnace volume.



Fan

Heater

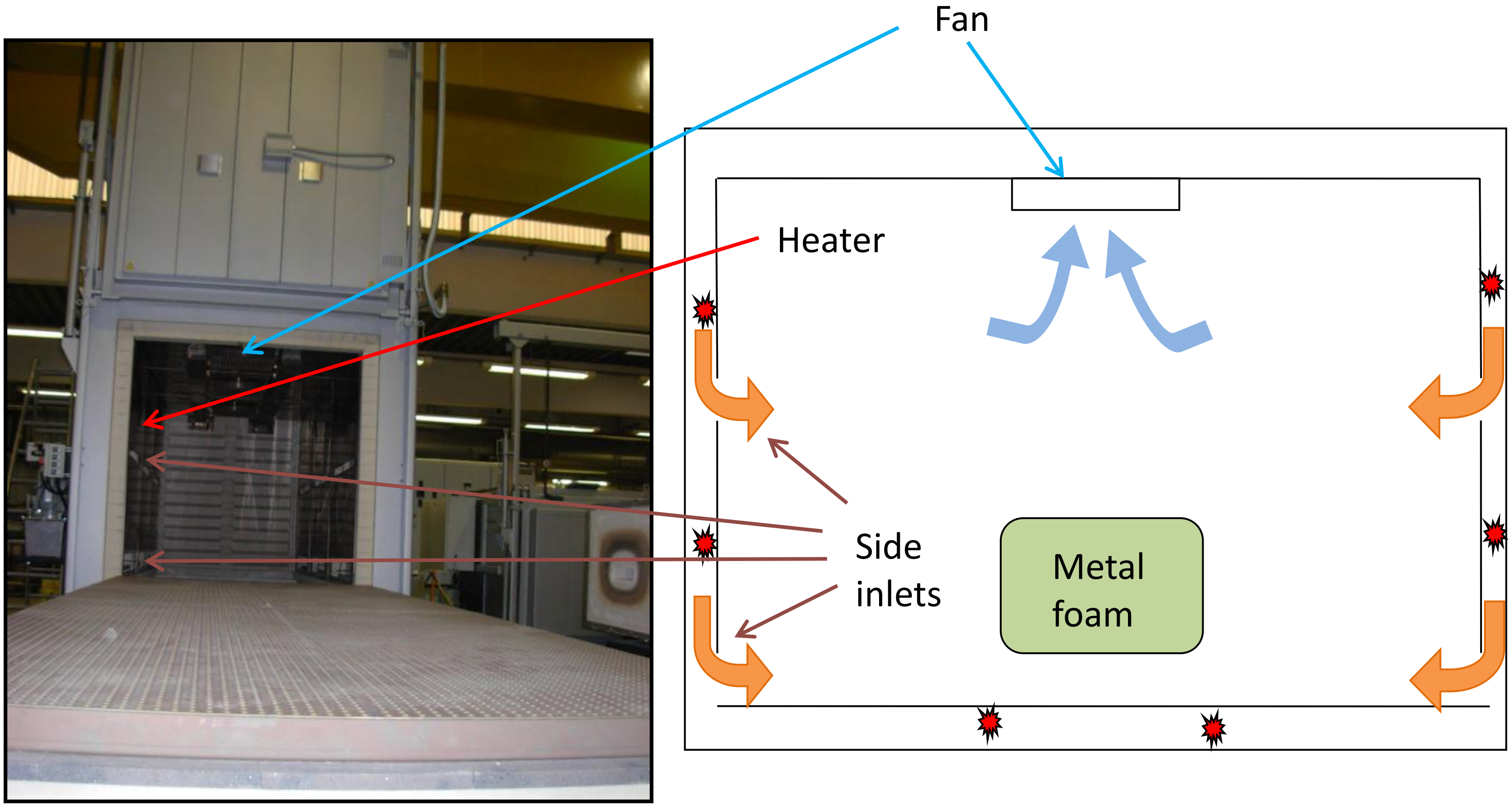
Side inlets

Metal foam

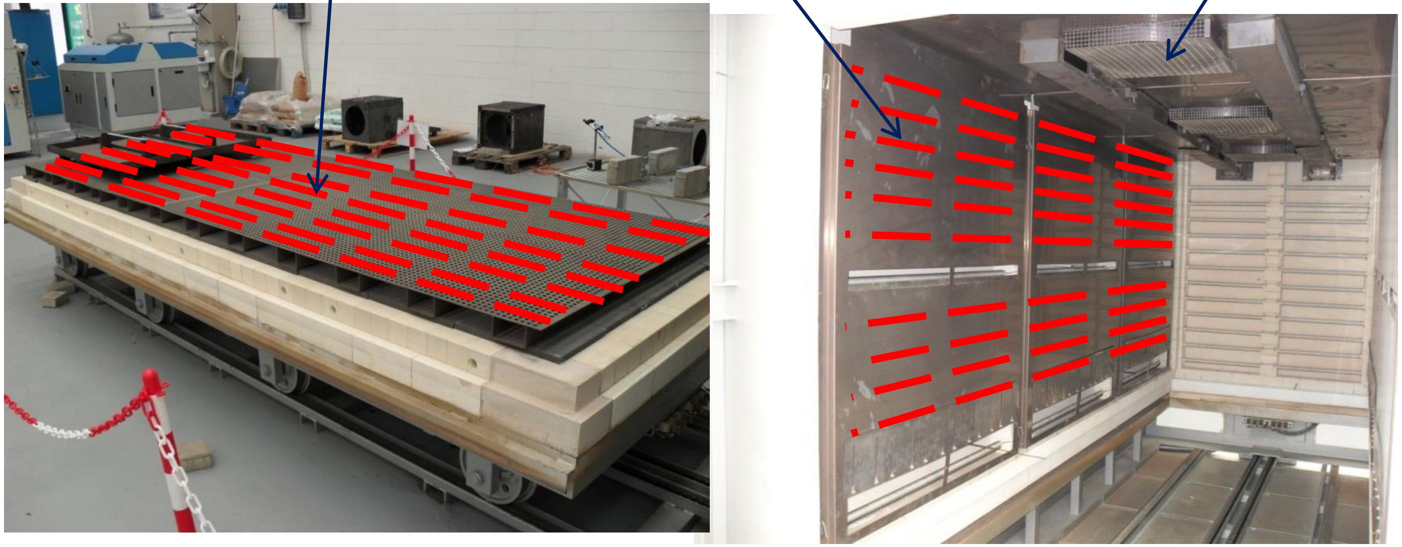
Metal foaming in a furnace

With the component in the furnace, the process time (t_{FIN}) need to foam it completely depends on:

- the foaming temperature (650-700 °C)
- the geometry of the component
- the position of the foam precursor (Al alloy + foaming agent).



Metal foaming in a furnace

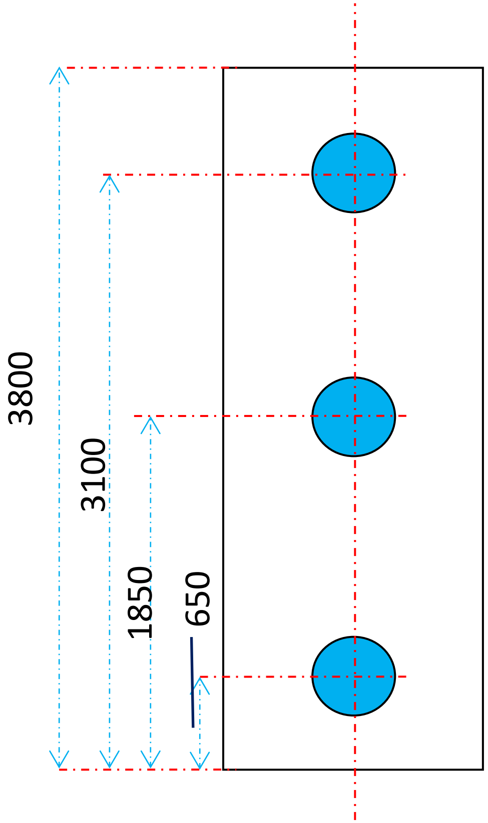


Electric heaters

Fans

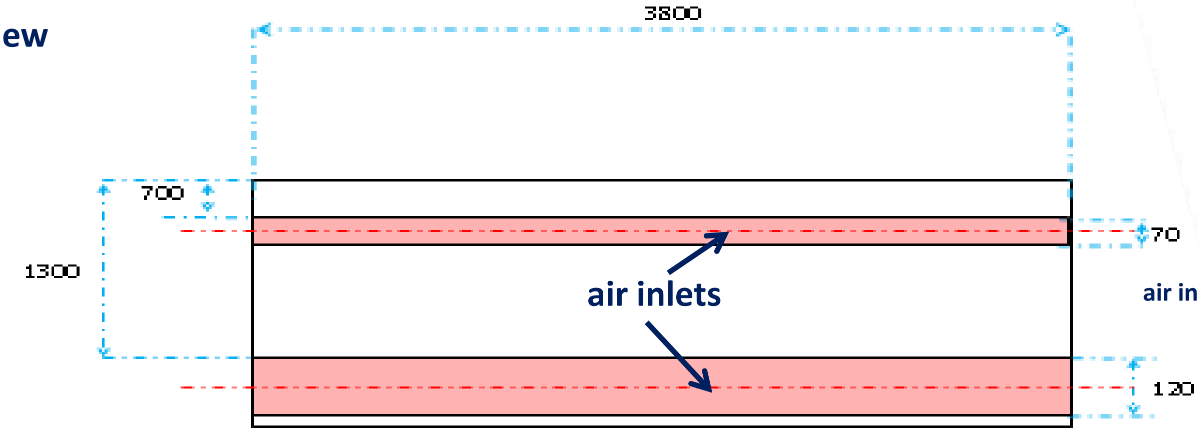
Distance (mm) between the fans

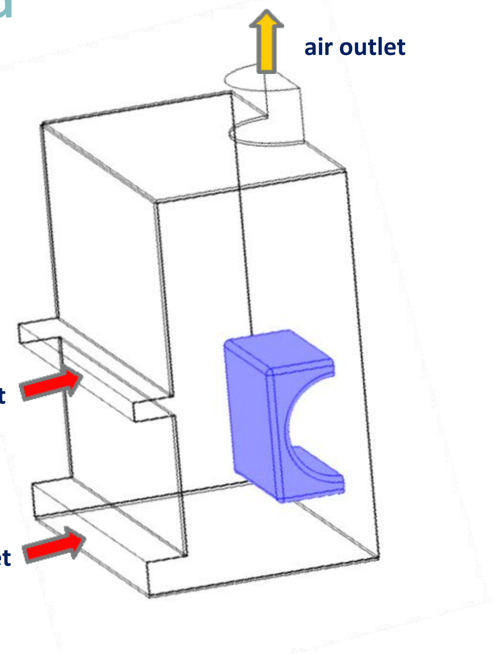
Fans



Dimensions (mm) of air inlets and component to be foamed

side view

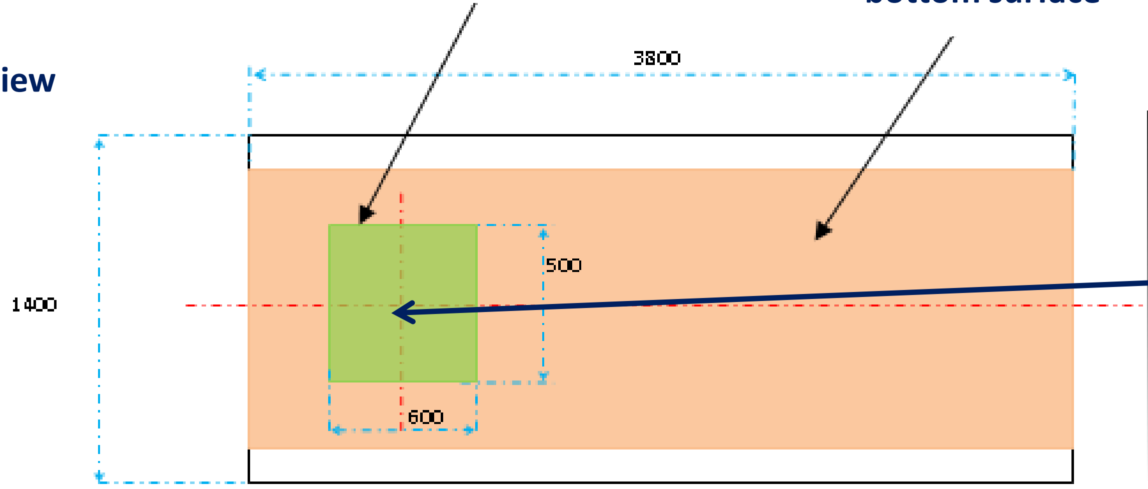




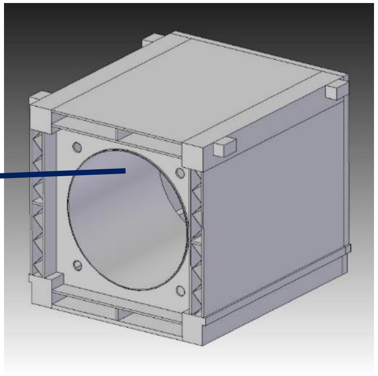
component

bottom surface

cross view



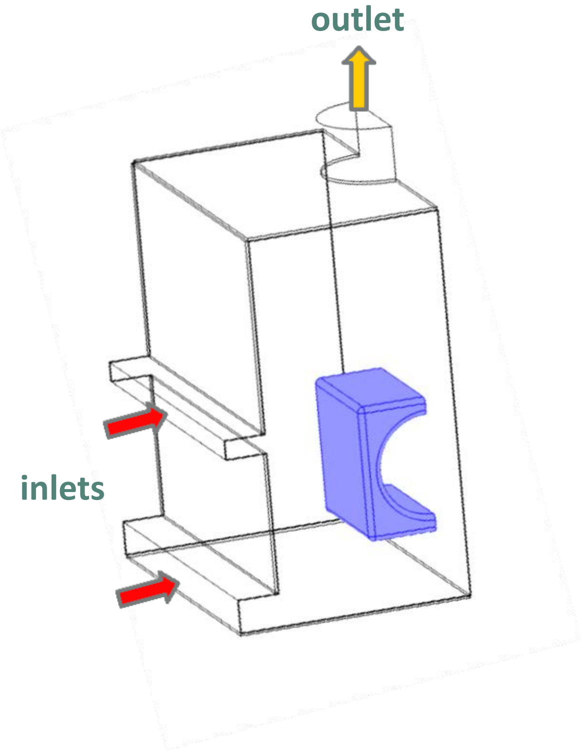
component



Modeling the heat transfer in the furnace

- The 3D furnace is divided in three similar sections. The first section containing the piece is modeled.
- The heating process is considered transient and the air flow is assumed to be compressible and turbulent. The foaming time is 1 hr.
- Electric heaters are not modeled, the air temperature is set at inlet.
- Conductive, convective and radiative heat phenomena are considered.
- The material of the piece is a common structural steel.
- The following emissivity of the structural steel, obtained experimentally [3], is used in the model:

$$\varepsilon_{steel} = 0.082 * \exp(0.0035\, T(^\circ C))$$



Mathematical model

The mathematical model is developed by coupling the equation of heat transfer to the fluid flow equations of conservation of mass and momentum (conjugate heat transfer in Comsol).

In the model we use the **Reynolds-averaged Navier-Stokes (RANS) equations** [5, 6] equations and the **transport equations for the turbulent kinetic energy** κ **and the dissipation rate** ε, given by:

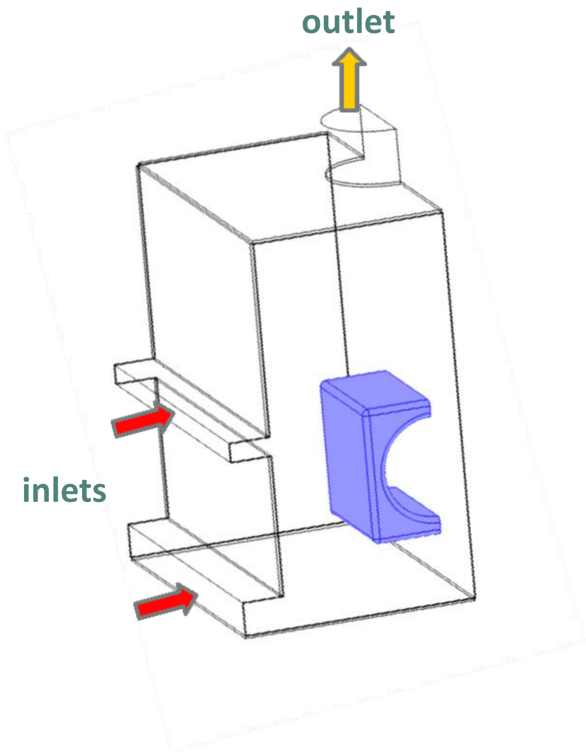
$$\rho\frac{\partial k}{\partial t}+\rho\mathbf{u}\cdot\nabla k=\nabla\cdot\left(\left(\mu+\frac{\mu_T}{\sigma_k}\right)\nabla k\right)+P_k-\rho\varepsilon$$

$$\rho\frac{\partial \varepsilon}{\partial t}+\rho\mathbf{u}\cdot\nabla \varepsilon=\nabla\cdot\left(\left(\mu+\frac{\mu_T}{\sigma_\varepsilon}\right)\nabla \varepsilon\right)+C_{\varepsilon 1}\frac{\varepsilon}{k}P_k-C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k}$$

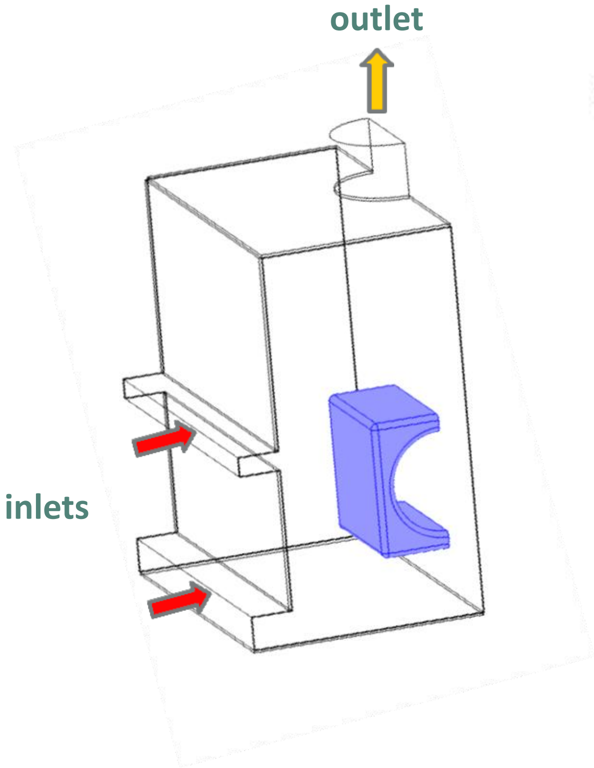
Standard coefficients of the k-ε model used.

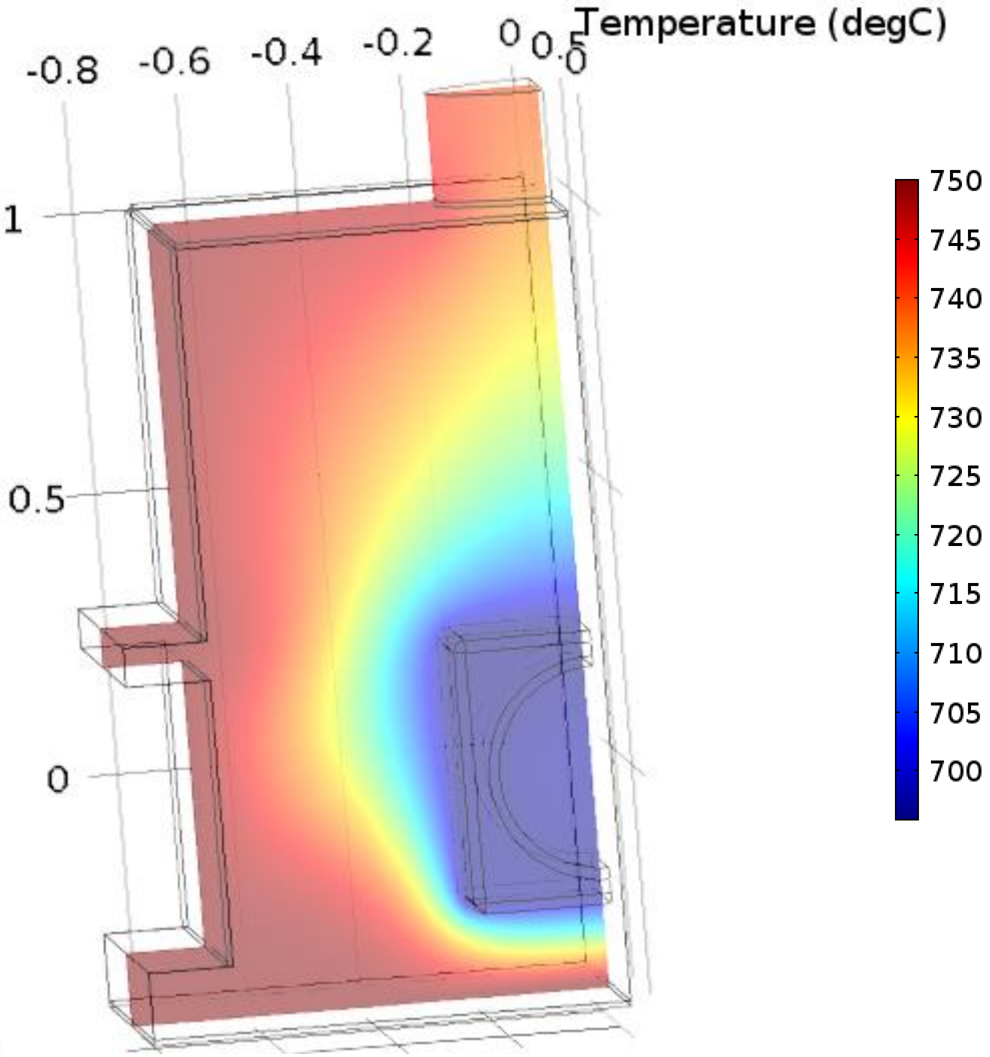
Boundary conditions

- Velocity of 4 m/s and temperature of 750 ^{0}C for the air at the inlets.
- Velocity of air (fan driven) set equal to 16 m/s at the outlet.
- The initial temperature of the component is 40 ^{0}C.
- The temperature of the wall is 750 ^{0}C.
- Slip condition for the air velocity at the walls.
- Symmetry in the vertical central plane.

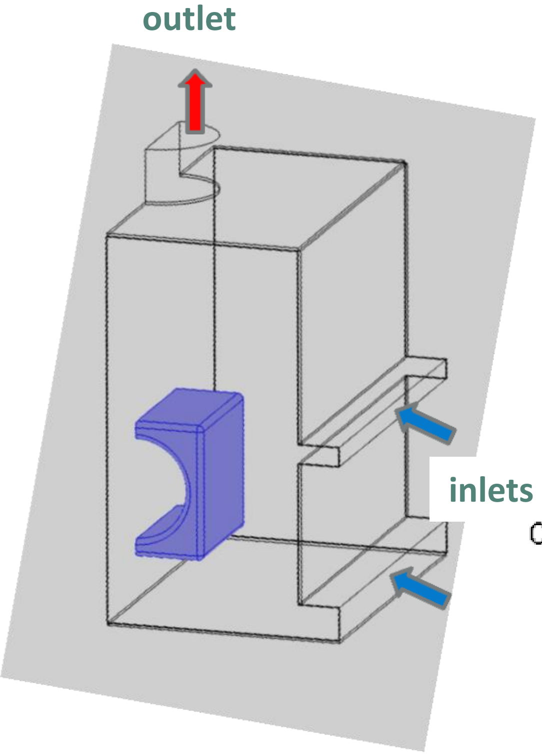


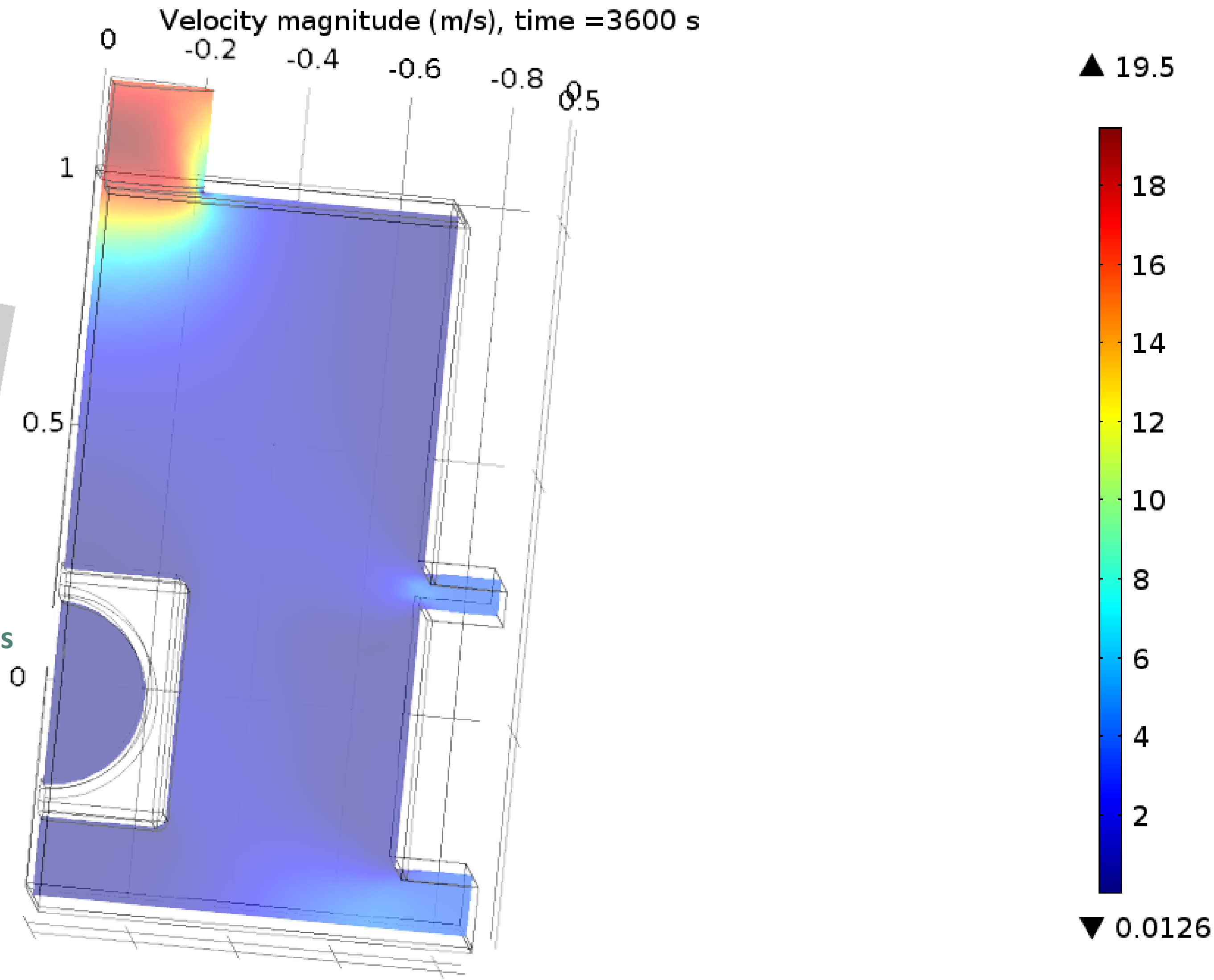
Numerical results: temperature in a vertical plane of the furnace



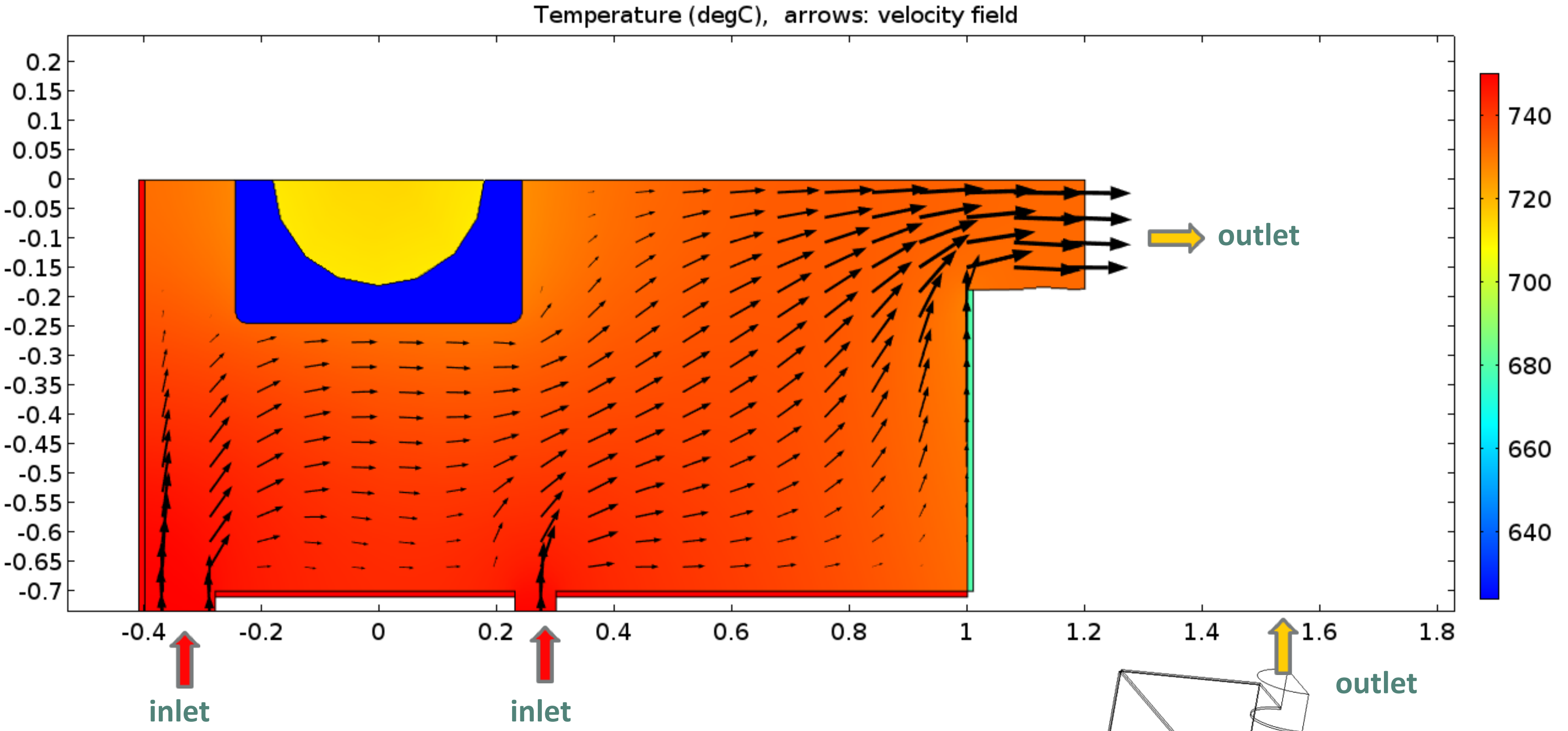


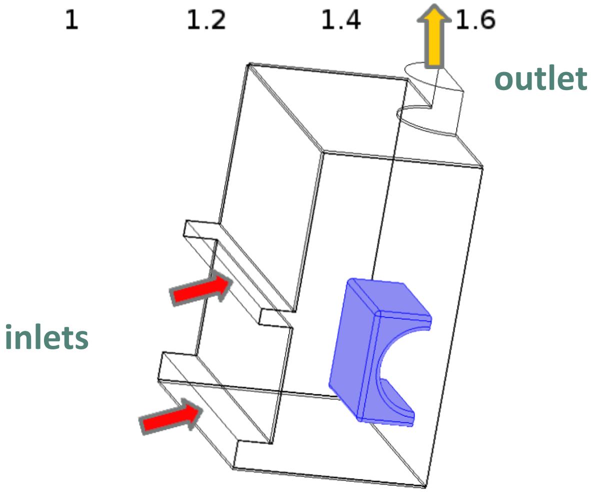
Numerical results: velocity magnitude of air



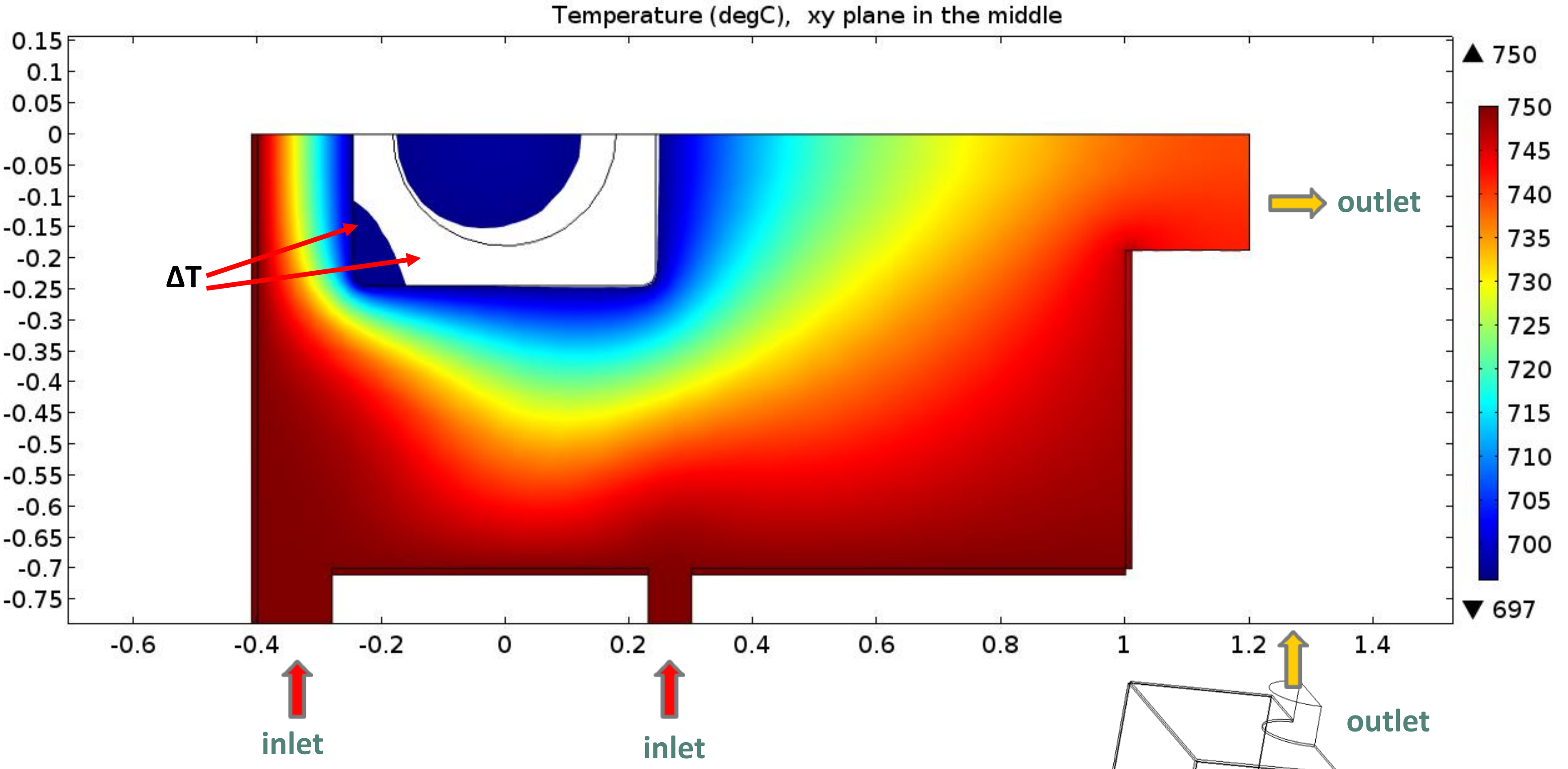


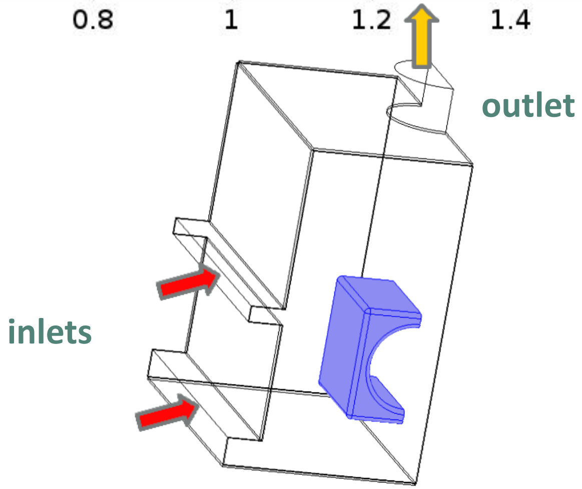
Numerical results: temperature and flow pattern



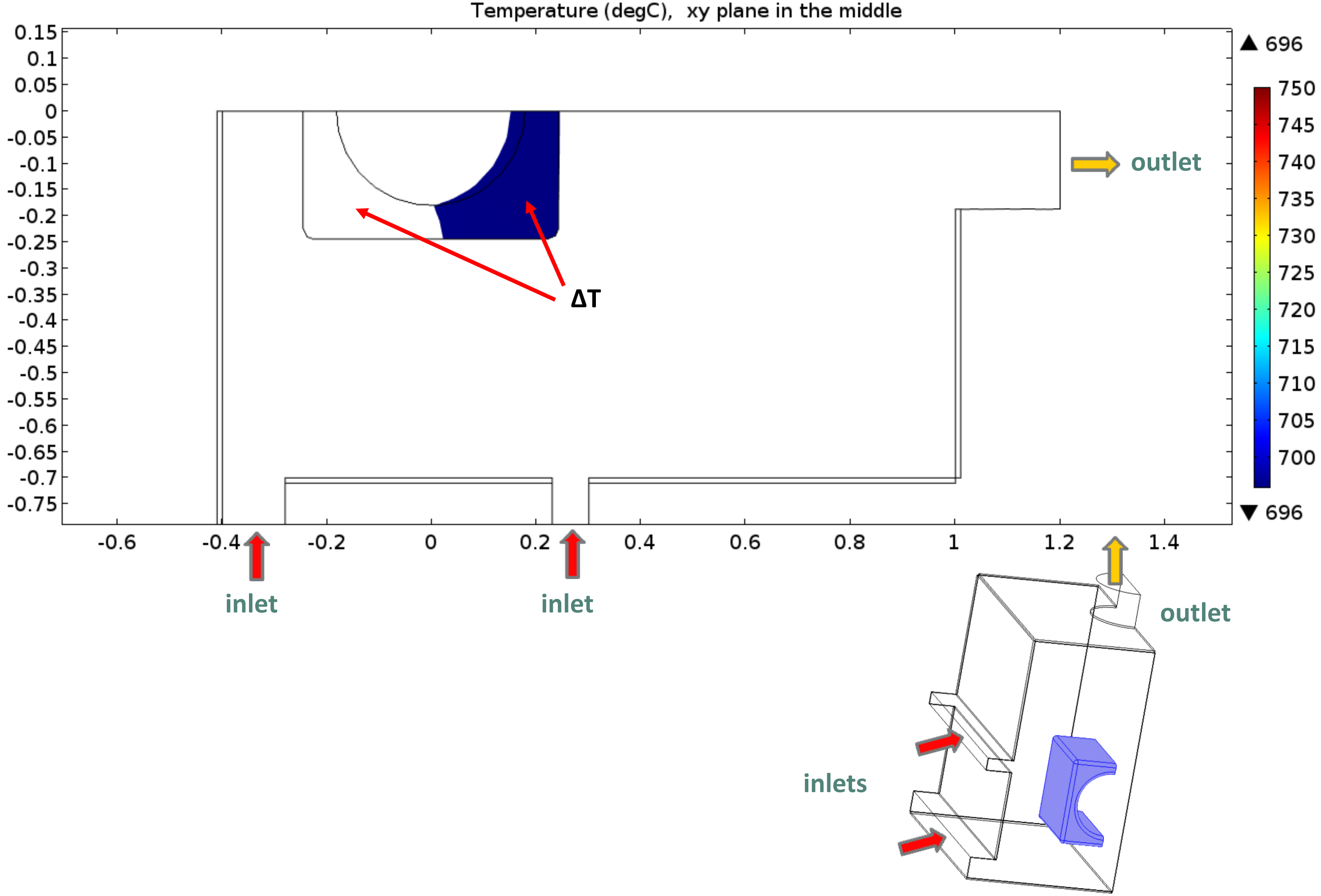


Numerical results: variation of the temperature in the component

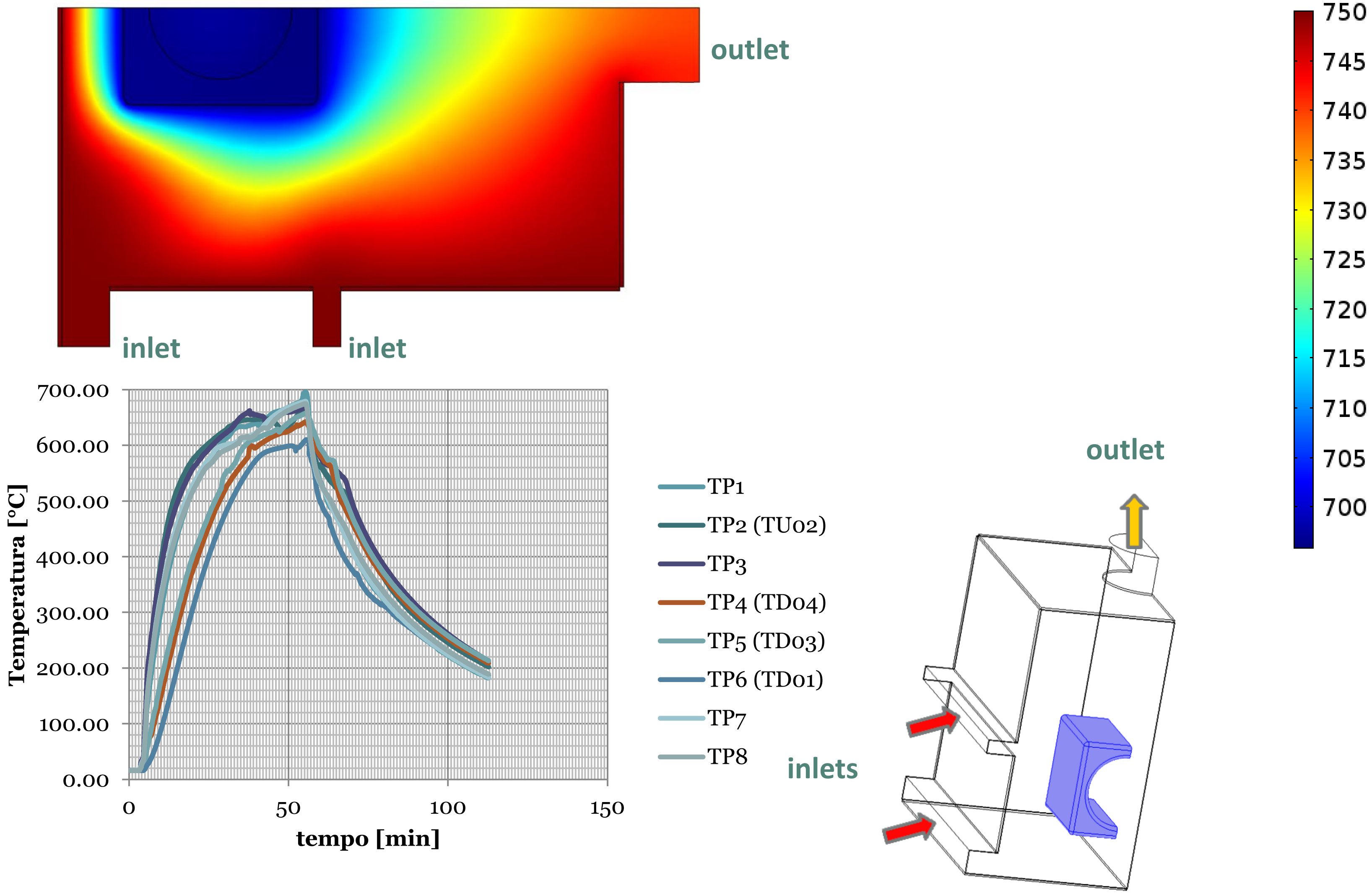




Numerical results: variation of the temperature in the component



Numerical results of temperature: comparison with experiments



Conclusions

- A modeling work by using Comsol Multiphysics has been developed for simulating a heating process of a metal foam in a furnace.

- Air velocity and air temperature fields have been obtained by modeling the compressible turbulent flow in the furnace.

- An experimental value of the emissivity has been used in the modeling work to describe the radiative heat transfer of a structural steel .

- The temperature values compare satisfactorily with the experimental measurements obtained in the same conditions.

- Finally, for more comprehensive transient turbulent models of metal foaming, computational requirements should be also considered.

References

[1] J. Banhart, Manufacture, characterization and application of cellular metals and metal foams, *Progress in Materials Science*, **46**, 559-632 (2001).

[2] J. Banhart, Light-metal foams-History of innovation and technological challenges, *Advanced Engineering Materials,* **15**, 82-111. doi: 10.1002/adem.201200217 (2012).

[3] T. Paloposki and L. Liedquist, Steel Emissivity at high temperatures, VRT Research Notes, Espoo 2005, Finland, (2005).

[4] F. Incropera, D.P. DeWitt, T.L. Bergman and A.S. Lavine, *Fundamentals of Heat and Mass Transfer*, 6th ed., John Wiley and Sons, Danvers, MA, USA, (2007).

[5] Comsol AB, Comsol Multiphysics-Heat Transfer Module, *User's Guide*, **Version 5.1,** (2015).

[6] Comsol AB, Comsol Multiphysics-CFD Module, *User's Guide*, **Version 5.1,** (2015).

[7] B. Chinè and M. Monno, Multiphysics modeling of a metal foam, *Proceedings of 2012 European Comsol Conference*, Milan, (2012).

[8] C. Körner, *Integral Foam Molding of Light Metals,* 124. Springer-Verlag, Berlin Heidelberg (2008).

Many thanks for your attention.

We would like to also acknowledge:

Valerio Marra, PhD, Comsol Inc.

TEC Tecnológico de Costa Rica **Vicerrectoría de Investigación y Extensión**

POLITECNICO MILANO

MUSP
Macchine Utensili e Sistemi di Produzione

… and to the organizers of the

COMSOL
CONFERENCE
2015 GRENOBLE