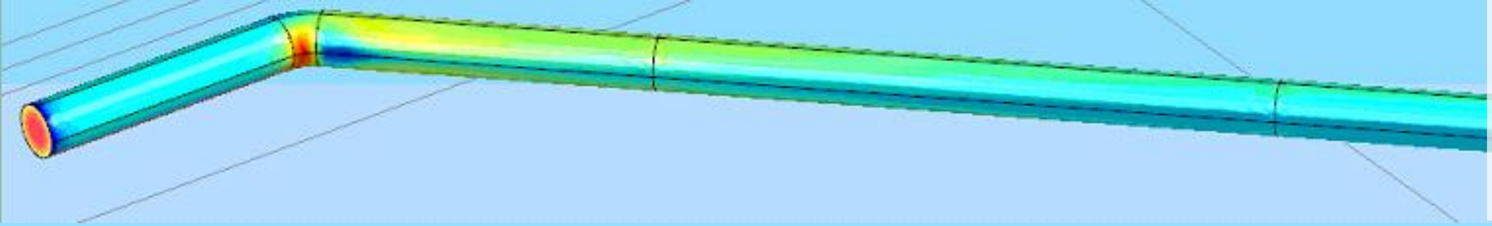
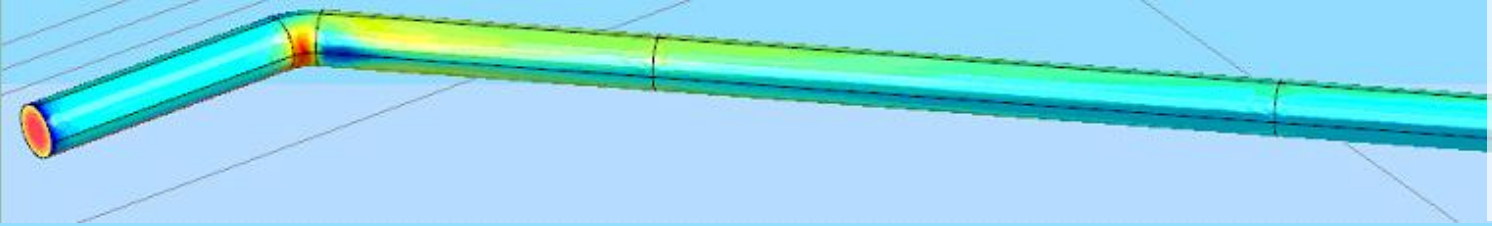


Heat-Accumulation Stoves: Numerical Simulations of Two Twisted Conduit Configurations

**Scotton P., *Rossi D., **Barberi M., **De Toni S.*

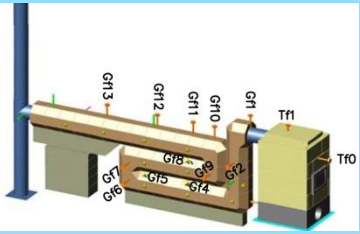
**University of Padova, Department of Geosciences*

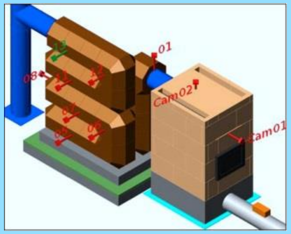
*** Barberi Srl, Trento (Italy)*



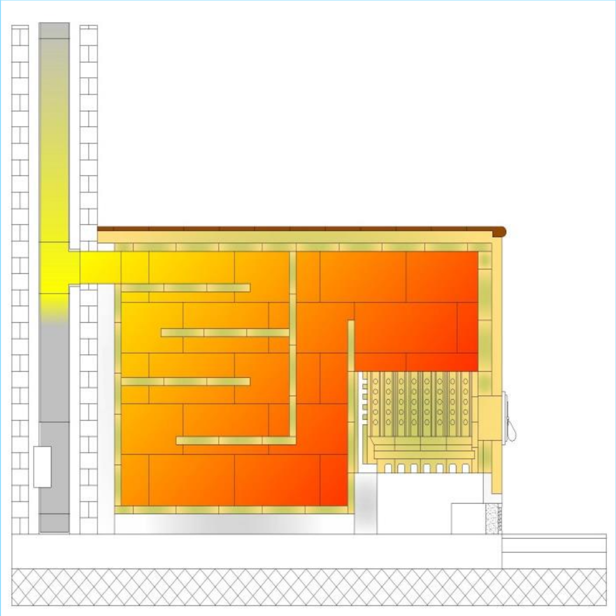
INDEX

- *Description of the Physical Problem;*
- *Hydrodynamic and Heat Transfer Equations;*
- *Results of* → *twisted refractory pipe on a vertical plane*
  → *refractory pipe spacially twisted*

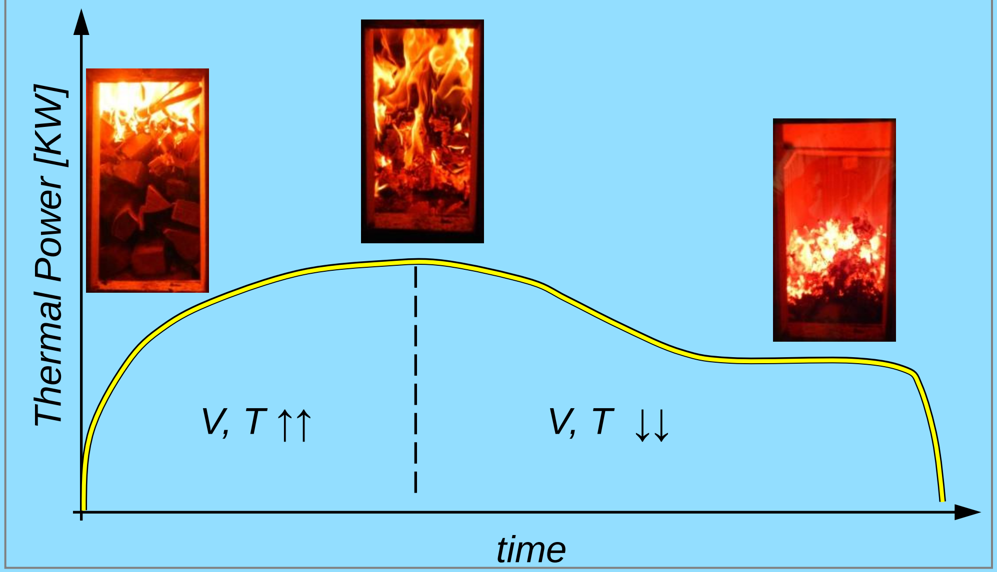




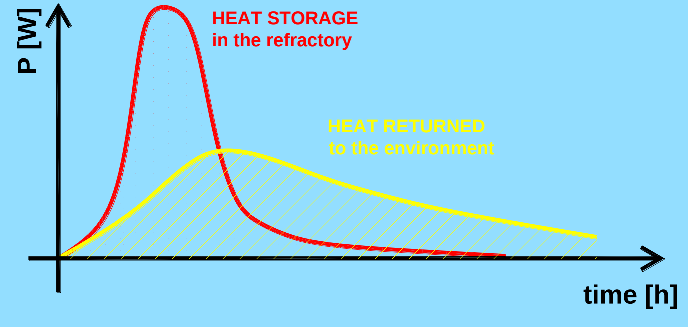
Components of a heat accumulation stove



Burning Process of Woody Material



Heat storage and release

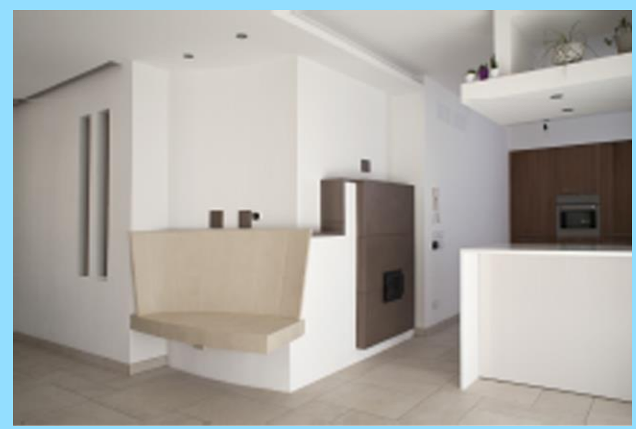


Examples of heat accumulation stoves

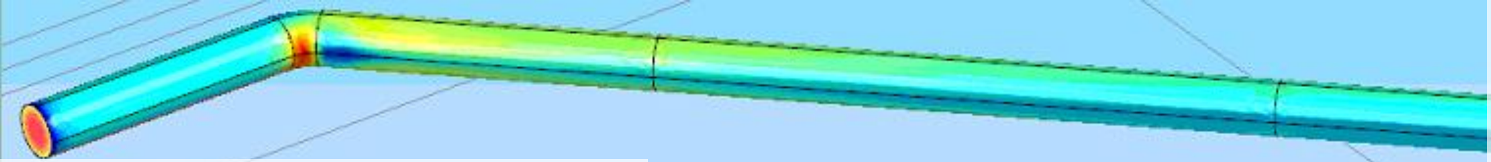
Historical heat accumulation stove “Sfruz” (Valle di Non, Trentino, Italy).

Classical stove

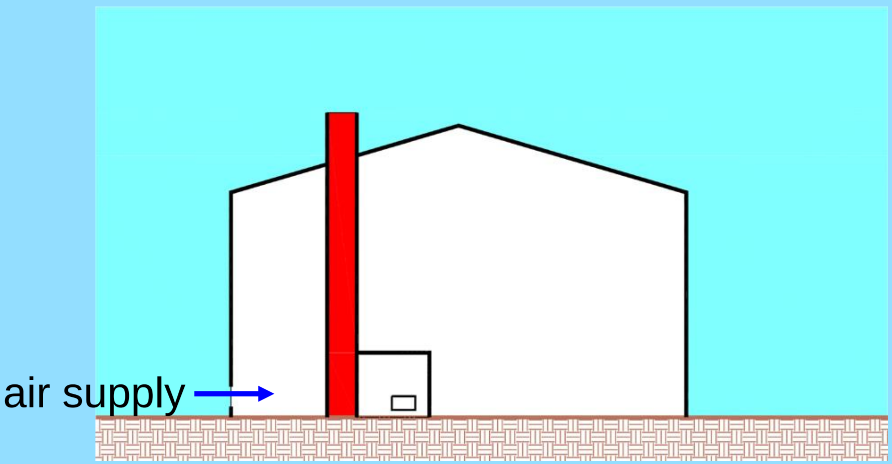
Modern stove

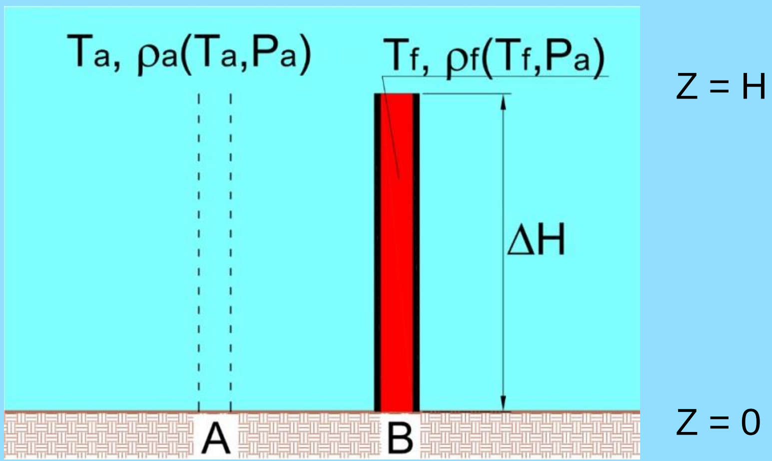


Contemporary stove



The driving force acting on the flue gases

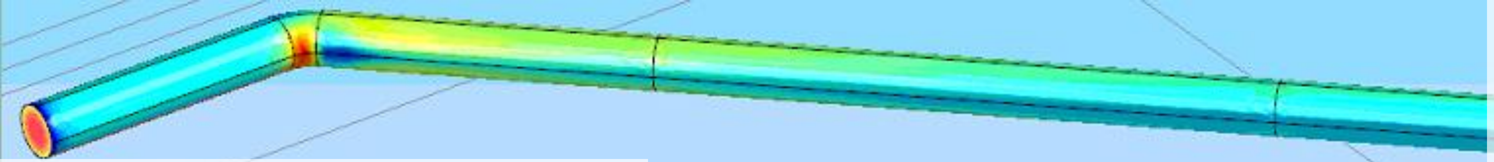




$$P_A = P_H + \rho_a(T_a, P_a) \cdot g \cdot \Delta H$$

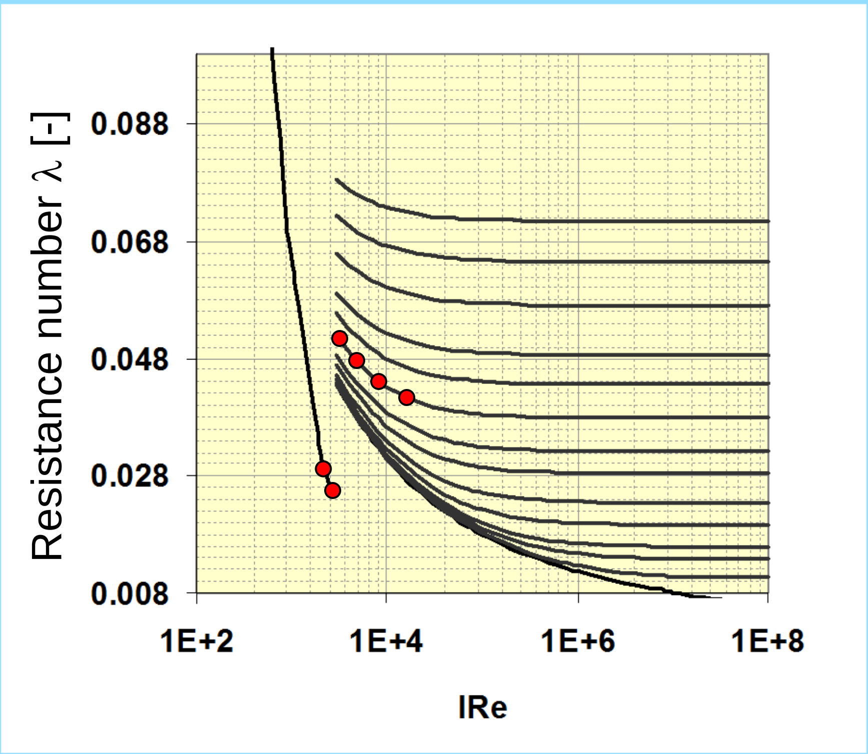
$$P_B = P_H + \rho_f(T_f, P_a) \cdot g \cdot \Delta H$$

$$P_A - P_B = \left[\rho_a(T_a, P_a) - \rho_f(T_f, P_a)\right] \cdot g \cdot \Delta H = \left(\rho_a - \rho_f\right) \cdot g \cdot \Delta H$$

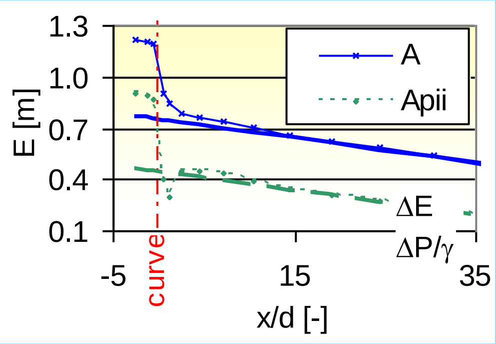


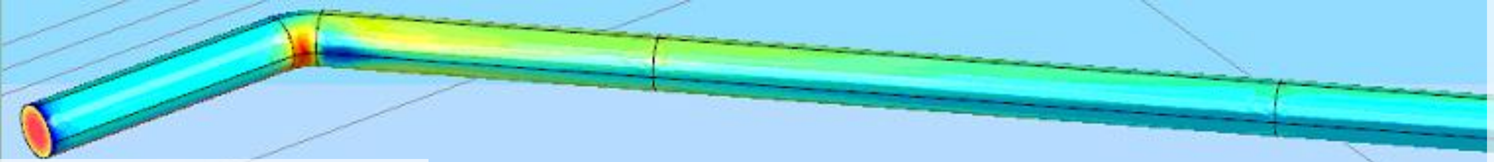
Hydrodynamic flow aspects

Temporal evolution of Reynolds number



Sharp Curve – Turbulent motion
IRe = 28400   x/D = 1.4





Transport Equations, k-ε model

Reynolds-averaged Navier–Stokes eq.

$$\begin{cases} \rho \cdot \left(\dfrac{\partial u}{\partial t} + (u \cdot \nabla) u \right) + \nabla \cdot (\rho u' * u') = \nabla \cdot \left[-p \cdot I + \mu \left(\nabla u + (\nabla u)^T \right) \right] + F \\ \dfrac{\partial \rho}{\partial t} + \nabla (\rho u) = 0 \end{cases}$$

+

Turbulent energy eq.

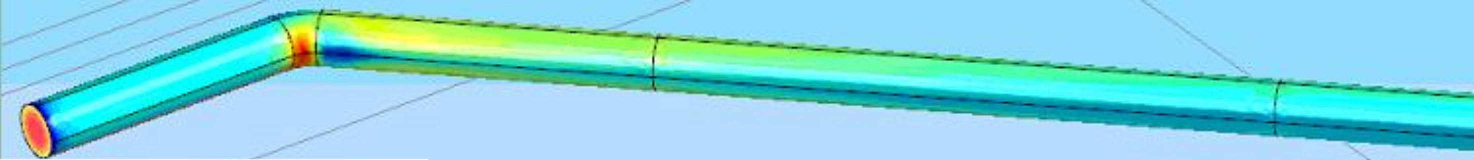
$$\rho \cdot \frac{\partial k}{\partial t} + \rho u \cdot \nabla k = \nabla \cdot \left[\left(\mu + \frac{\mu_T}{\sigma_k} \right) \nabla k \right] + P_k - \rho \varepsilon$$

Turbulent Dissipation energy eq.

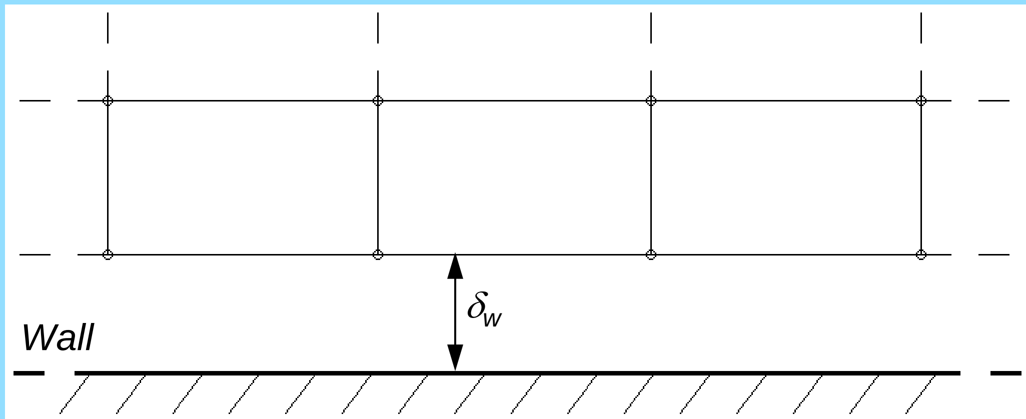
$$\rho \cdot \frac{\partial \varepsilon}{\partial t} + \rho u \cdot \nabla \varepsilon = \nabla \cdot \left[\left(\mu + \frac{\mu_T}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + C_{\varepsilon 1} \frac{\varepsilon}{k} P_k - C_{\varepsilon 2} \rho \frac{\varepsilon^2}{k}$$

where

$$\mu_T = \rho C_\mu \frac{k^2}{\varepsilon}$$

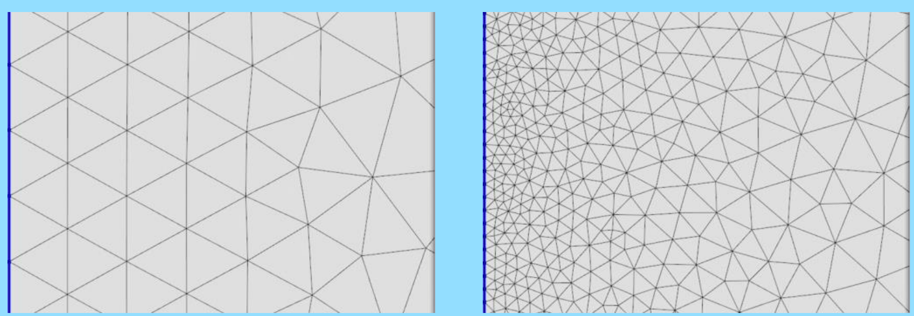


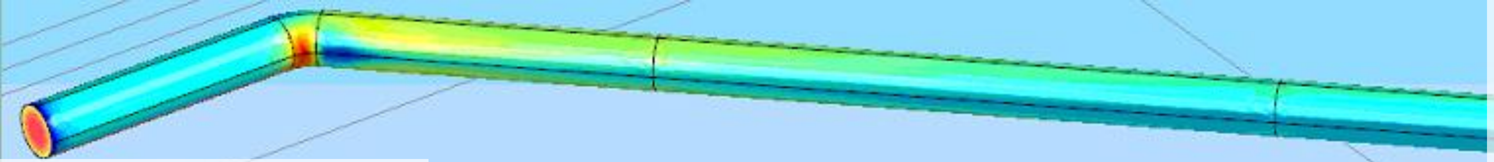
Wall Functions



$$\delta_w \rightarrow \delta_w^+ = \frac{\rho u_\tau \delta_w}{\mu} \le 11.06$$

influence of choosen mesh on the results





Heat Transfer

Heat transfer is guaranteed by three terms:

- *conduction* $q_i = -k \frac{\partial T}{\partial x_i}$
- *convection* $q = h A (T_s - T_\infty)$
- *radiation* $q = A \sigma T_s^4$

Equation of heat transfer

$$\rho C_p \left(\frac{\partial T}{\partial t} + (u \cdot \nabla) T \right) = -\nabla \cdot q + \tau : S - \frac{T}{\rho} \frac{\partial \rho}{\partial T}\bigg|_p \left(\frac{\partial p}{\partial t} + (u \cdot \nabla) p \right) + Q$$

heat flux by conduction (q)

viscous heating ($\tau : S$)

Equation of mass conservation

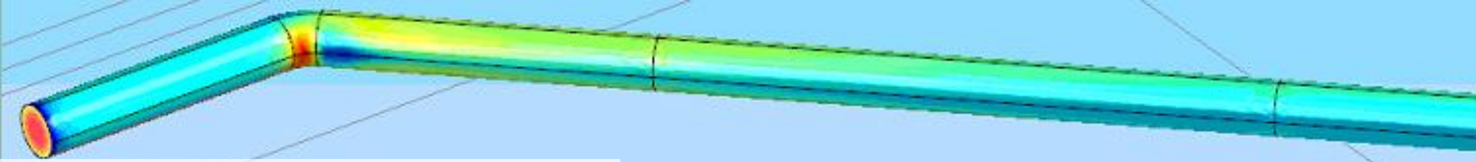
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0$$

.. the conserved property is the total energy not the heat

$$\rho u (H_0 + \Psi) - k \nabla T + \tau \cdot u + q_r$$

total energy flux

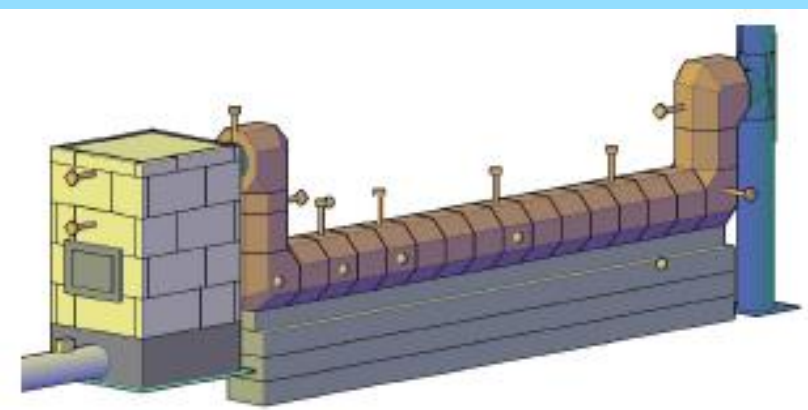
heat flux by radiation (q_r)



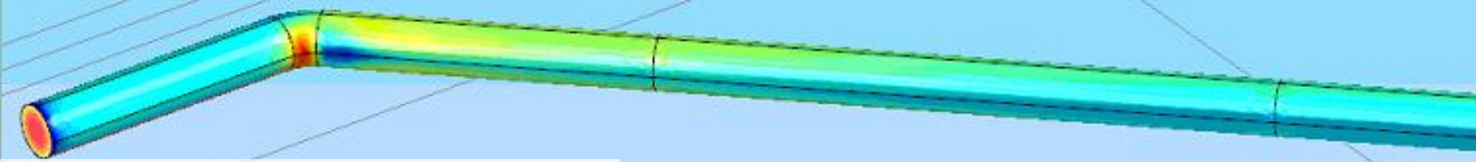
Straight Steel Pipe

Thermotechnical characteristics		
	stainless steel	black steel
thickness [mm]	0.2	2.0
emissivity [-]	0.1	0.95
conductivity [W/mK]	17	50

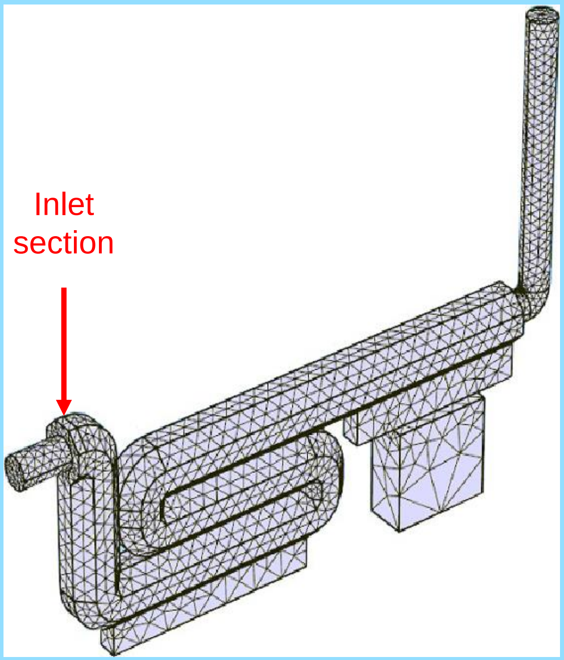
C-shaped refractory pipe



Thermotechnical characteristics		
	refractory	calcespan
density [kg/m^3]	2550	600
heat cap. [J/kgK]	859	1000
conductivity [W/mK]	3.16	0.15
emiss. [–]	0.95	0.70



Twisted Refractory Pipe on a vertical plane: numerical model

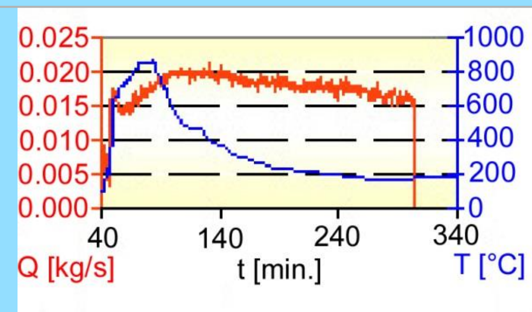


Mesh properties

h_{BL}	$h_{FL} = \frac{h_C}{20} \cdot TAF$
h_{Tr}	0.025
h_{Te}	0.065
$N^{\circ}\ El.$	36274
$D.O.F.$	771075

Radiation in participating media – Discrete ordinate method: S2
Scattering = 0; absorption k = 1.524 E-3 [1/cm] *Modest, '83*

Mass flow rate and temperature at the inlet section.

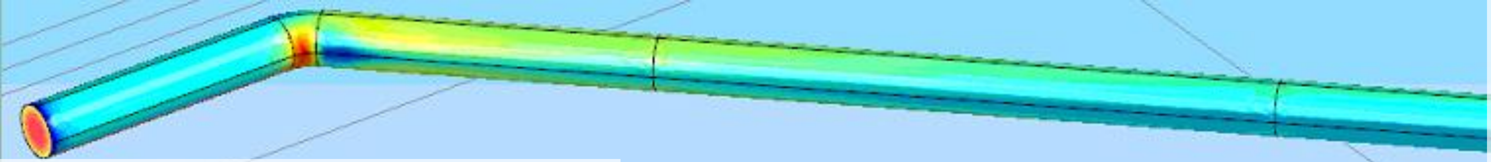


Boundary conditions:1. Mass flow rate + Temperature at the inlet face;

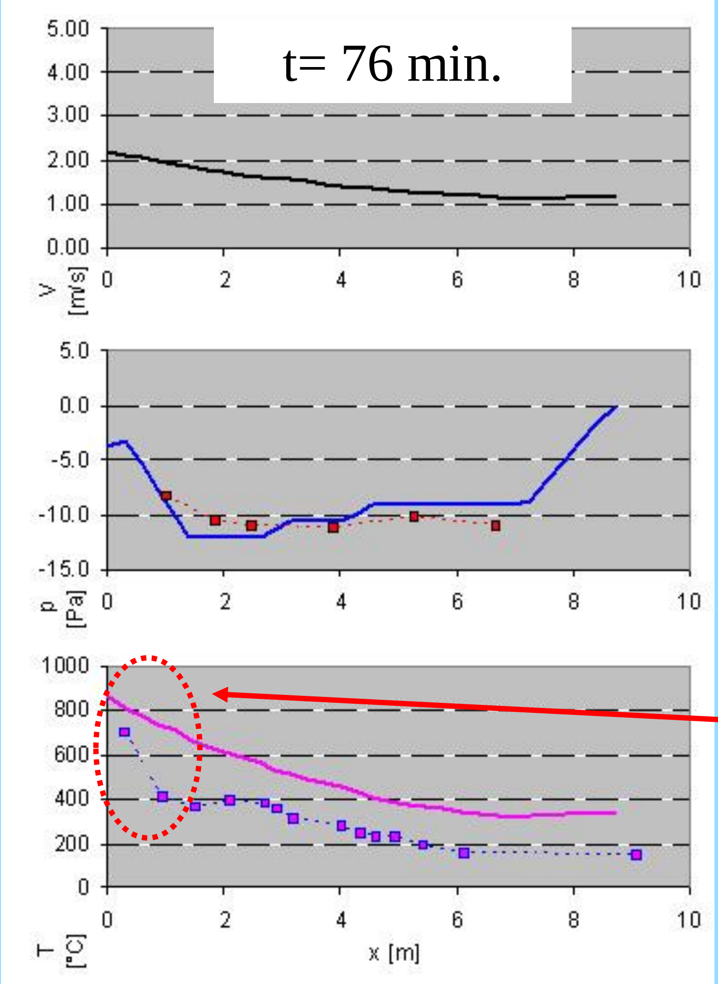
2. Pressure at the outlet face;

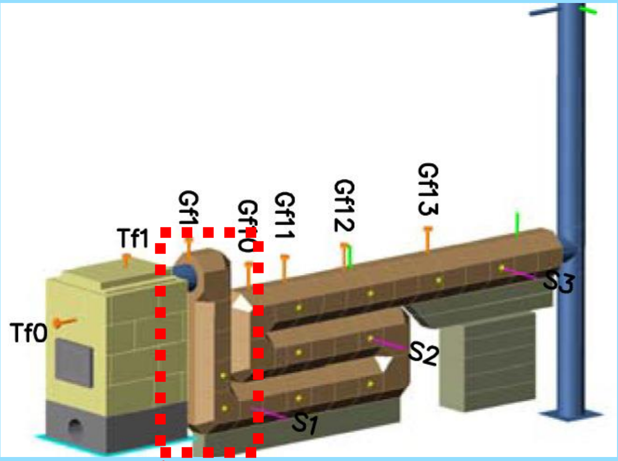
3. Convective cooling on the outer surface: $-\hat{n} \cdot (-k\nabla T) = h\,(T_{Amb} - T)$ *;*

4. Surface to Ambient Radiation: $-\hat{n} \cdot (-k\nabla T) = \epsilon\sigma\,(T_{Amb}^4 - T^4)$ *;*



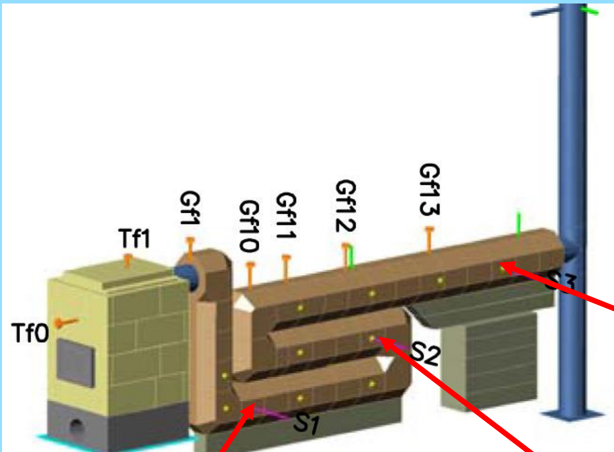
Twisted Refractory Pipe on a vertical plane: numerical results

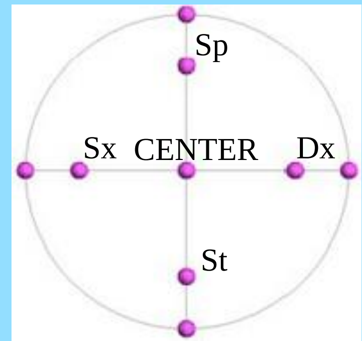




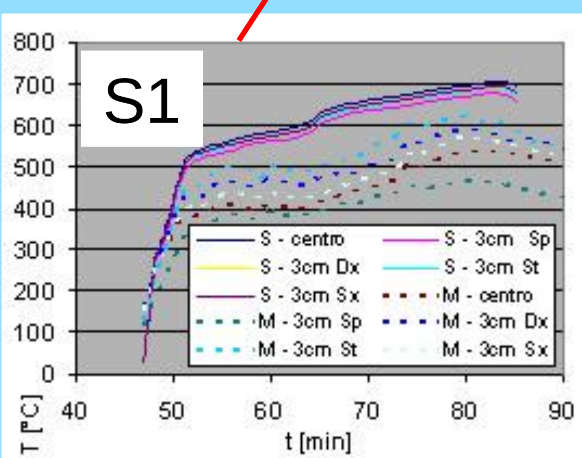
Residual combustion activity inside the first vertical stretch ?

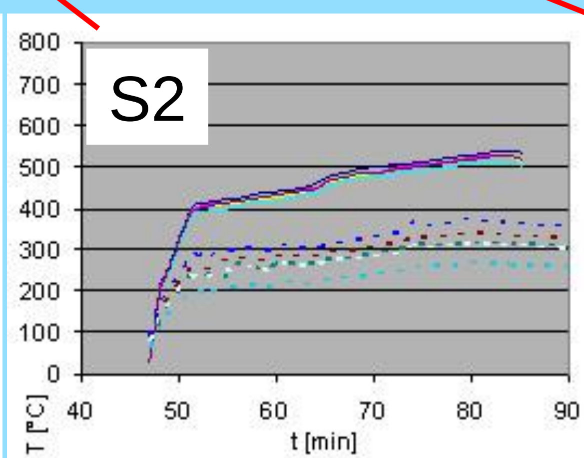
Twisted Refractory Pipe on a vertical plane: numerical results

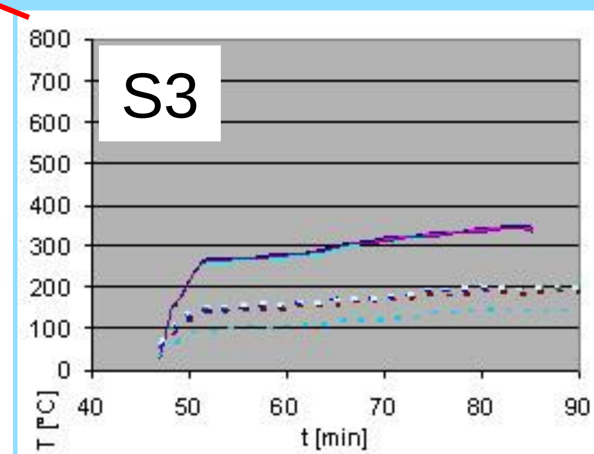


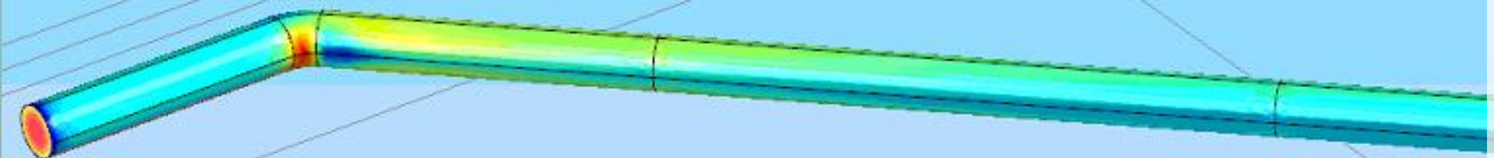


Temperature gauges distribution inside an instrumented section





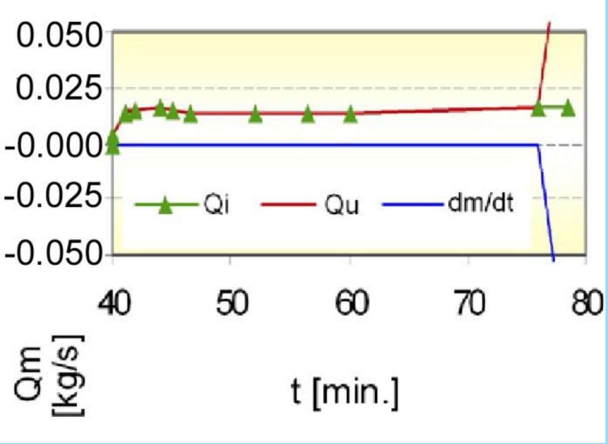




Twisted Refractory Pipe on a vertical plane: numerical results

MASS BALANCE

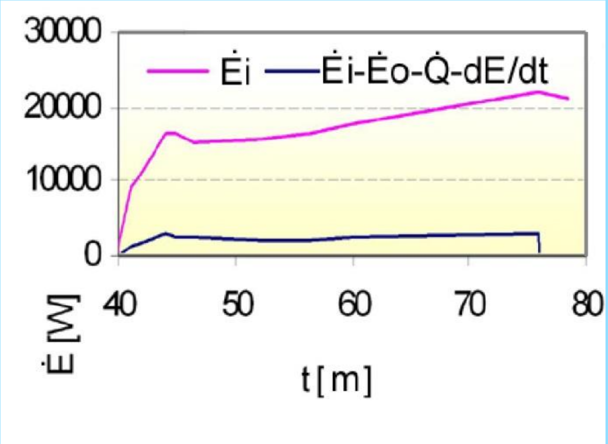
$$Qm_{inp} - Qm_{out} = \left[\frac{dm}{dt}\right]_V$$



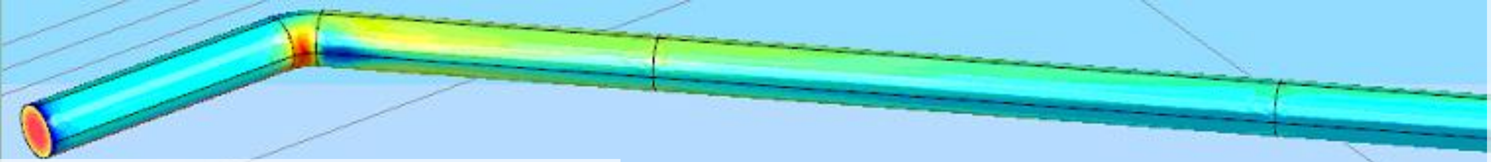
ENERGY BALANCE

$$\left(h_1 + g\ z_1 + \frac{V_1^2}{2}\right)\dot{m}_1 - \left(h_2 + g\ z_2 + \frac{V_2^2}{2}\right)\dot{m}_2 - \dot{Q} = \frac{dE}{dt}$$

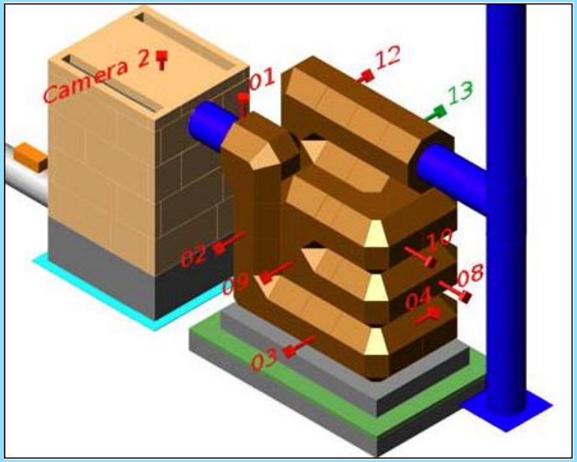
$$E = \iiint_v \left(u + g\ z + \frac{V^2}{2}\right)\rho\ dv$$

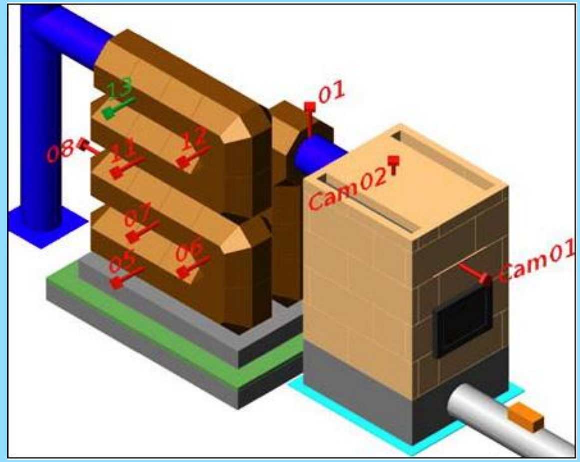


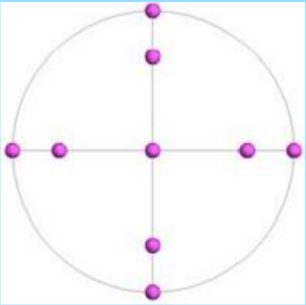
ERROR ≈ 15%



Refractory Pipe spacially twisted: physical model



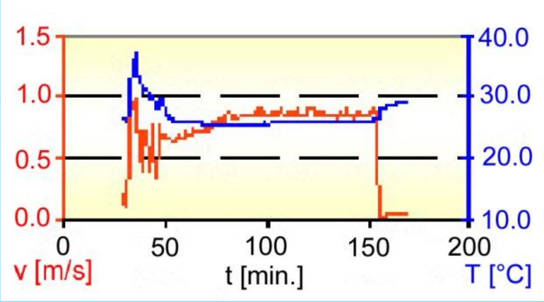




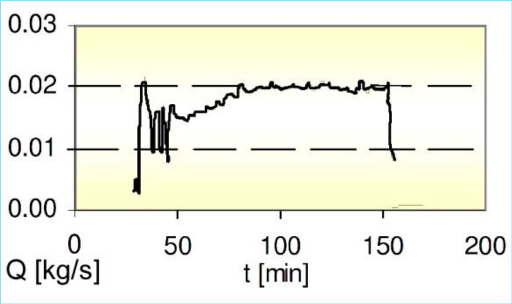
Measurement positions of the temperature at the section 13.

Thermotechnical characteristics		
	refractory	*calcespan*
density [kg/m³]	*2550*	*600*
heat cap. [J/kgK]	*859*	*1000*
conductivity [W/mK]	*3.16*	*0.15*
emiss. [–]	*0.95*	*0.70*

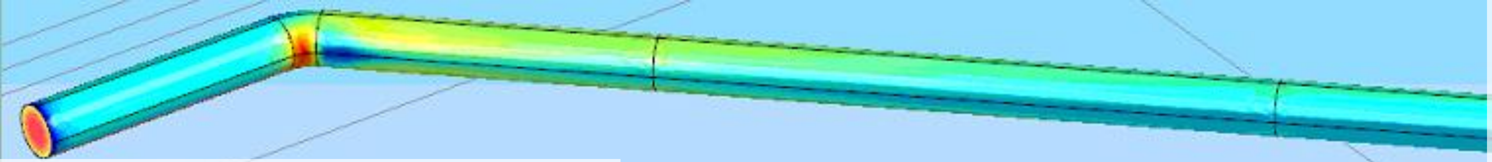
Thermotechnical properties of the materials.



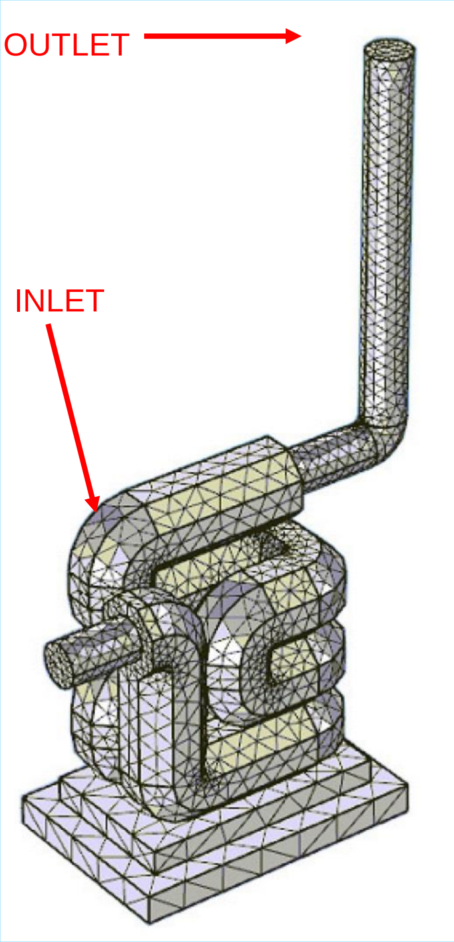
Temperature and mean velocity of the combustion air (pipe diameter = 0.16 m) .



Calculated flue gas mass discharge at section 01.



Refractory Pipe spacially twisted: numerical model



	M1	M2	M3
h_{MAX} Boundary	0.05	0.05	0.05
h_{MIN} Boundary	0.025	0.025	0.005
B.L.	no	yes	no
N° Elem	45,643	52,348	84,598
D.O.F.	518,235	863,164	1,045,237

Tethraedical meshes

Radiation in participating media – Discrete ordinate method: S2
Scattering = 0; absorption k = 1.524 E-3 [1/cm]

Boundary conditions:

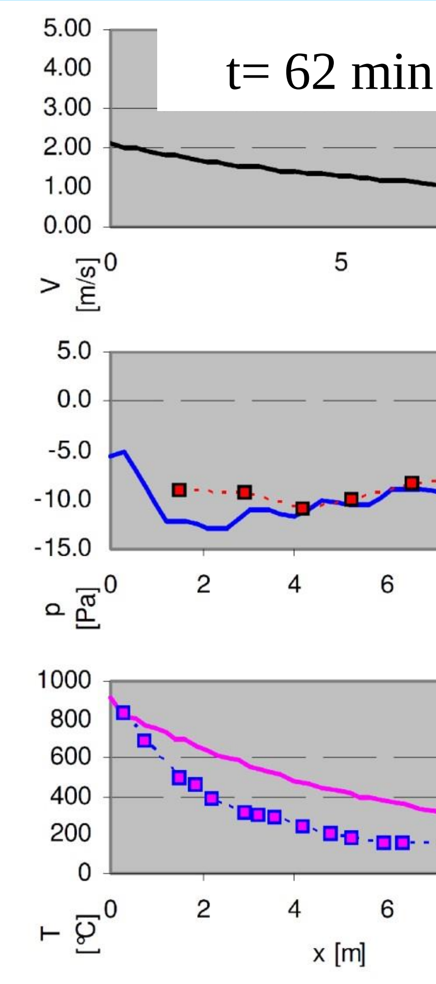
1. Calculated mass flow rate + Measured temperature at the inlet face;

2. Pressure at the outlet face;

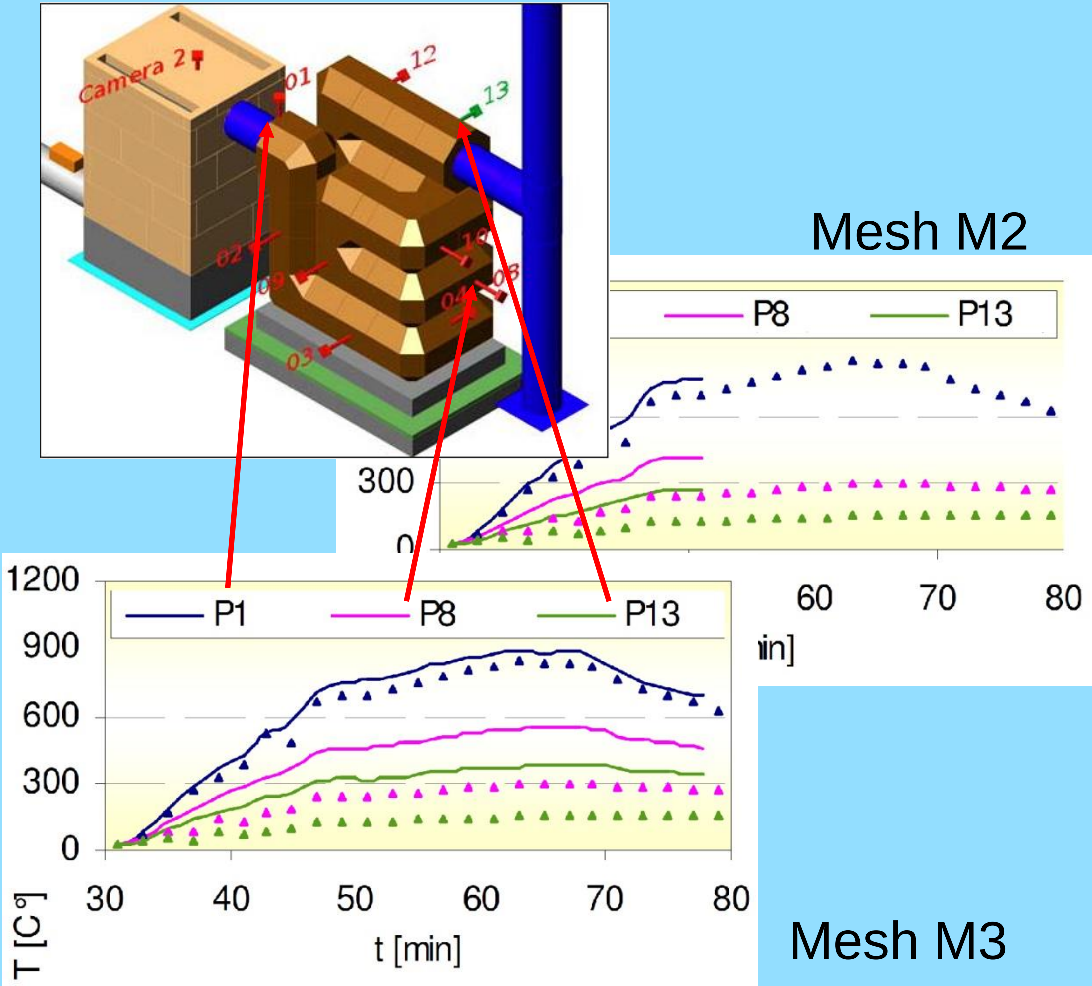
3. Convective cooling on the outer surface;

4. Surface to Ambient Radiation;

Refractory Pipe spacially twisted: numerical results

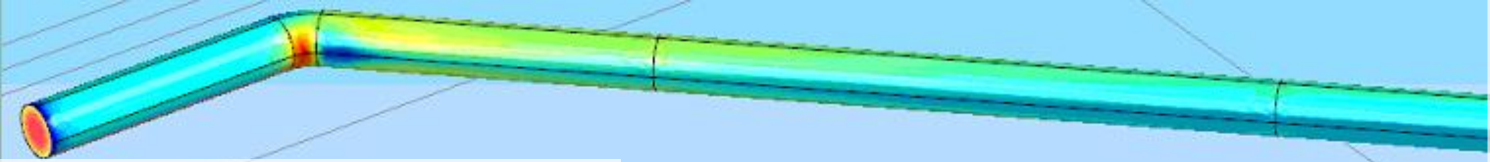


Mesh M3



Mesh M2

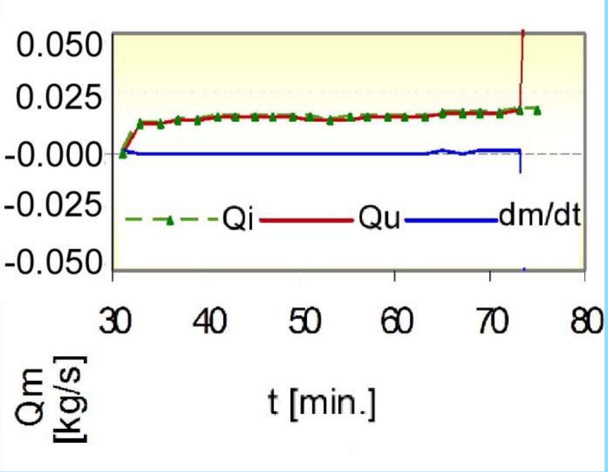
Mesh M3



Refractory Pipe spacially twisted: numerical results

MASS BALANCE

$$Qm_{inp} - Qm_{out} = \left[\frac{dm}{dt}\right]_V$$

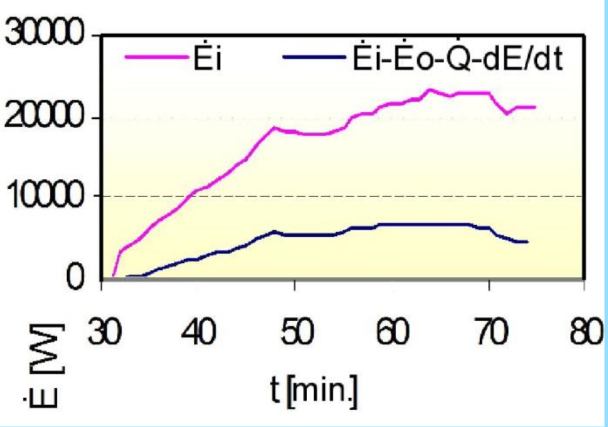


Mesh M3

ENERGY BALANCE

$$\left(h_1 + g\ z_1 + \frac{V_1^2}{2}\right)\dot{m}_1 - \left(h_2 + g\ z_2 + \frac{V_2^2}{2}\right)\dot{m}_2 - \dot{Q} = \frac{dE}{dt}$$

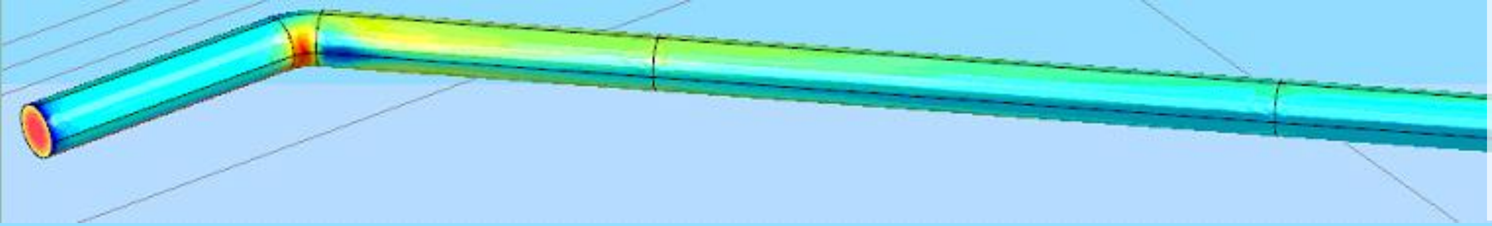
$$E = \iiint_v \left(u + g\ z + \frac{V^2}{2}\right)\rho\ dv$$



Mesh M3

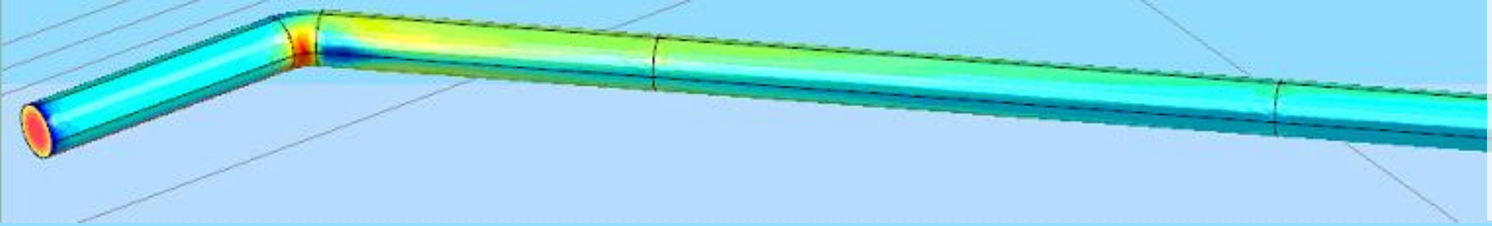
Mesh M3: ERROR ≈ 30%

Mesh M2: ERROR ≈ 17%



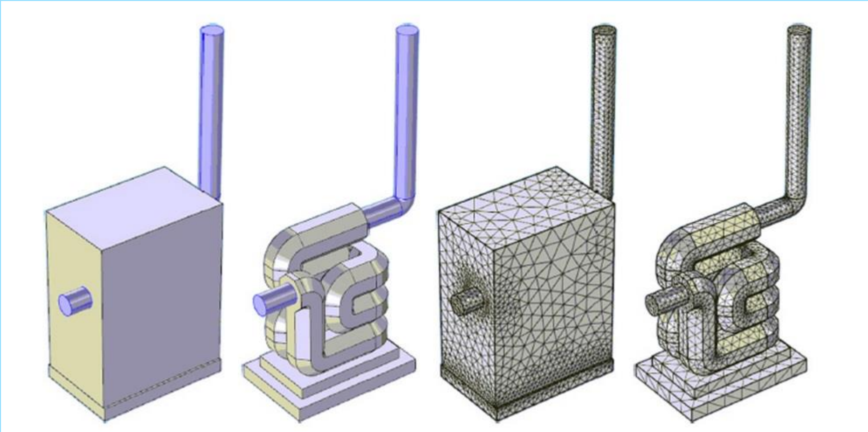
Conclusions

- *The numerical results have been obtained considering the thermal- and the hydrodynamic equations, including buoyancy forces (Boussinesque approximation). Radiation has been considered both outside and inside the pipe;*
- *The software is able to describe correctly the mass balance until the time of occurrence of a numerical instability;*
- *The energy balance depends strongly on the mesh refinement. A refined mesh, realized with the use of a boundary layer, can induce an anticipated instability;*
- *The pressure variations are not significantly far from the measured ones (this experimental measure is very difficult);*
- *The mean velocity values along the pipes are coherent with the mean temperature values;*
- *The calculated mean temperature values along the pipes are generally much higher than the measured ones; the measured temperature variation inside the pipes are much larger than the measured ones; temperature variations inside the pipe, both measured and calculated, decrease increasing the distance along the pipe;*
- ***The use of a boundary layer is not always the best choice, having an influence on the reduction of the stability period**.*



What's more …

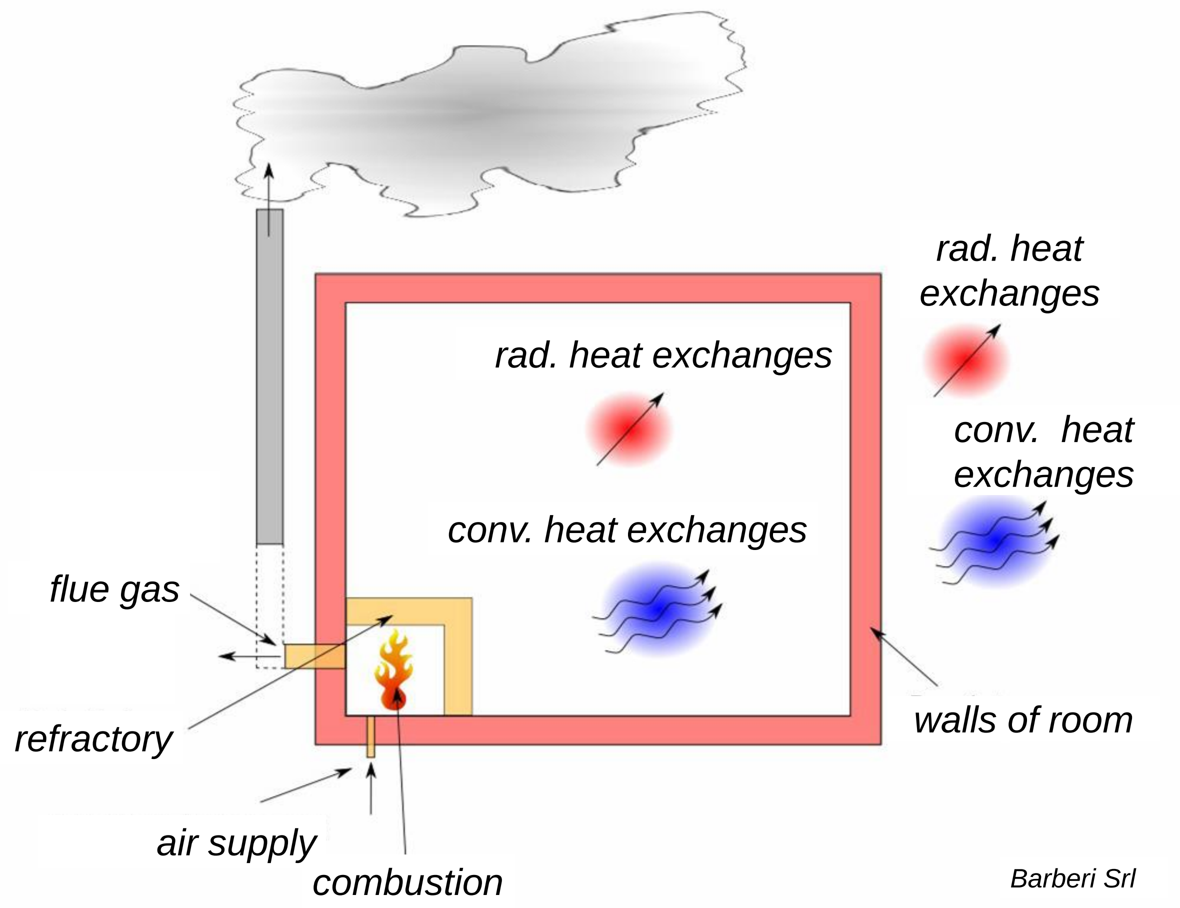
- *Use of Comsol in the final stove configuration, where a radiant covering envelops the twisted pipe;*
- ***Need of a higher computing power (**now Dell T7500 24GB Ram) **to reduce the energy loss and to hope to give technical importance in the design process. At the moment, due to the large calculation time, of the order of a week, is almost useless**;*

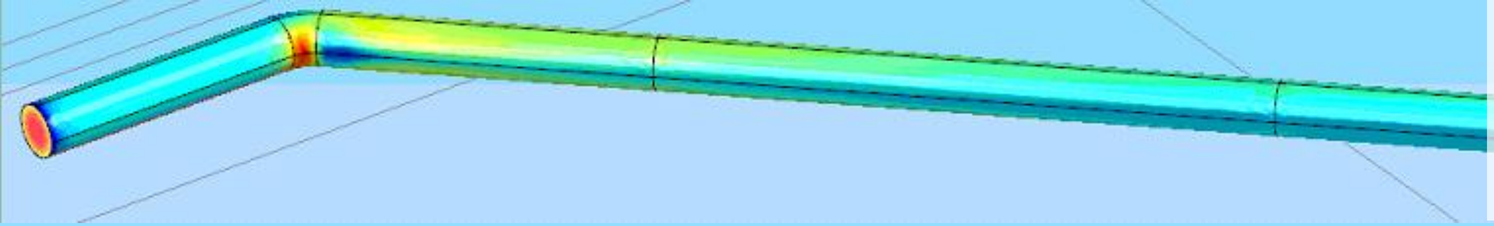


- *Another road: decoupling the hydrodynamic equations relevant to the pipe from the thermal equations relevant to the refractory;*

Thank you for your attention

General Features of global system



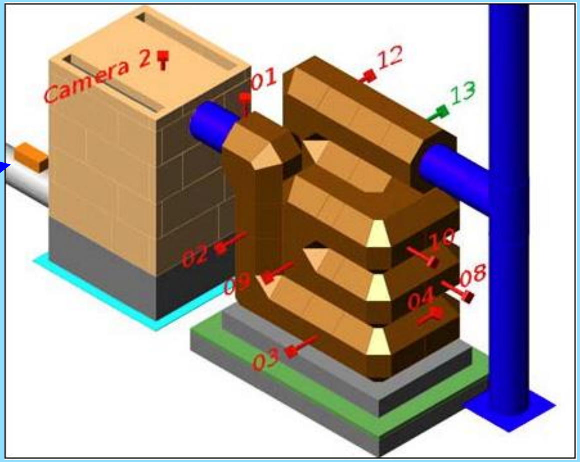


Software version: Comsol 4.3

Computing machine: Workstation Dell T7500 equipped with two Intel R Xeon R Processor X5550 and 24GB DDR3 1333MHz ECC-RDIMM.

Temperature gauges distribution inside an instrumented section

THE MASS FLOW RATE HAS BEEN DETERMINED BY MEANS OF VELOCITY AND TEMPERATURE MEASURED UPSTREAM DEL COMBUSTION CHAMBER.



The technical regulation prEN15544 has been used.

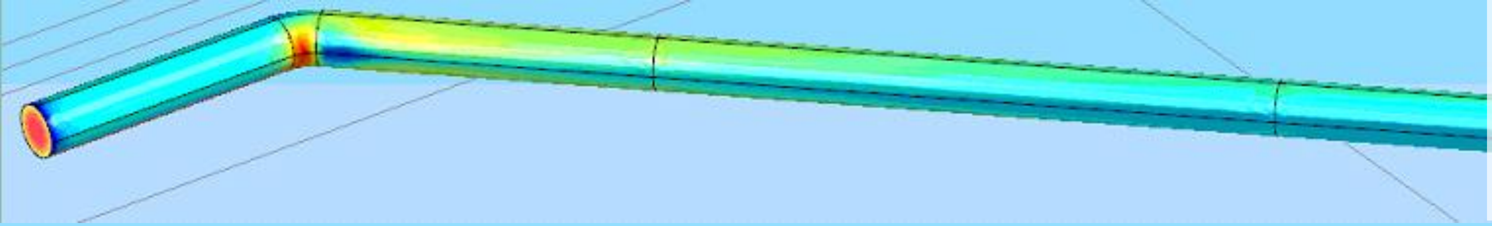
prEN 15544 – "One off tiled/kachelofen stoves - Calculation method"

Velocity measurement

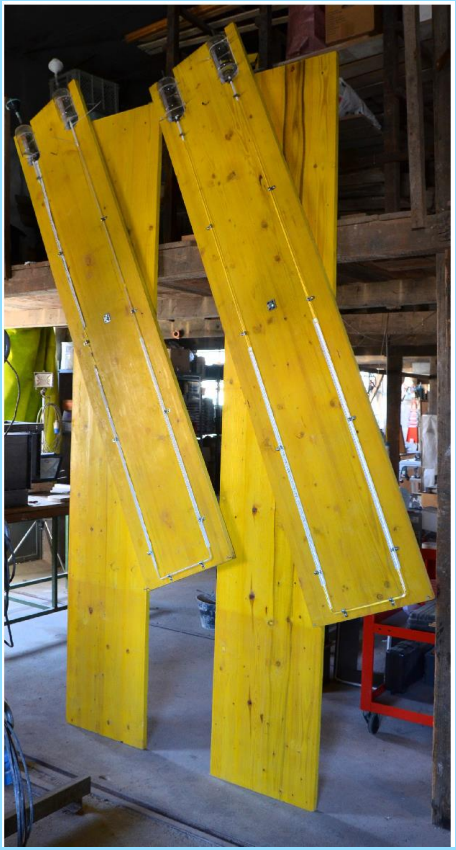
Propeller anemometer

Hot wire anemometer

Pitot

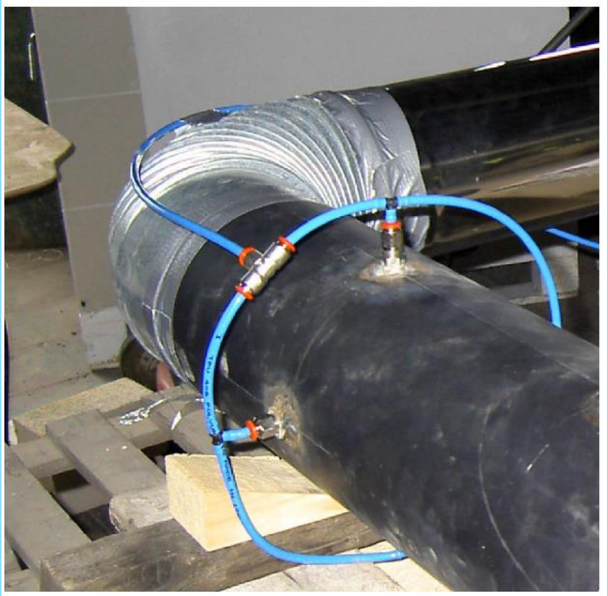


Pressure measurement



Analogical piezometer

Furness FC0332



Testo 521

Temperature measurement

Thermocouples k;
Pt100;
Pt1000.