Ultra-Fast Modeling of Heat Treatment furnace. Advanced online control.

Center for Energy Efficiency of Systems (CES) - Mines ParisTech

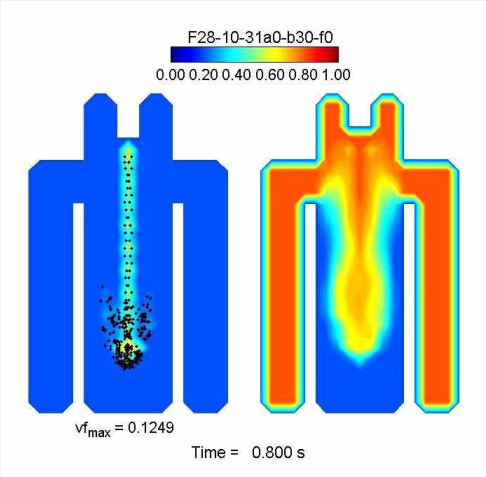
Thursday, May 04, 2017

Boutros Ghannam

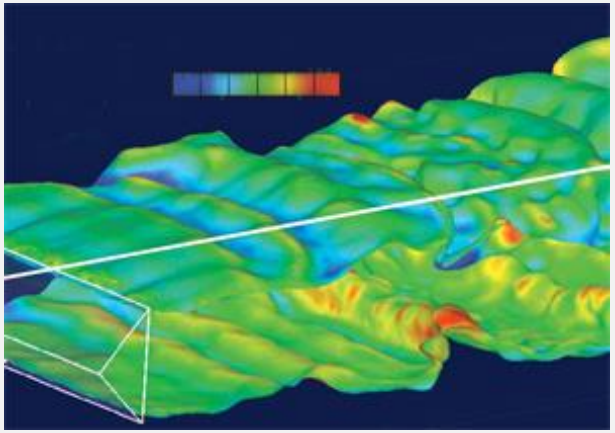
Maroun NEMER

60 Boulevard Saint Michel, 75014 Paris | France

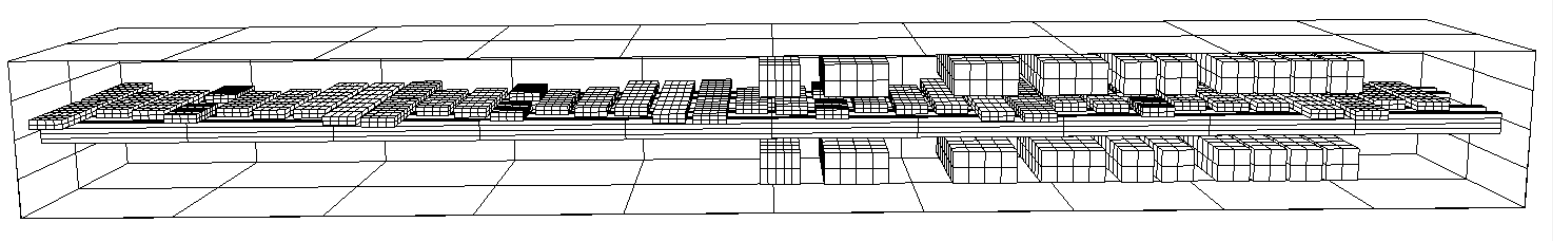
Thermal numerical simulation, some examples



Steam explosion with nuclear fuel
The radiativeheat transfer between the hot molten UO2 and the surrounding water is a key mechanism for controlling the boiling process
Image courtesy of Walter W. Yuen



iSGTW: A flame held by a flameholder. The FOCUS project simulations have demonstrated that taking radiation into consideration when making calculations modifies the dynamics of the flame.
Time: *300000 hours and 400 CPUs*
Image courtesy of FOCUS

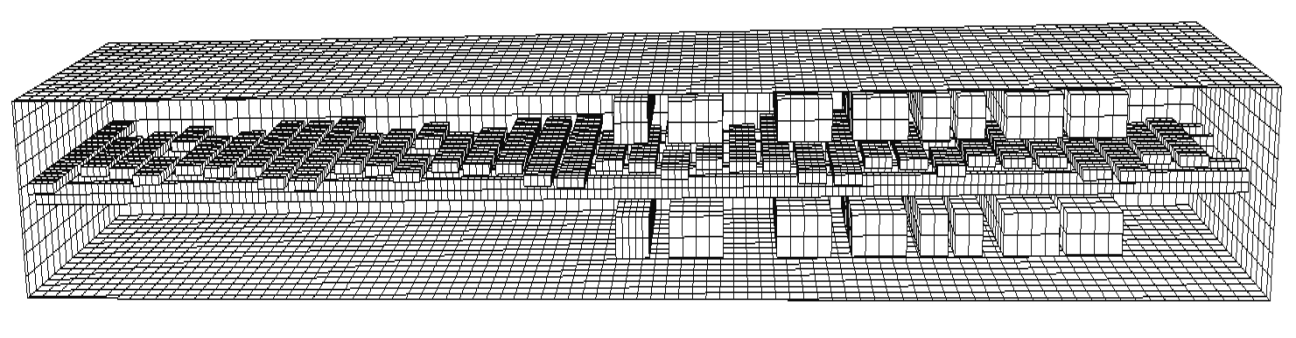


Steel Slabs Reheating Funace
Coupled Radiation and heat diffusion
Control strategies allow less energy consumption and better heating quality / Nevertheless their accuracy is very sensitive to the speed and the precision of the numerical simulations

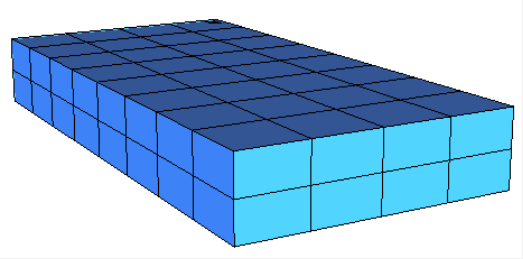
Steel Slabs Reheating Furnace

Context and objectives of the thesis work

- **Computing 3D radiation heat Transfer**
  - Direct exchange factors
  - Total exchange factors

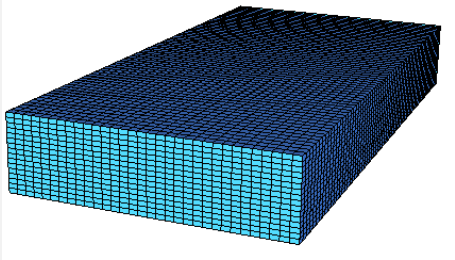


- **Computing heat diffusion in the slabs**



Radiation heat flux B.C.

Coupling → 3DFTDT

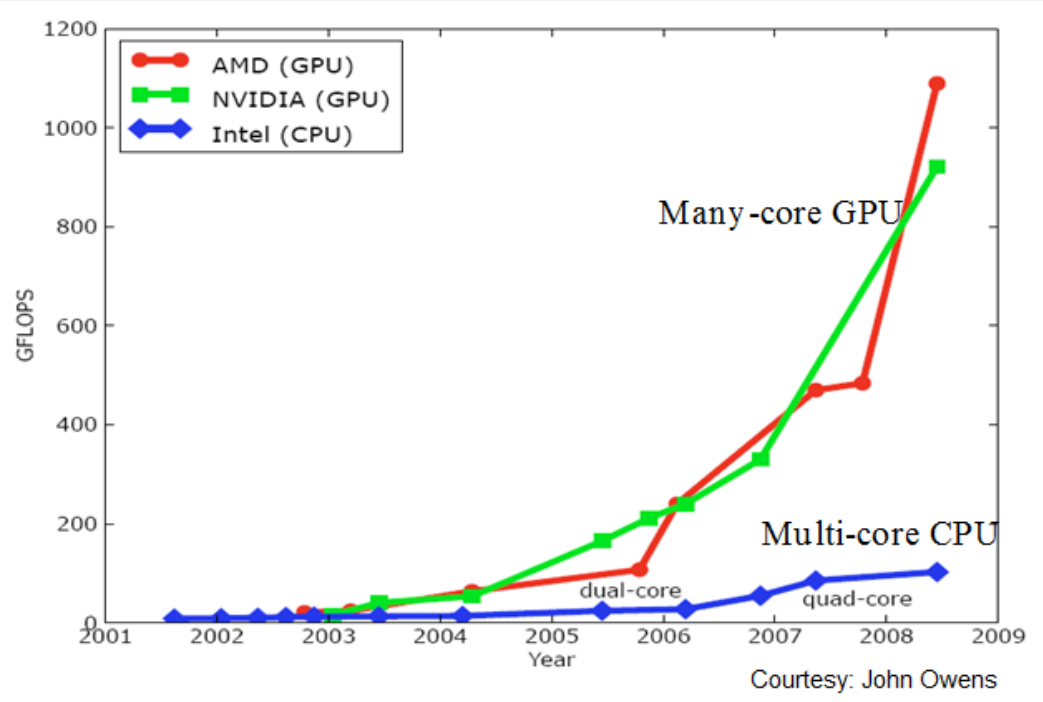


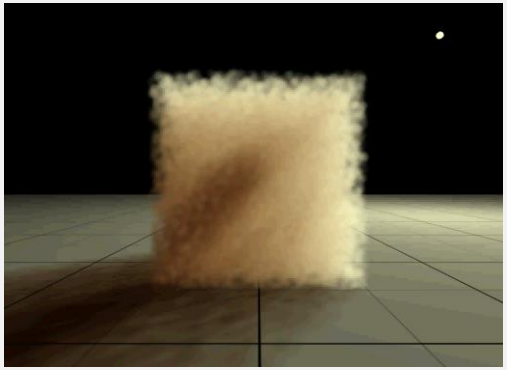
3D Temperature Profile in the slab

Graphics Processing Unit (GPU) Computing (1/2)

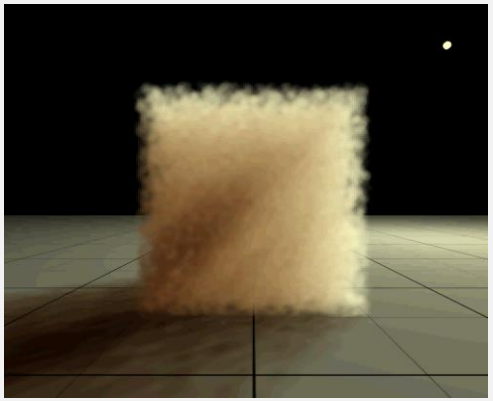
Comparison of CPU and GPU performances

- **CPU and GPU peak performance**
  - Calculation : Tflops vs. 100 Gflops
  - Memory bandwidth: ~10x





CPU smoke simulation

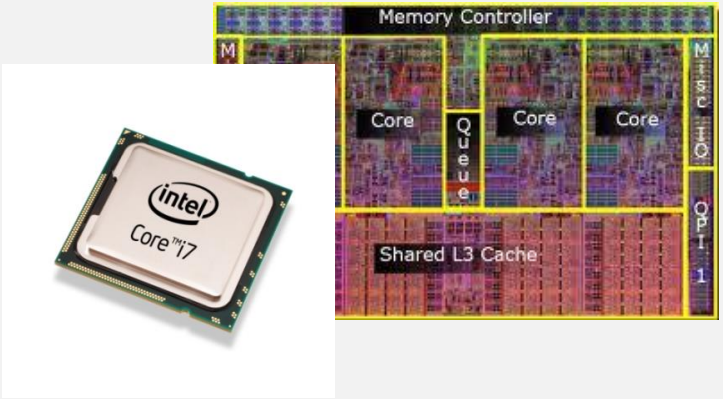


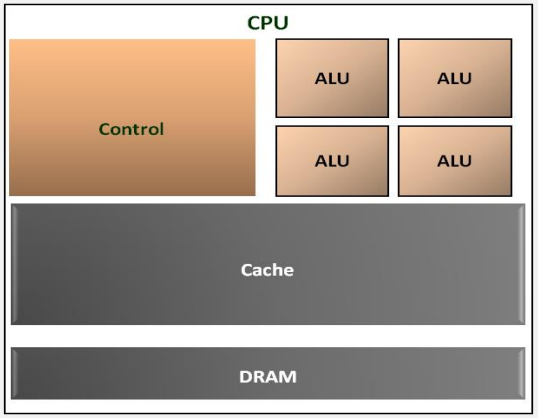
GPU smoke simulation

Graphics Processing Unit (GPU) Computing (2/2)

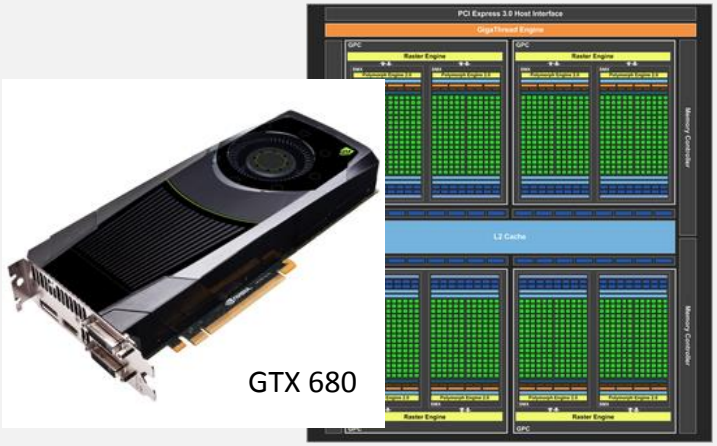
Comparison of CPU and GPU architectures

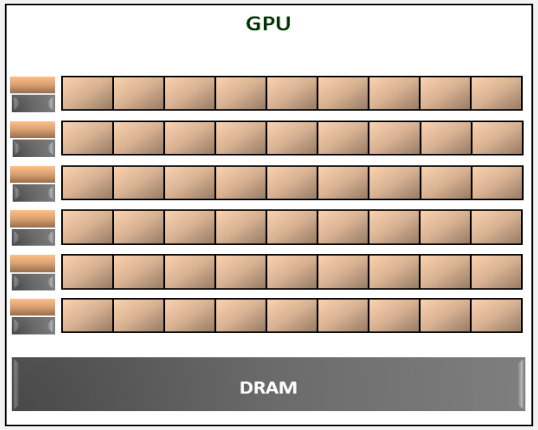
CPU Architecture





GPU Architecture

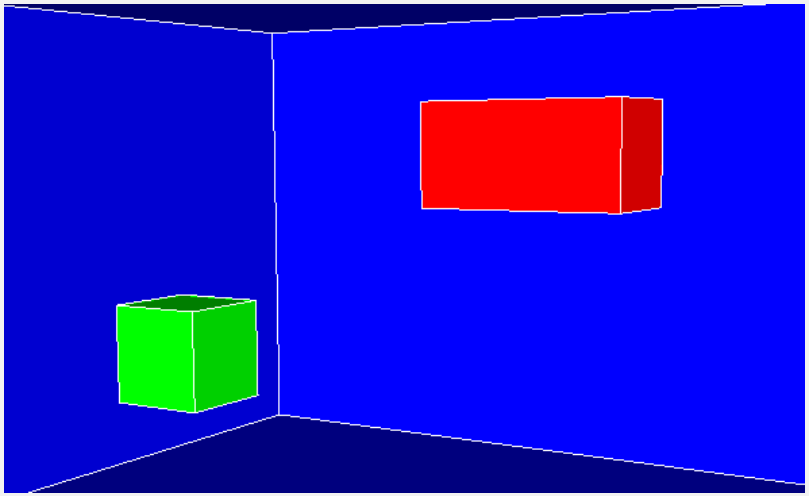




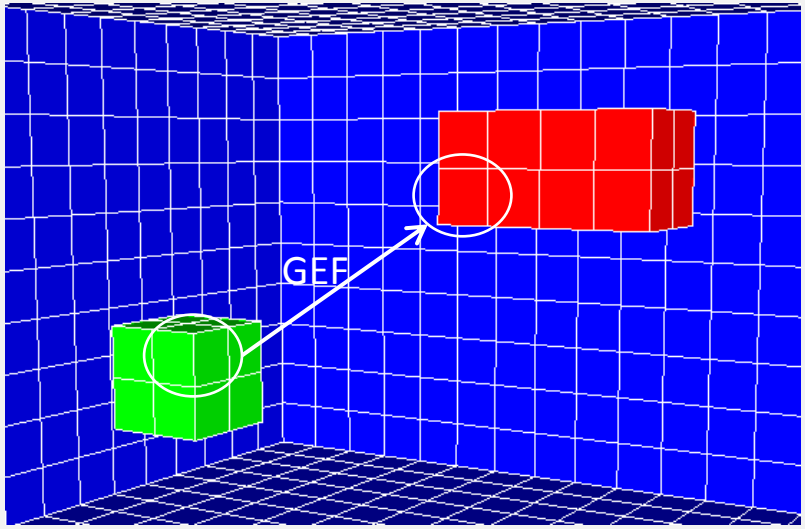
Discretization

The Multiple Absorption Coefficient Zonal Method (MACZM)

- Volume elements (voxels) :
  - Uniform radiative properties (mean value)
  - Uniform temperature



Continuous space



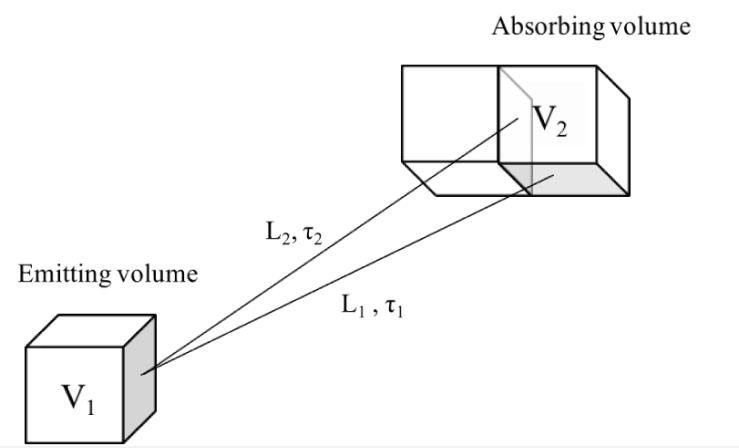
Voxelized space

Computation acceleration by Artificial Neural Networks

The Multiple Absorption Coefficient Zonal Method (MACZM)

- Artificial Neural Networks (ANNs) replace the integral computation for GEFs

Generic Exchange Factors (GEFs)



$$GEF = f(a_1, a_2, n_x, n_y, n_z, \tau_1 \dots \tau_9)$$

Artificial Neural Networks (ANNs)

$$\begin{pmatrix} X \end{pmatrix} = \begin{bmatrix} W_1(20 \times 5) \end{bmatrix} \times \begin{pmatrix} P \end{pmatrix} + \begin{pmatrix} B_1 \end{pmatrix}$$

$$Z = F\begin{pmatrix} X \end{pmatrix} \times \begin{pmatrix} W_2 \end{pmatrix} + b_2$$

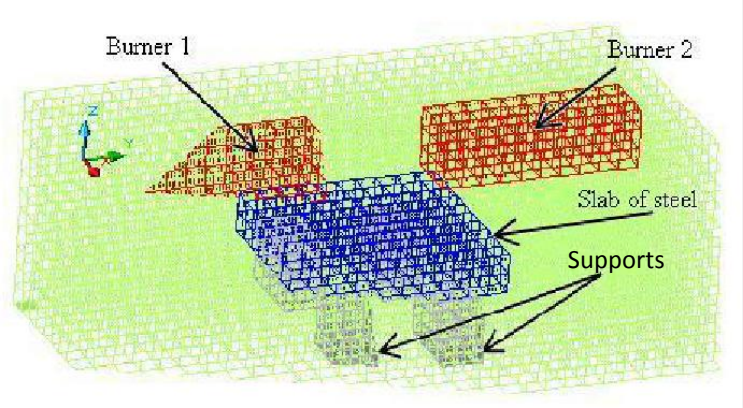
$$(P) = (a_1, a_2, n_x, n_y, n_z, \tau_i)$$

Application to a test furnace

Numerical and experimental verification

External view

Internal view



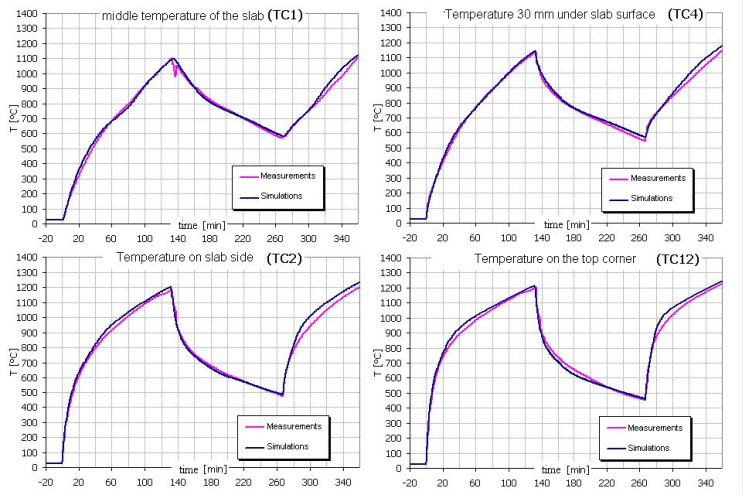
Test Furnace mesh

Numerical validation

Comparison ***MACZM – MODRAY***

Direct exchange factors [Computation time]	MACZM [2 sec]	MODRAY (a) [25 min]	MODRAY (c) [2 min]
Combustion volume(1)-combustion volume(2)	1.13560^{E}-04	9.98015^{E}-05	1.27992^{E}-02
Combustion volume(1)-steel slab	1.03177^{E}-02	1.00157^{E}-02	8.68062^{E}-02
Combustion volume(2)-steel slab	1.04588^{E}-02	1.01281^{E}-02	8.56366^{E}-02
Base - base	3.28529^{E}-02	3.09024^{E}-02	3.09022^{E}-02

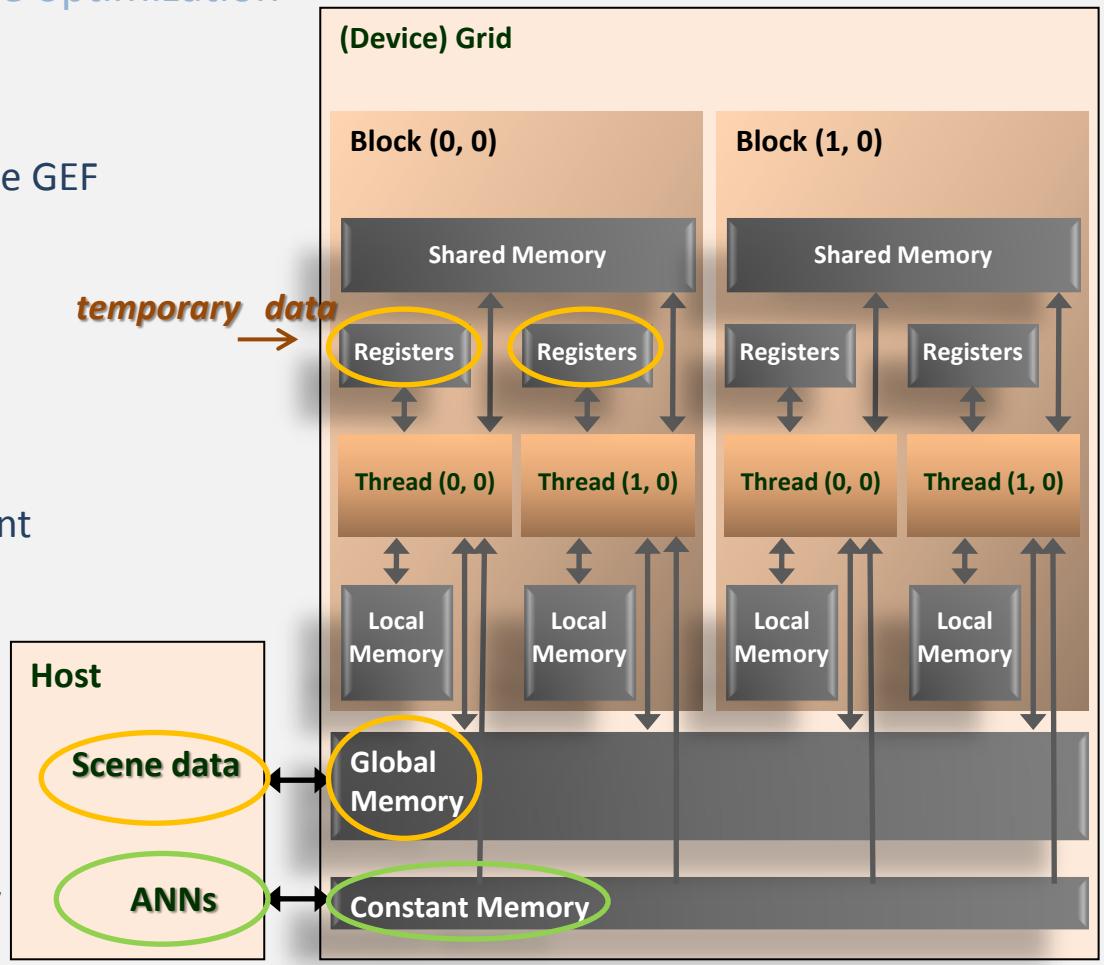
Experimental validation



Implementation of MACZM on the GPU

Parallelization and device code optimization

- **GPU parallelization**
  - SIMD mode
  - Each thread computes one GEF (discrete line and ANN)
- **Discrete line algorithm**
  - Parametric 6-line (No-divergence)
  - Scene data in char
  - Performance enhancement using registers
- **Artificial Neural Networks**
  - Constant memory matrix multiplication
  - Synchronized call for memory access efficiency



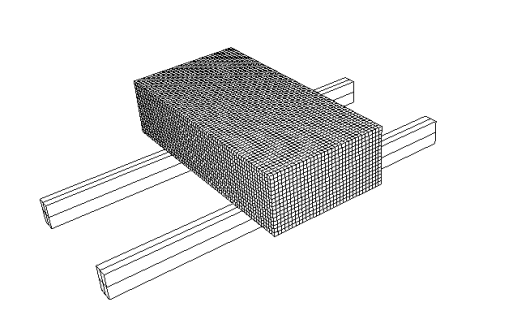
3D Finite difference method

Discretization and Differentiating schemes

- **Heat diffusion PDE (3D):**

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial x^2}D + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right), \alpha = k/\rho c_p$$

B.C.: Radiation heat flux



Steel slab

- Finite difference discretization schemes (1st order time - 2nd order space)
  - **Simple explicit** : Forward time – centered space
    Stability condition
    Accuracy : ***O(Δt)***

$$\frac{T_{i,j,k}^{n+1} - T_{i,j,k}^{n}}{\Delta t} = \alpha\left[\frac{\partial_x^2 T^n}{(\Delta x)^2} + \frac{\partial_y^2 T^n}{(\Delta y)^2} + \frac{\partial_z^2 T^n}{(\Delta z)^2}\right]$$

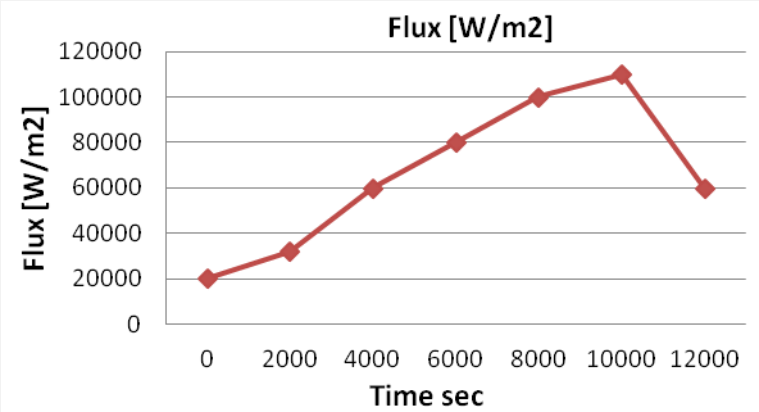
  - **Simple implicit** : Backward time – centered space
    Unconditionally stable
    Accuracy : ***O(Δt)***
    N^3 x N^3 matrix

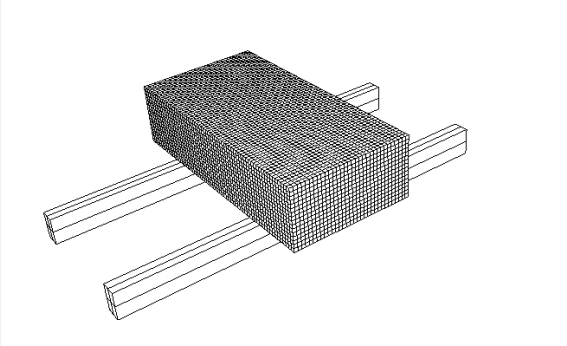
$$\frac{T_{i,j,k}^{n+1} - T_{i,j,k}^{n}}{\Delta t} = \alpha\left[\frac{\partial_x^2 T^{n+1}}{(\Delta x)^2} + \frac{\partial_y^2 T^{n+1}}{(\Delta y)^2} + \frac{\partial_z^2 T^{n+1}}{(\Delta z)^2}\right]$$

  - **Crank-Nicolson** scheme: ½ explicit & ½ implicit
    Unconditionally stable
    Accuracy : ***O(Δt²)***
    N^3 x N^3 matrix

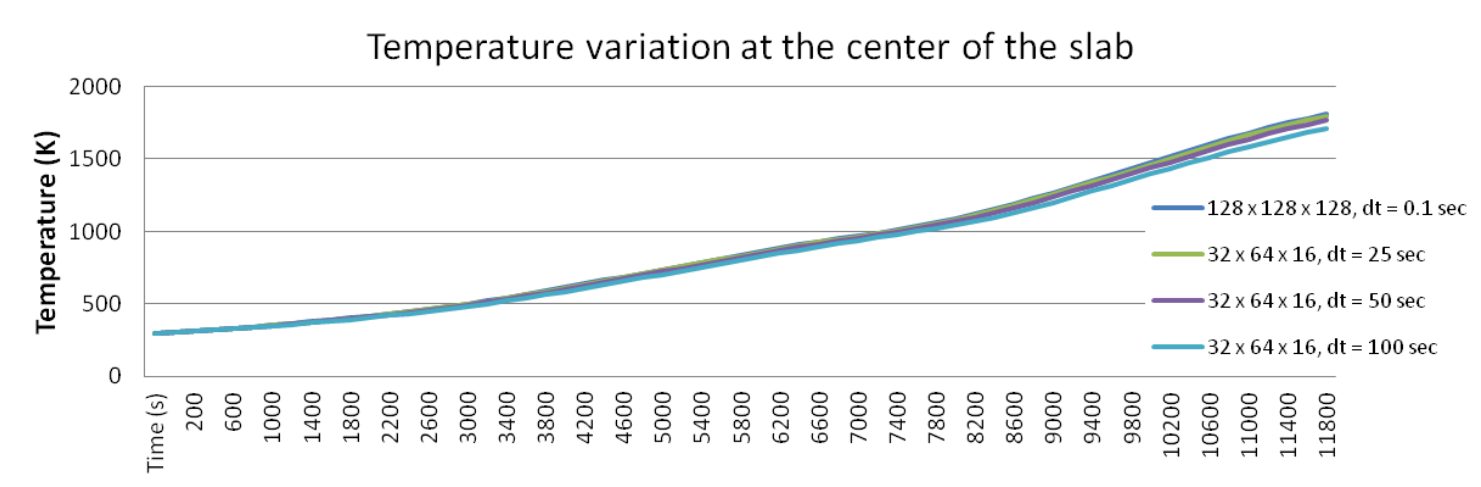
$$\frac{T_{i,j,k}^{n+1} - T_{i,j,k}^{n}}{\Delta t} = \alpha\left[\frac{\partial_x^2 T^n + \partial_x^2 T^{n+1}}{(\Delta x)^2} + \frac{\partial_y^2 T^n + \partial_y^2 T^{n+1}}{(\Delta y)^2} + \frac{\partial_z^2 T^n + \partial_z^2 T^{n+1}}{(\Delta z)^2}\right]$$

Application to the simulation of a slab

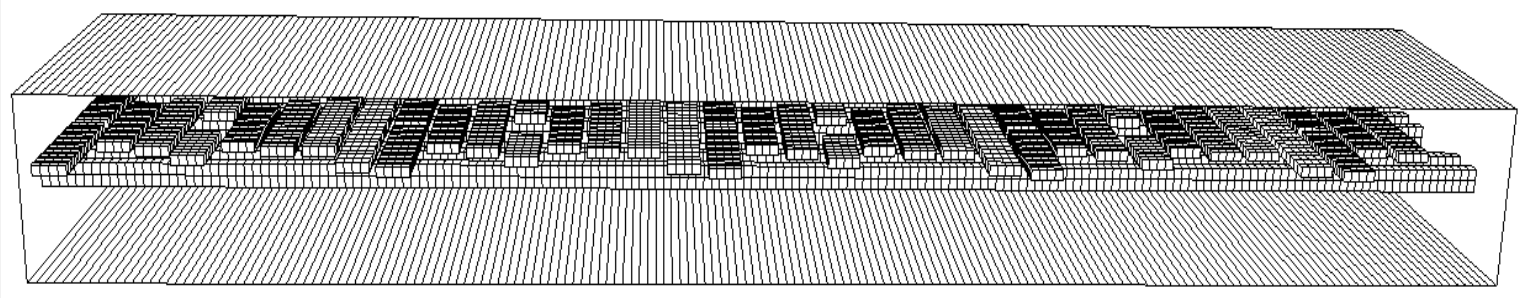




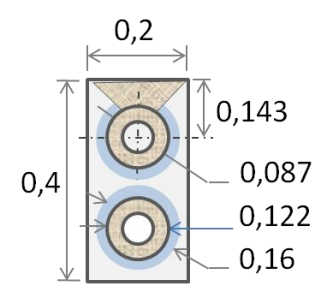
- **3000 simulations/second for 32 x 64 x 16 meshes**



Thermal model

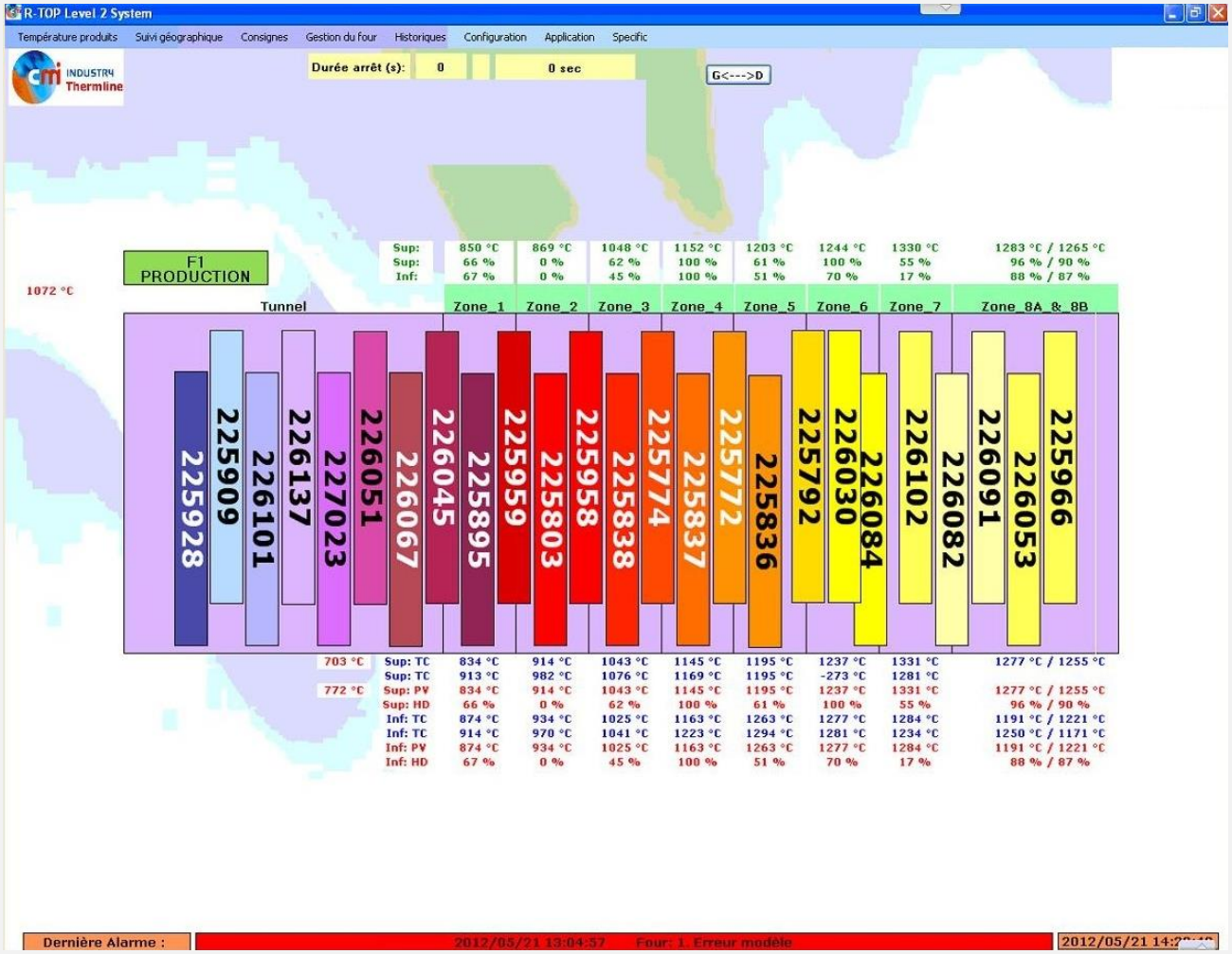


- Wall temperature:
  - Constant in vertical sections
  - Input for the heat balance
- Gas temperature supposed constant in vertical sections
- Radiation flux is projected on the slabs for computing heat diffusion in the slabs
- Rails
  - Cooled by water flow
  - 2D analytical model (steady state)

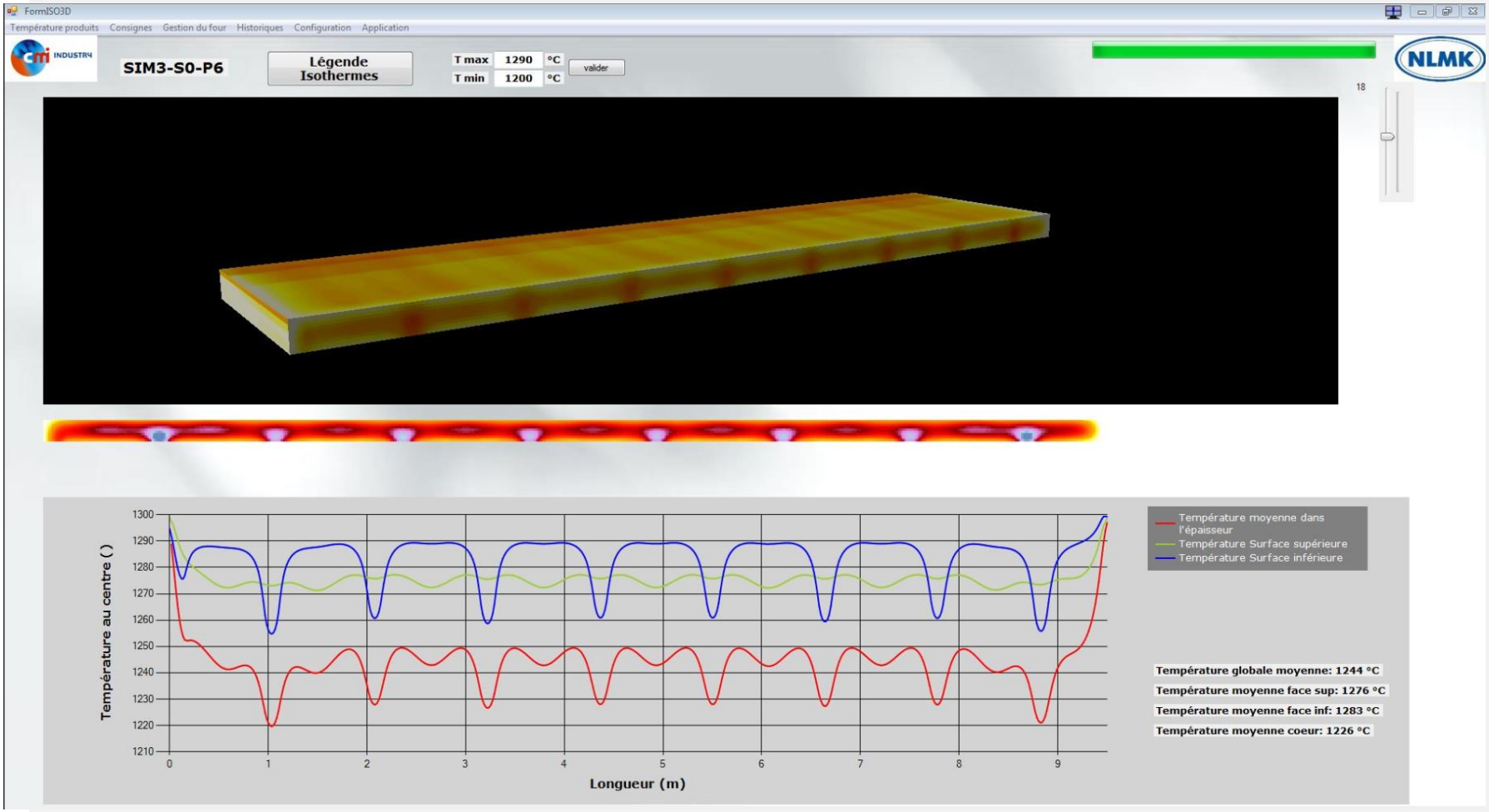


Rail Vertical section

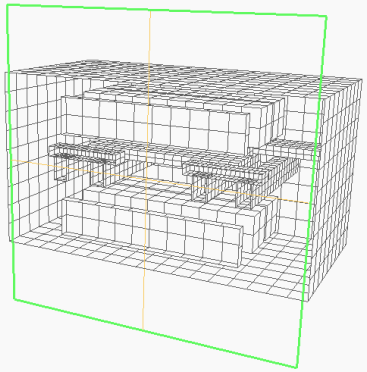
Industrial Solution

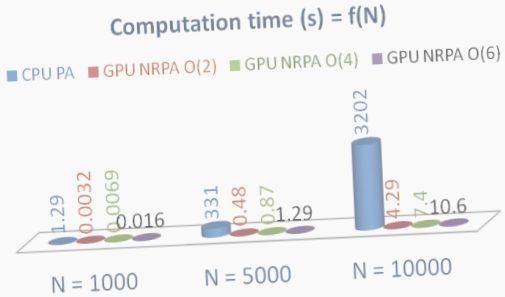


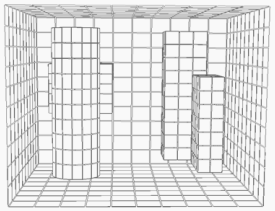
Industrial Solution

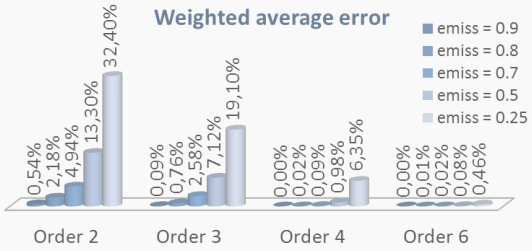


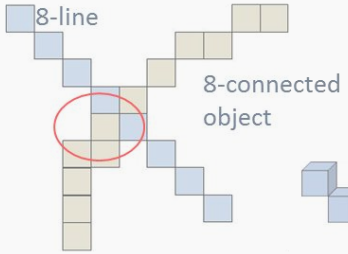
Thank you



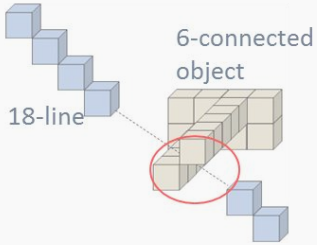








3D



2D