
Center for Energy Efficiency of Systems (CES) - Mines ParisTech
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**Thermal numerical simulation, some examples**

**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*

Steam explosion with nuclear fuel
The radiative heat 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*

Steel Slabs Reheating Furnace
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
Comparison of CPU and GPU performances

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

![Comparison of CPU and GPU performances](image-url)
Comparison of CPU and GPU architectures

**CPU Architecture**

**GPU Architecture**

GTX 680
Discretization

The Multiple Absorption Coefficient Zonal Method (MACZM)

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

\[ GEF = f(a_1, a_2, n_x, n_y, n_z, \tau_1 \ldots \tau_9) \]

**Artificial Neural Networks (ANNs)**

\[
\begin{align*}
\begin{bmatrix} X \end{bmatrix} &= \begin{bmatrix} W_1(20 \times 5) \end{bmatrix} \times \begin{bmatrix} P \end{bmatrix} + \begin{bmatrix} B_1 \end{bmatrix} \\
Z &= F\left(\begin{bmatrix} X \end{bmatrix} \times \begin{bmatrix} W_2 \end{bmatrix} \right) + b_2 \\
(P) &= (a_1, a_2, n_x, n_y, n_z, \tau_i)
\end{align*}
\]
Application to a test furnace

Numerical and experimental verification

- External view
- Internal view

Test Furnace mesh

Numerical validation

<table>
<thead>
<tr>
<th>Comparison MACZM – MODRAY</th>
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<tbody>
<tr>
<td>Direct exchange factors</td>
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<tr>
<td>Combustion volume(1)-</td>
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<td>combustion volume(2)</td>
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<td>Combustion volume(1)-</td>
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<td>steel slab</td>
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<tr>
<td>Combustion volume(2)-</td>
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<td>steel slab</td>
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<td>Base - base</td>
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Experimental validation

- Burner 1
- Burner 2
- Slab of steel
- Supports

- External view
- Internal view

Supports
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):**

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

  B.C.: Radiation heat flux

- **Finite difference discretization schemes (1\textsuperscript{st} order time - 2\textsuperscript{nd} order space)**
  - **Simple explicit**: Forward time – centered space
    - Stability condition
    - Accuracy: \(O(\Delta t)\)
  - **Simple implicit**: Backward time – centered space
    - Unconditionally stable
    - Accuracy: \(O(\Delta t)\)
    - \(N^3 \times N^3\) matrix
  - **Crank-Nicolson** scheme: ½ explicit & ½ implicit
    - Unconditionally stable
    - Accuracy: \(O(\Delta t^2)\)
    - \(N^3 \times N^3\) matrix
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)
Industrial Solution
Industrial Solution
Thank you