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Characterization of thermal properties of ceramic foams by a numerically simulated Flash method

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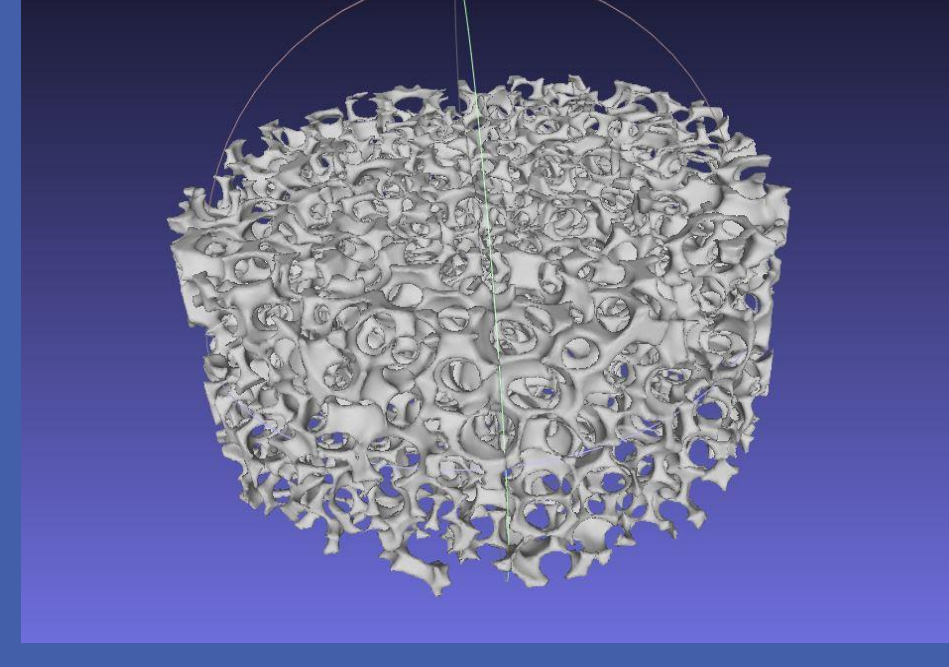
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Introduction

- Interesting thermomechanical properties of **ceramic foams** for heat recovery / storage / transport at **high temperatures**
- Need for the most relevant **modeling** from the point of view of **coupled heat transfer** (conduction, convection and radiation) on complex geometries
- Better understanding and quantification of the physics involved
- Support for the **geometric, textural and thermal optimization** of ceramic foams
- Determination of **thermal and radiative properties** by **Flash method**. Coupled model in **conduction and radiation** with equivalent properties on a representative elementary volume (**REV**)



Practical experiment :

Thermogram obtained at high temperature from a flash method in **practical conditions**

Numerical experiment :

Thermogram obtained at high temperature from a **numerical method** with Monte-Carlo Method (**MCM**)

1. Practical Experimental Flash Method

Measuring bench High Temperature :

Structured and stochastic foam :

Cooled windows : Pulsed by CO2 laser:

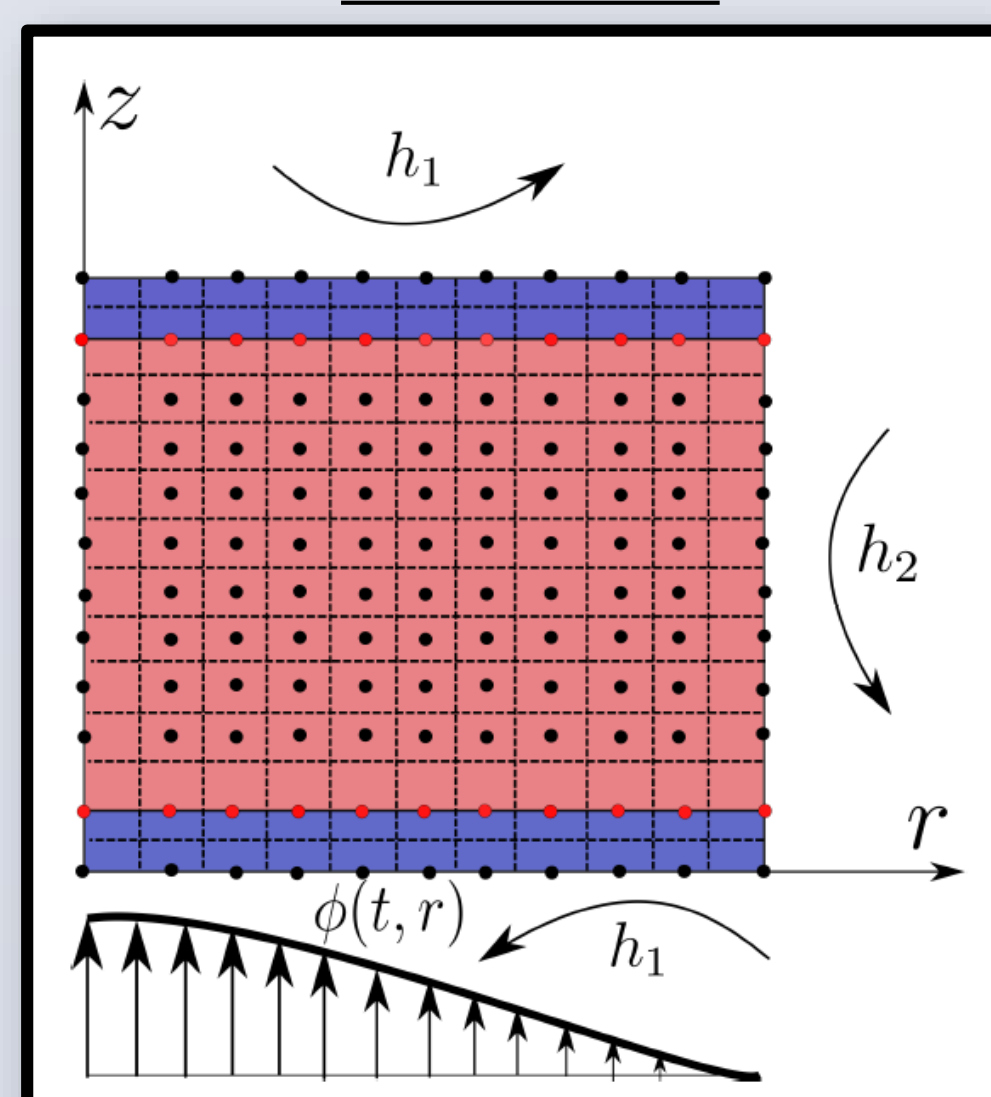
- Model 2D-axi-symmetric.
- Conduction : Finite Volume Method

$$\rho C \frac{\partial T}{\partial t} = \lambda \Delta T - \text{div}(\mathbf{q}_r)$$

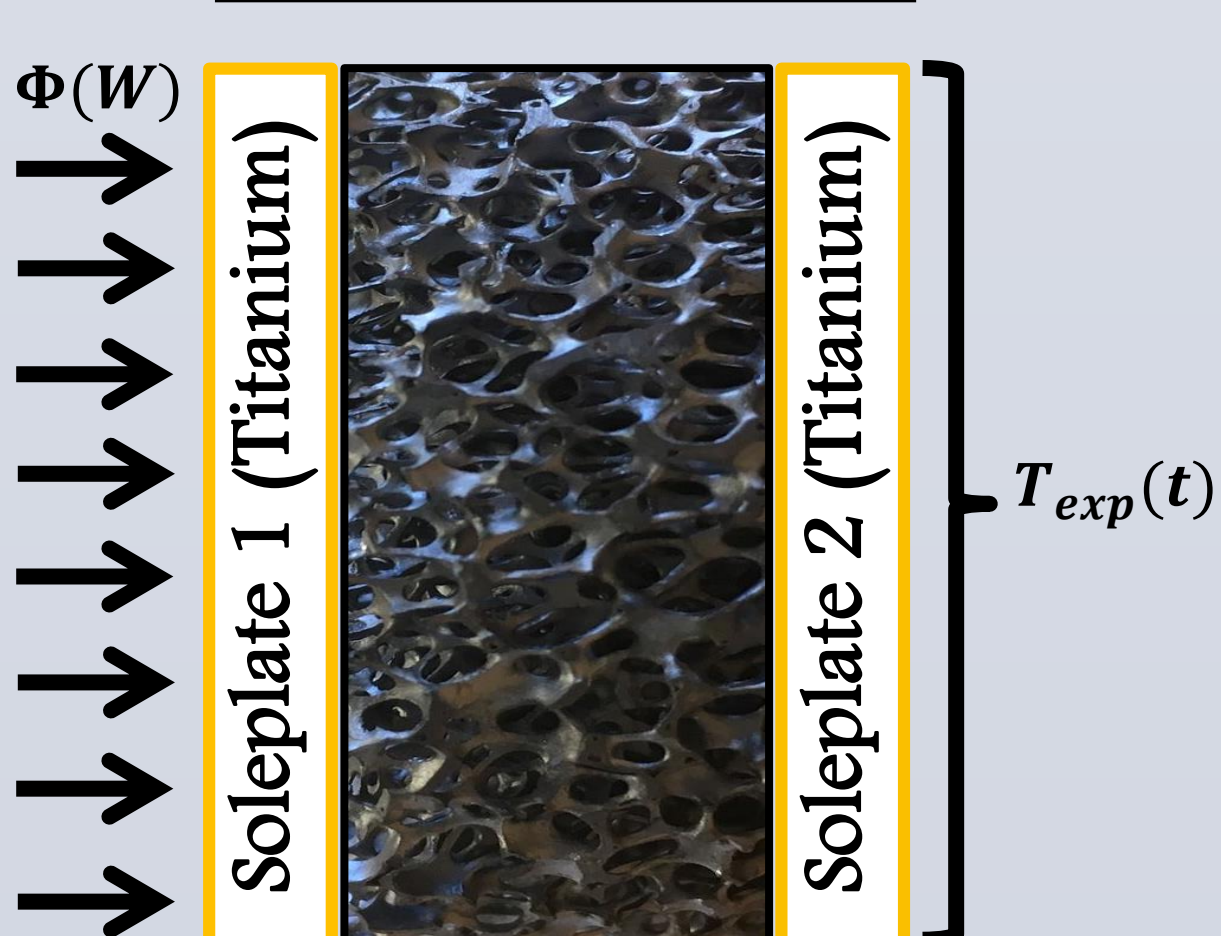
- Radiation : Optimized Reciprocity Monte-Carlo Method [1]

$$\text{div}(\mathbf{q}_r)_i^{ARM} = \sum_{j=0}^{N_{elem}} \int_{\nu_{min}}^{\nu_{max}} P_{jt,i,\nu}^{ea} \left(\frac{I_{\nu}^0(T_i, n_i)}{I_{\nu}^0(T_j, n_j)} - 1 \right) d\nu$$

Geometry :



Three-Layer system.



- Inverse Method (Levenberg-Marquardt) : Characterization of equivalent diffusivity and optical thickness

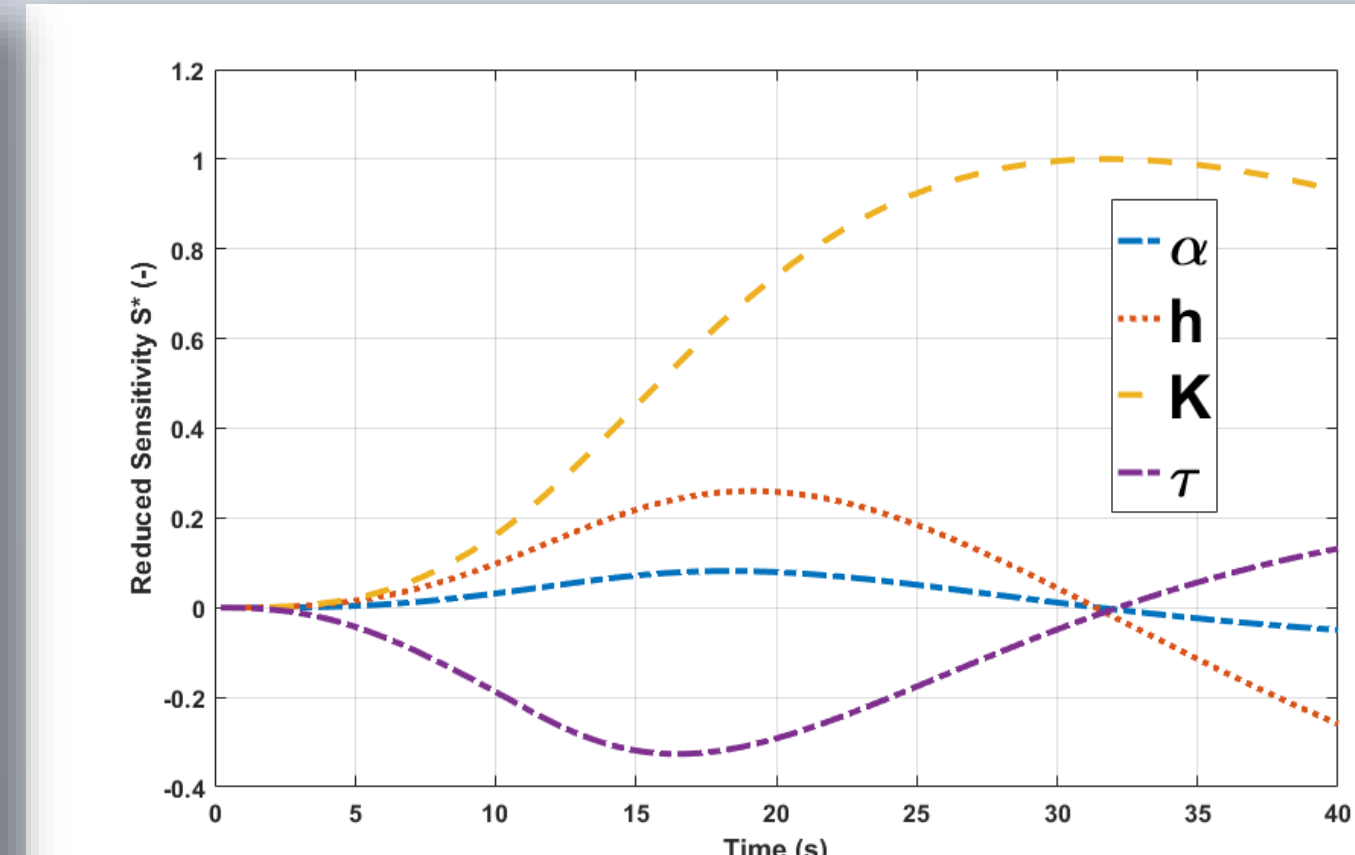
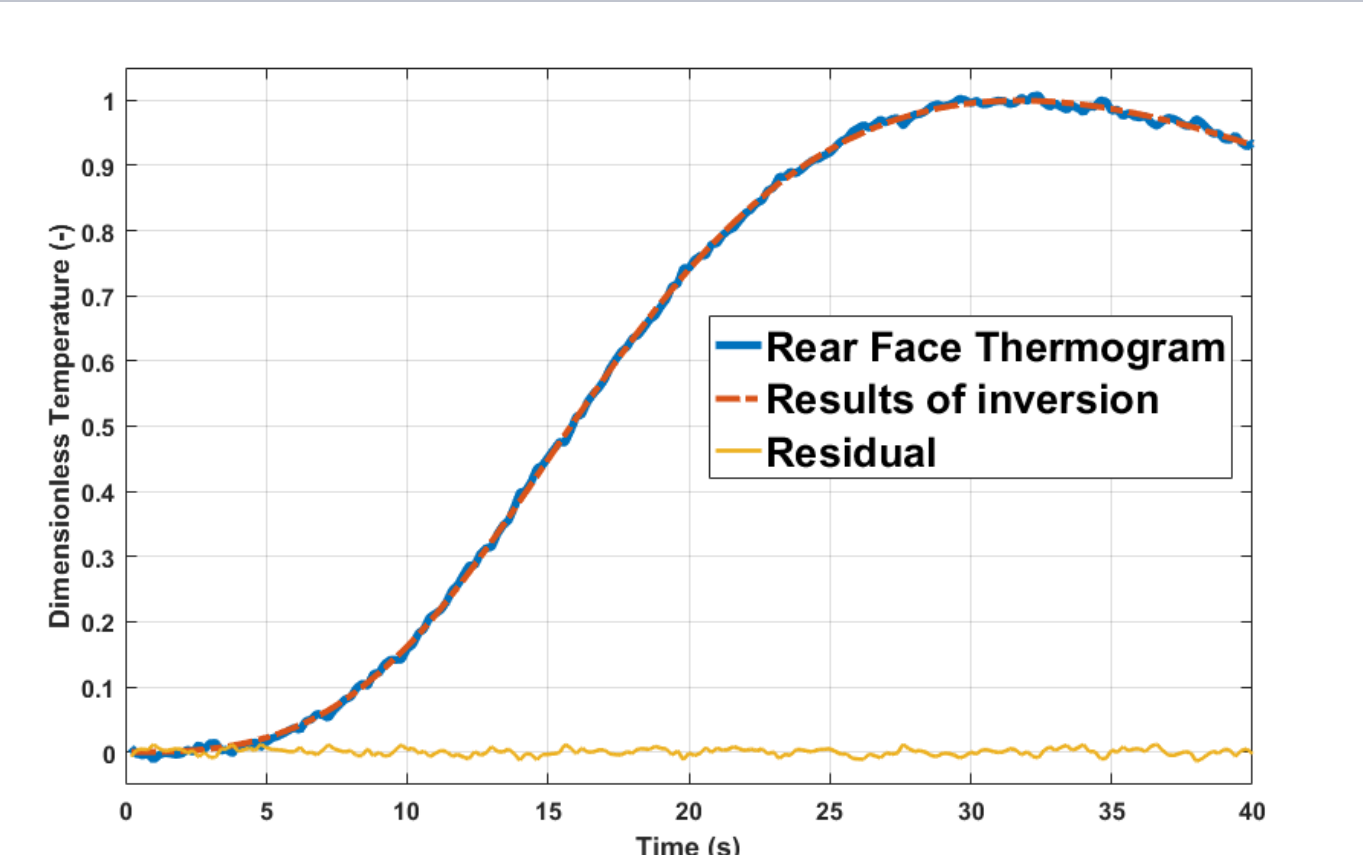
$$\beta = [\alpha \ h \ K \ \tau]$$

$$J(\beta) = \|T_{exp} - T_{mod}(\beta)\|^2$$

$$J'(\beta_{opt}) = 0$$

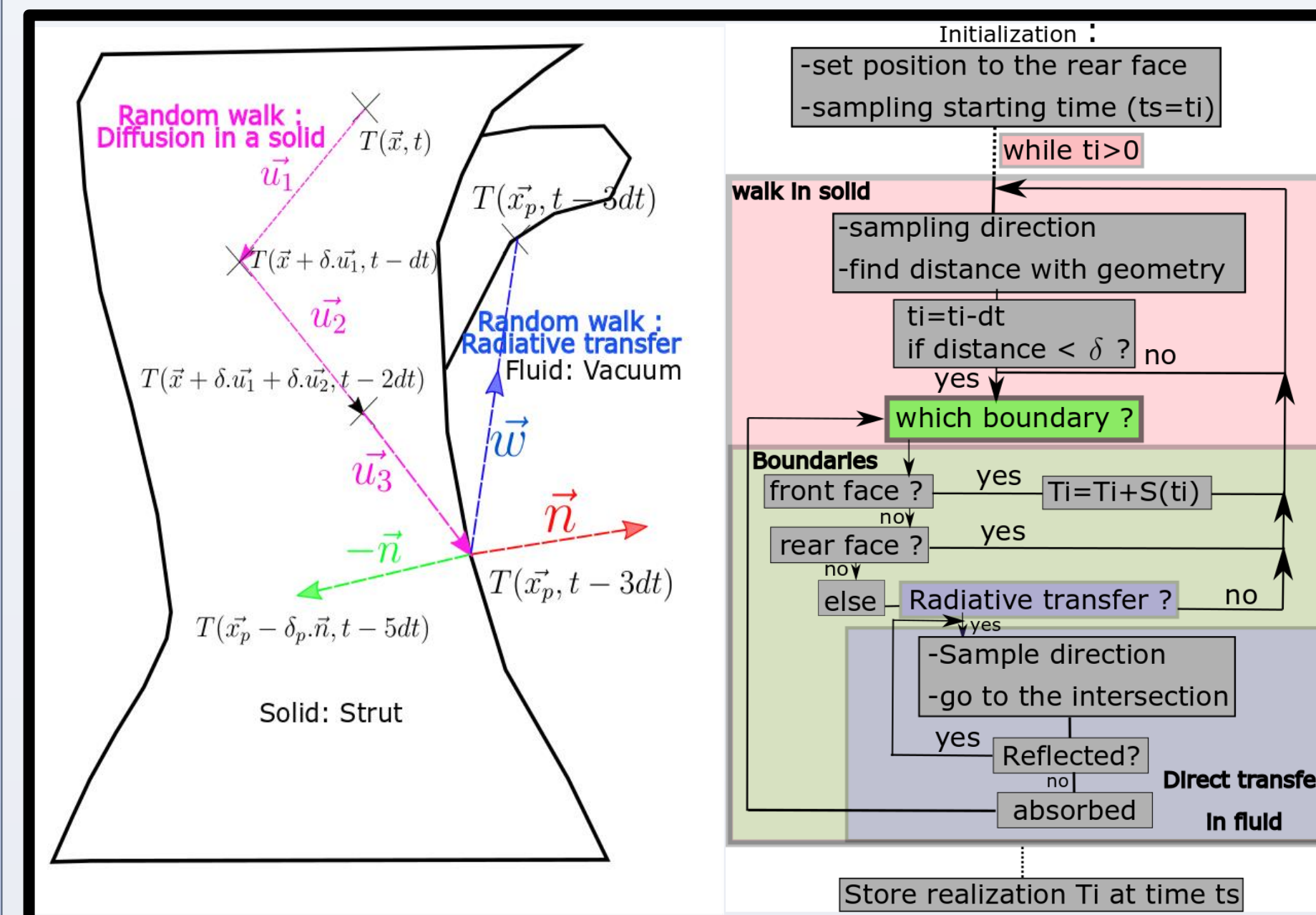
$$\beta^{(k+1)} = \beta^{(k)} + \underline{M} \cdot (y_{exp} - y_{mod}(\beta^{(k)}))$$

- Results** : structured foam (Kelvin-Cell pore diameter 7.5mm 800°C SiSiC) Characterization: **flat residual** Sensibility Analysis: **no correlation**



2. Numerical Experiment Flash Method

- Algorithm Monte-Carlo Conduction and radiative transfer [2]:



Value of the temperature at t_j : $\bar{T}(\bar{x}, t_j) = \frac{1}{N} \sum_i T_i(\bar{x}, t_j)$

Fast computation of intersections between the paths and the surface mesh. Star-Engine library (<https://www.meso-star.com/projects/star-engine.html>)

- Problem Definition:

- Compute Temperature $T(t)$ at the rear face
- Imposed moving step δ
- Recursive in time: $dt = \frac{\delta}{6\alpha}$
- Surface source excitation at front face: $S(t)$
- Probability of conductive or radiative path
- Probability of reflection/absorption: $R_p < \rho$
- Transfer along \bar{z} direction
- Periodicity boundaries for \bar{x} and \bar{y}

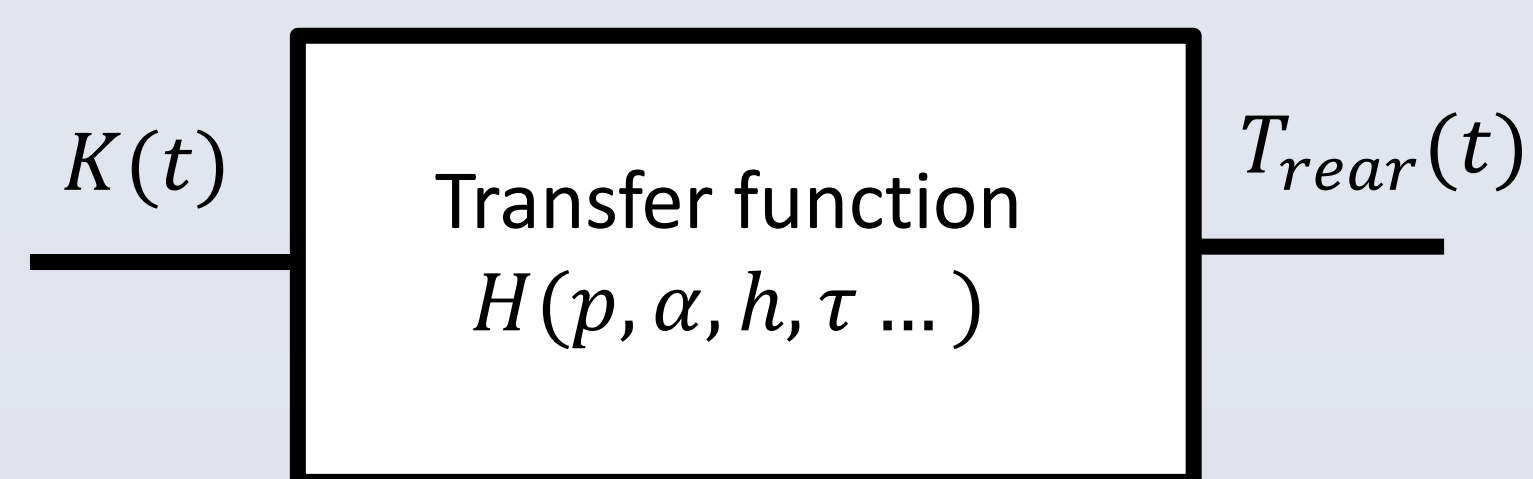
- Model: **Quadrupole approach**

- Geometry:

- Three-layer**: 2 Pure conduction in soleplate, 1 absorbing-emitting media

- Model 1D semi-analytic (Laplace domain)

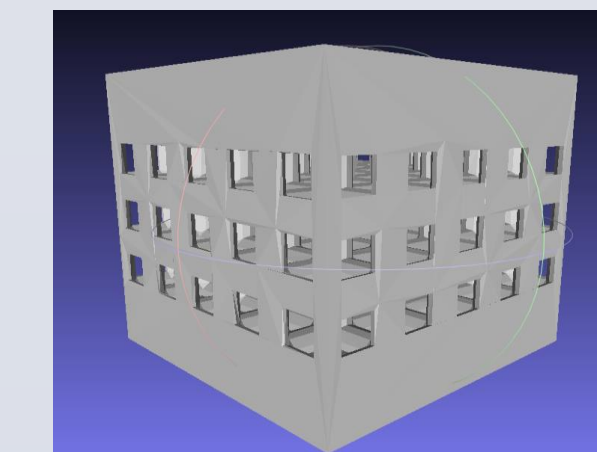
$$T_{rear}(t) = K(t) \cdot \mathcal{L}^{-1}[H(p, \beta)](t)$$



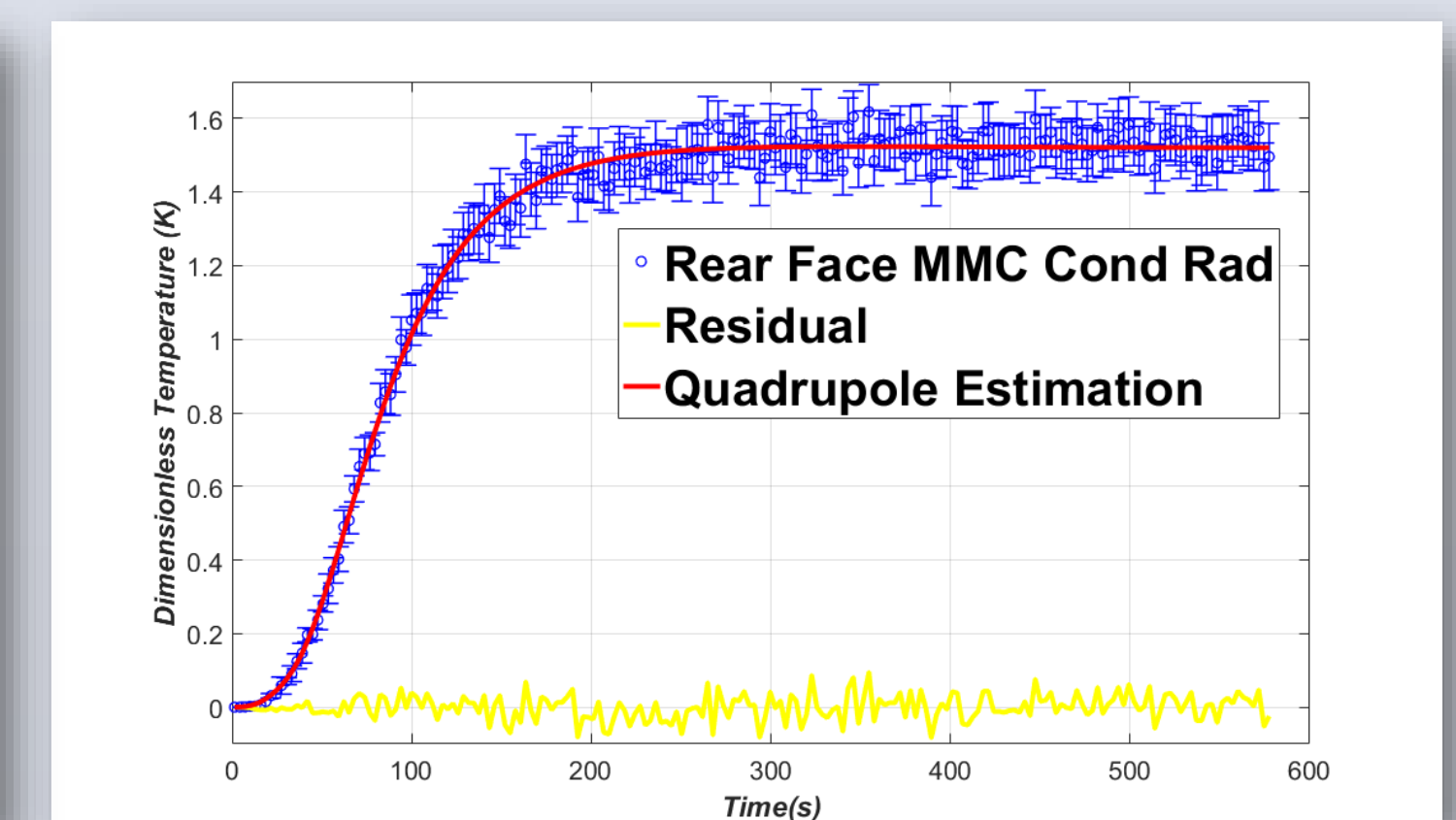
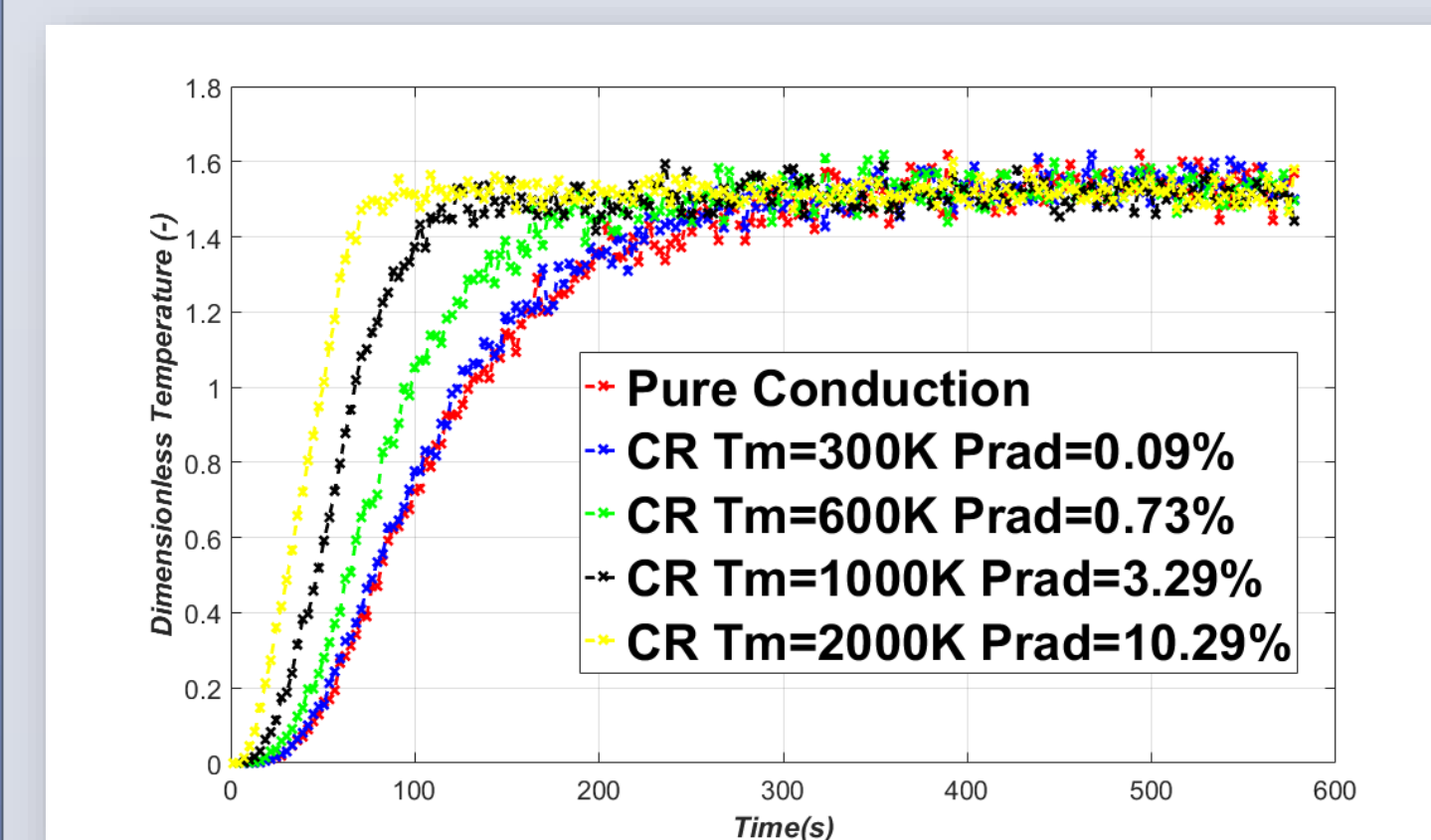
- Inverse method with $\beta = [\alpha \ \tau \ K]$

- Stochastic effect of Monte Carlo is considered as a **real experimental noise**
- Generated by GenMat© (LTEN): **Stochastic Kelvin-Cell structure** [3]

- Effect of radiative transfer on a cubic structured foam with cylindrical struts
- $d_{struts} = 0.1 \text{ mm}$ $\epsilon = 0,75\%$



- Result of the inversion. Estimation of both equivalent diffusivity and optical thickness
- $\frac{\alpha_{eq}}{\alpha_{bulk}} = 0,46$ $\tau_{eq} = 1.89$



- Acceleration of heat transfer when the radiation increases

- Good fit with flat residual

Conclusion and prospect

- Possibility to characterize the equivalent conductive and radiative behavior at high temperature. Other experiments with different ceramics (ZrO₂, Al₂O₃ ...) and different textural properties are planned.
- First encouraging results. Next step, influence of various parameters on the thermogram (possible bias, CPU-time, ...). Impact of the geometry on the equivalent parameter. Computation with stochastic foams generated by GenMat and with real tomographic mesh.

References

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