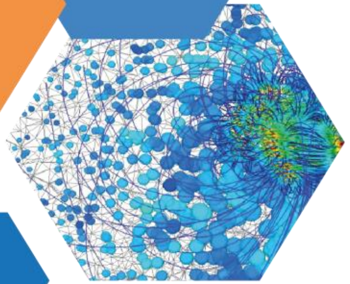
SC-Consultants

Replace **trial & error** with numerical simulation
to save **time & money**



SCIENCES
COMPUTERS
CONSULTANTS

Simulation du chauffage dans un four

Mecamat – Aussois 2024

Sacha El Aouad, Giulia Lissoni, Laurent Ratte et Lucas Sardo

WHO ARE WE?

SCIENCES COMPUTERS CONSULTANTS edits and markets **numerical simulation software** dedicated to industrial processes.

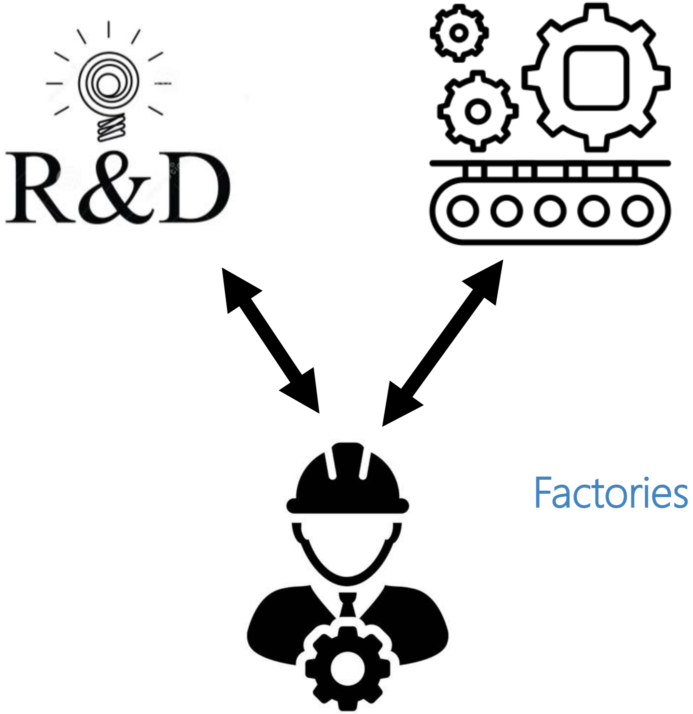
In a context where raw materials and energies are becoming more and more expensive, halving conventional methods «trials/errors» is a considerable argument.

OUR FOCUS AREAS

INDUSTRY

RESEARCH

Materials transformation processes



Factories Technical Support

SCIENCES COMPUTERS CONSULTANTS

WHAT WE DO ?

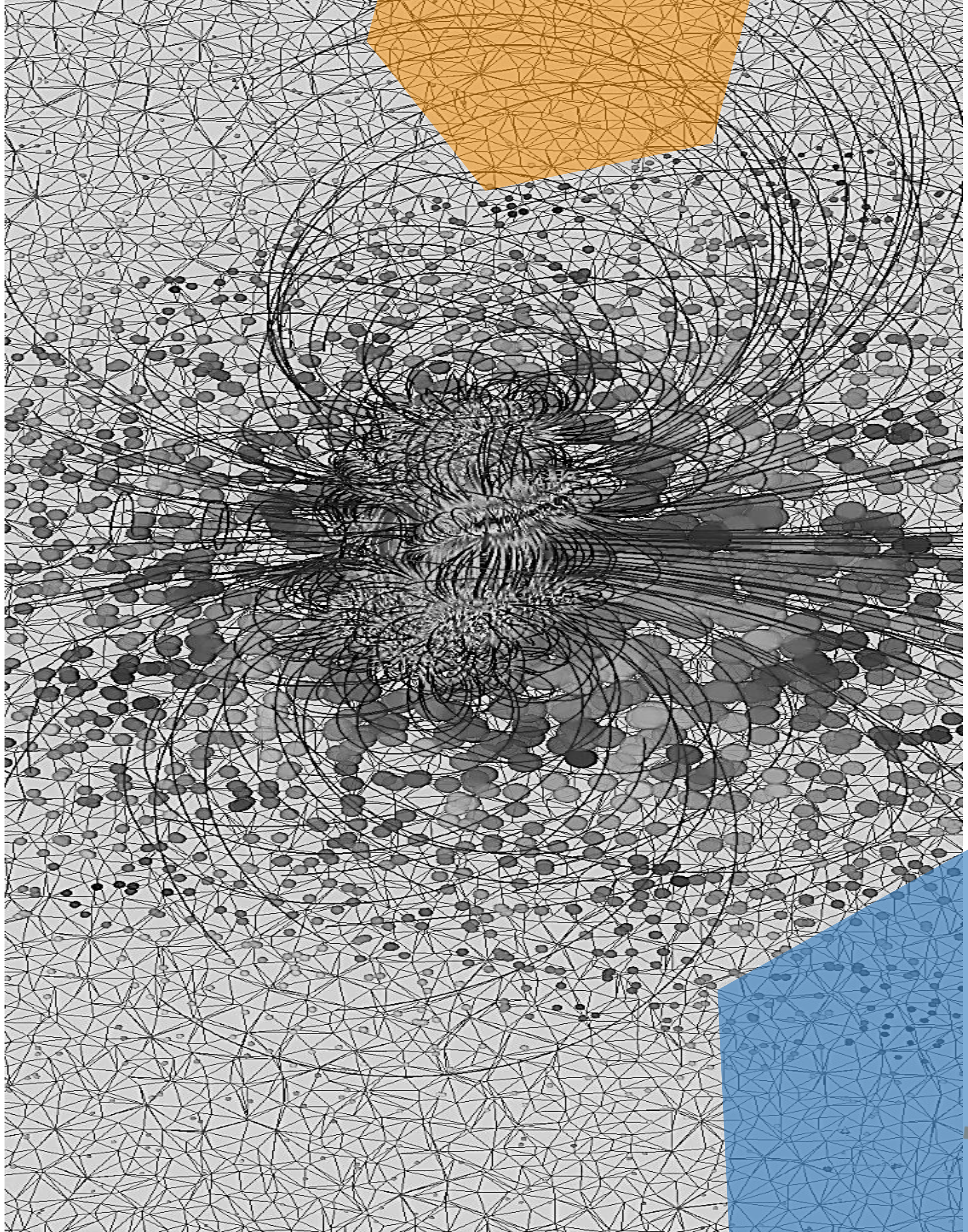
SOFTWARE LICENSE

CONSULTING

R&D Support

TRAINING

OUR SOFTWARE



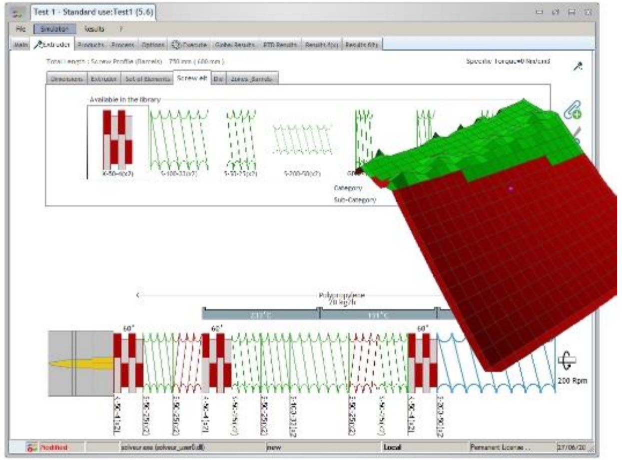
Twin Screw

OUR SOFTWARE 01

Ludovic®

XimeX® TSE

Opening the TSE black box



INRAE

MINES PARIS | PSL | Cemef

cnrs

SCIENCES COMPUTERS CONSULTANTS

Mixing & Extrusion

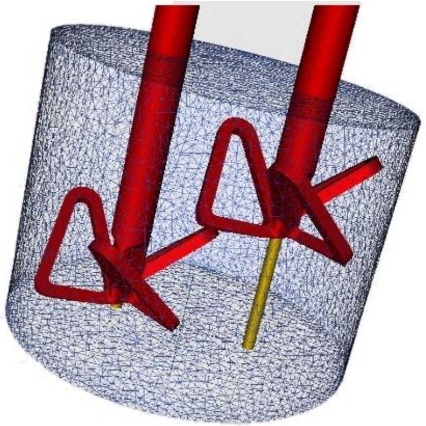
XimeX®

ASAP

DIE

MXR

Master mixing with precision and control



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SCIENCES COMPUTERS CONSULTANTS

Ingot Casting

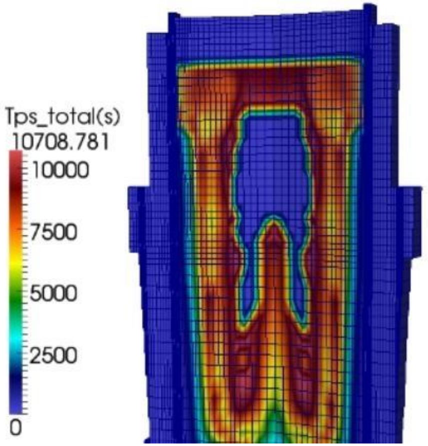
OpenSolid

CC DCC

CFG

ING

Optimize casting processes by accurately predicting segregation.



INSTITUT JEAN LAMOUR

UNIVERSITÉ DE LORRAINE

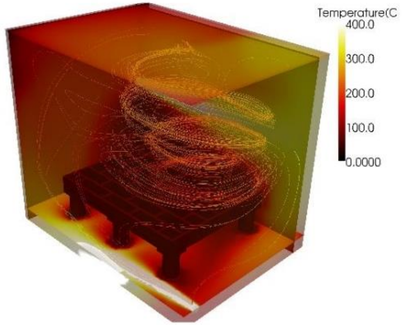
SCIENCES COMPUTERS CONSULTANTS

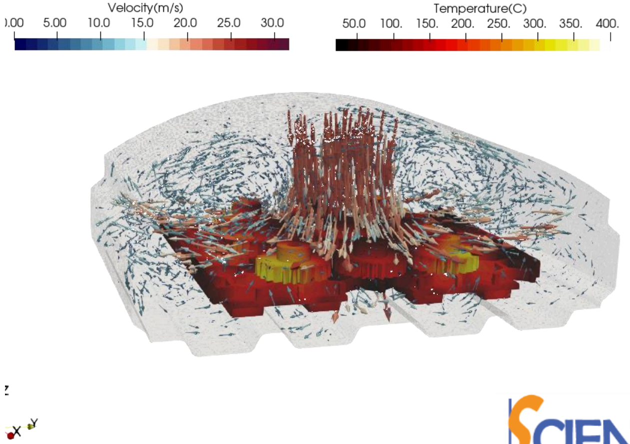
Heating & Cooling

[qobeo] Thermal Optimisation Solution

S2S **AIR** **BUB**

Optimize furnace efficiency: Simulate. Save. Succeed.





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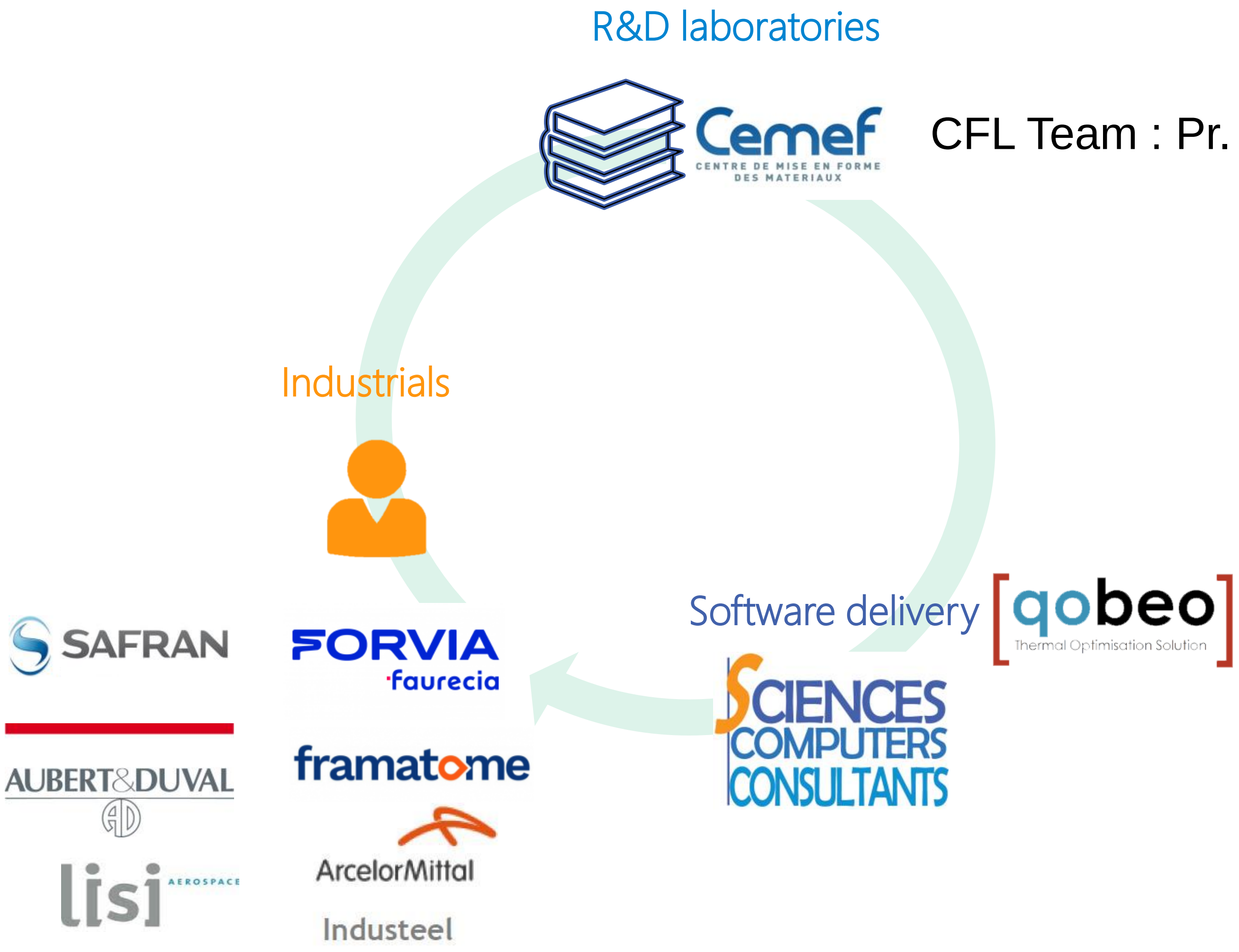
The qobeo® project



R&D laboratories

Cemef
CENTRE DE MISE EN FORME DES MATERIAUX

CFL Team : Pr. Elie HACHEM

Industrials

SAFRAN
FORVIA faurecia
AUBERT&DUVAL
framatome
lisi AEROSPACE
ArcelorMittal Industeel

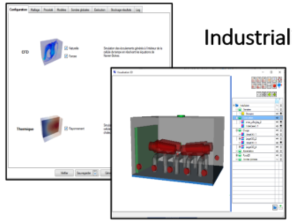
Software delivery

[qobeo] Thermal Optimisation Solution

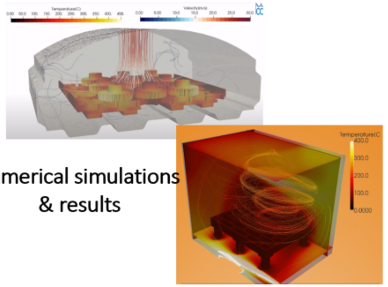
SCIENCES COMPUTERS CONSULTANTS

The qobeo® project

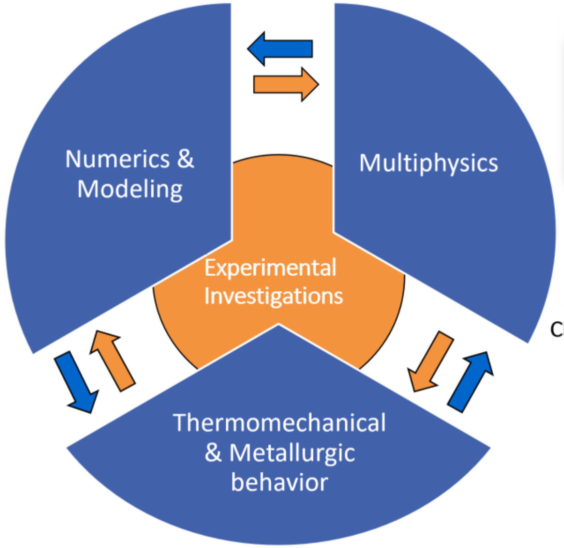
- Based on
  - Research work
  - Characterizations and experimental validations
- Continuous developments
  - Private fundings: the initial framework (~2006)
  - ADEME: Ademe call
  - ANR-Cosinus (**REALisTIC**):
    - Large Scale and Long Time Computation
  - ANR (**HECO**):
    - Moving mesh for heating and cooling processes
  - ANR Industrial Chair (**INFINITY**):
    - Numerical and physical framework for boiling and quenching applications



Industrialization



Numerical simulations & results

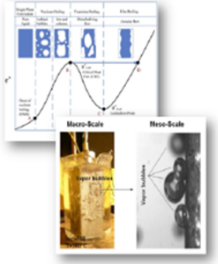


Numerics & Modeling

Multiphysics

Experimental Investigations

Thermomechanical & Metallurgic behavior

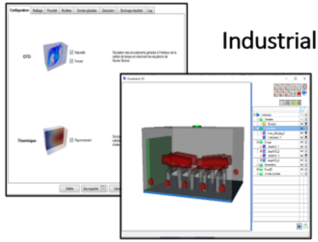


CEMEF experimental results

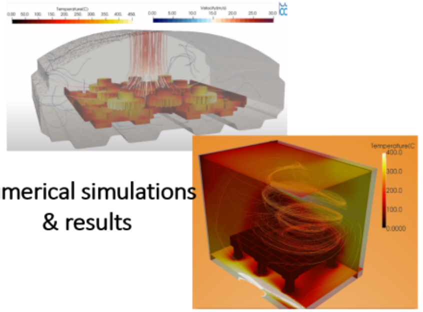
Industrial results, testing & database

qobeo
Thermal Optimisation Solution

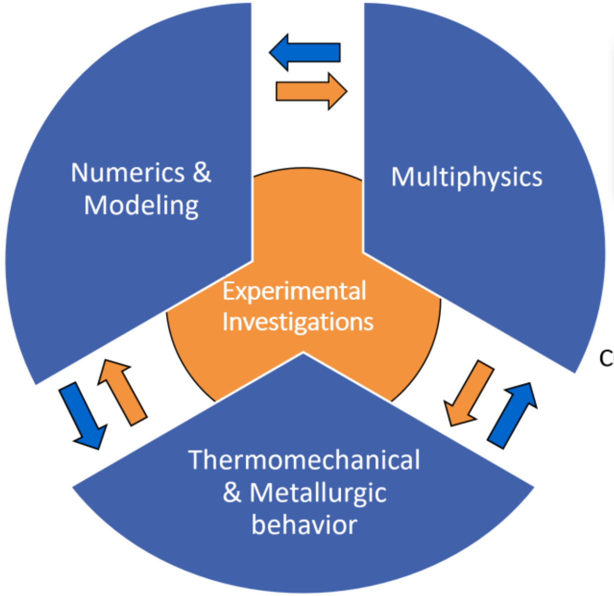
Simulation of heating & cooling processes



Industrialization



Numerical simulations & results



Numerics & Modeling

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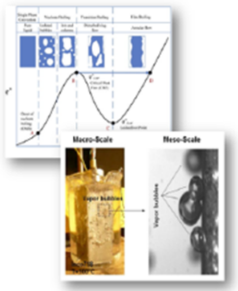


CEMEF experimental results

Industrial results, testing & database

S2S Radiation “Surface to Surface”
(Four électrique, déplacement, ...)

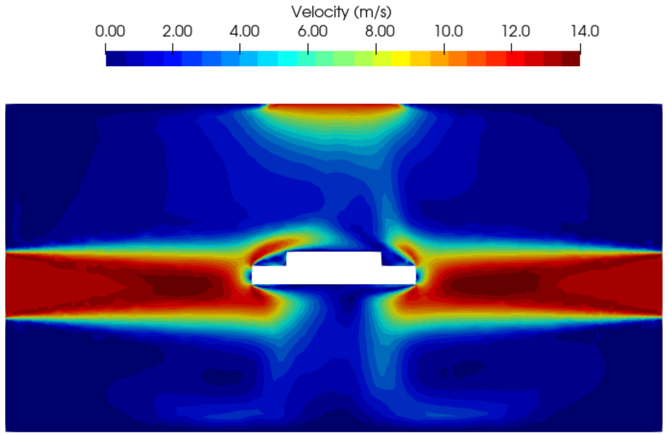
AIR Heating & Air quenching

BUB Water/oil quenching

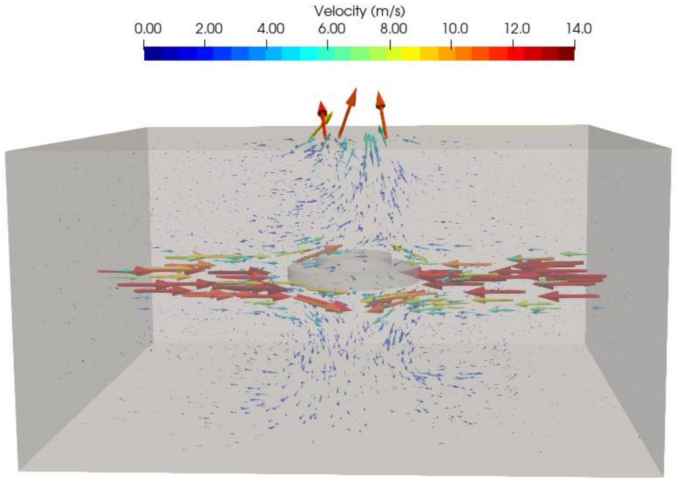
qobeo-AIR® : software principles

- Simulates air heating / cooling
- Tetrahedral Meshes, Anisotropic meshes
- Finite Element method
- CFD Solver applied on the hollow mesh
  - Natural Convection
  - Forced Convection
    - Choice of turbulent model:
      - K-epsilon
      - Smagorinsky
  - PID Regulation for nozzles flow rate

Cooling of a load from 2 nozzles



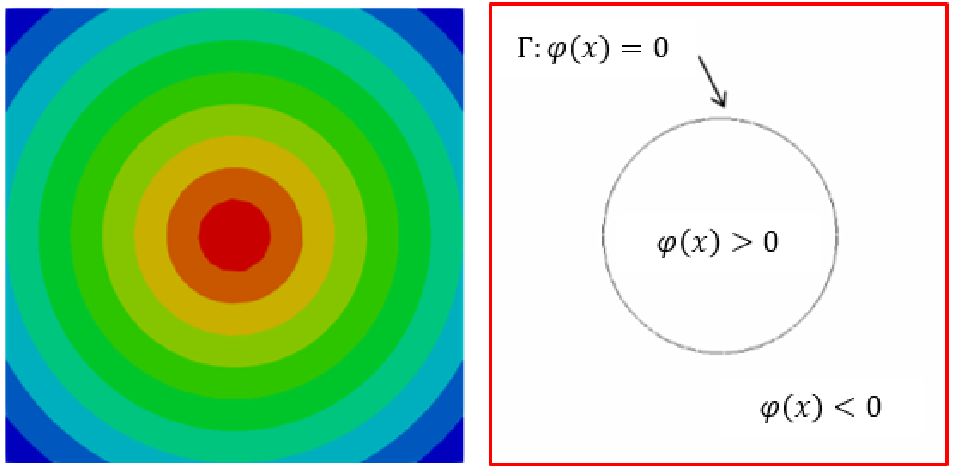
Velocity field evolution



Immersed Volume Method

- Only one domain considered (the furnace)
  - Loads immersed in domain
  - LevelSet Function
    - Signed distance function to the interface Γ
    - Localize interface of immersed body

$$\phi(x) = \begin{cases} dist(x,\Gamma) & \text{if} \quad x \in \Omega_s \\ 0 & \text{if} \quad x \in \Gamma \\ -dist(x,\Gamma) & \text{if} \quad x \in \Omega_f \end{cases}$$



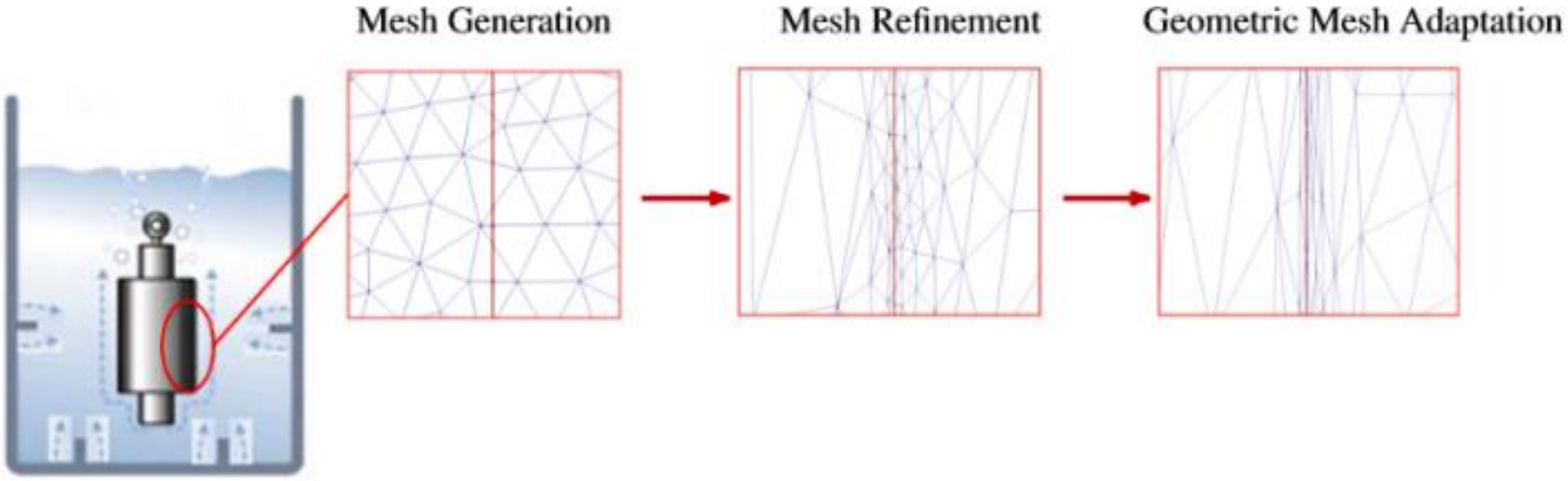
Level set function

S. Osher, J. A. Sethian, Fronts propagating with curvature-dependent speed: Algorithms based on Hamilton -Jacobi formulations, Journal of computational physics 79 (1) (1988) 12-49

O. Desjardins, V. Moureau, H. Pitsch, An accurate conservative level set/ghost fluid method for simulating turbulent atomization, Journal of computational physics 227 (18) (2008) 8395-8416.

Immersed Volume Method / Meshing

- Only one domain considered
  - Mesh refinement close to the edges
    - Anisotropic meshes (tetrahedral meshes)



Immersed Volume Method / Meshing

- Only one domain considered
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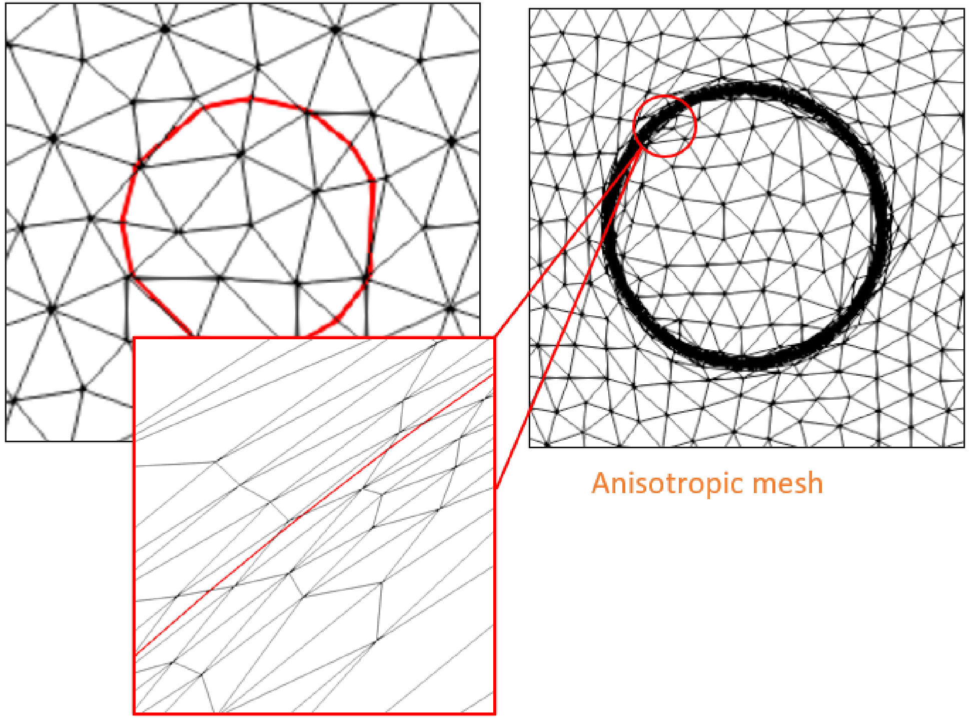
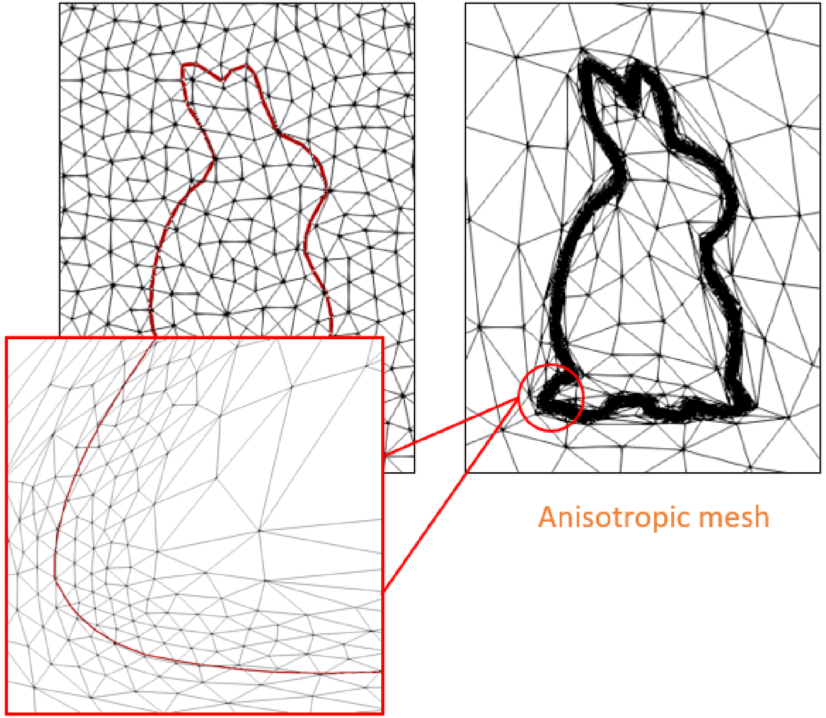
    - Anisotropic meshes



Anisotropic mesh



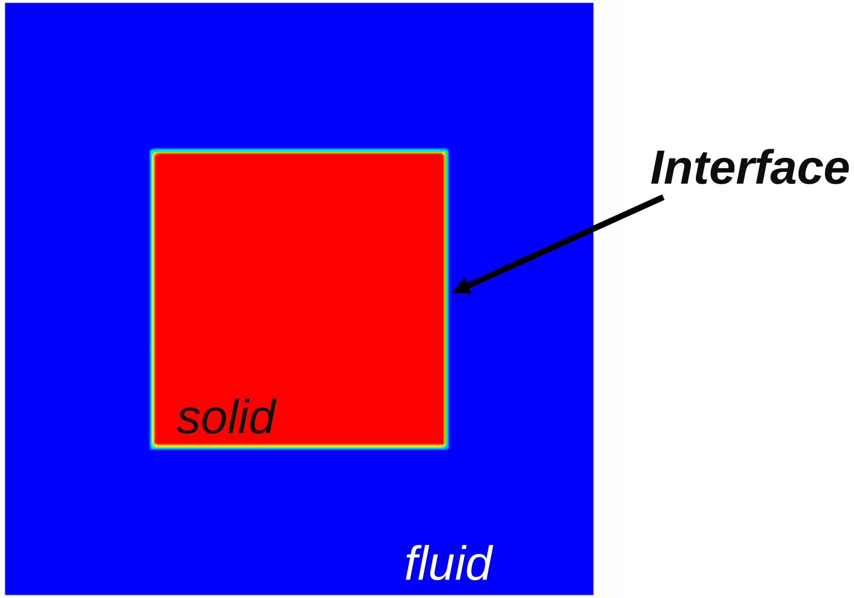
Anisotropic mesh

S. EL Aouad, Numerical and parallel modeling of anisotropic fitted mesh for industrial quenching applications, Thèse de doctorat Mathématiques numériques, Calcul intensif et Données Université Paris sciences et lettres 2022

Immersed Volume Method

- Mixing laws for thermal properties
  - Smoothed Heaviside function on a narrow band region ϵ

$$H_\epsilon(x) = \begin{cases} 1 & \text{for } \phi(x) > \epsilon \\ \frac{1}{2}\left(1 + \frac{\phi(x)}{\epsilon} + \frac{1}{\pi}\sin\left(\frac{\pi\phi(x)}{\epsilon}\right)\right) & \text{for } |\phi(x)| \leq \epsilon \\ 0 & \text{for } \phi(x) < -\epsilon \end{cases}$$



$$\rho = \rho_{fluid} H_\epsilon\big(\phi(x)\big) + \rho_{solid} (1 - H_\epsilon(\phi(x))$$

$$\eta = \eta_{fluid} H_\epsilon\big(\phi(x)\big) + \eta_{solid} (1 - H_\epsilon(\phi(x))$$

$$k = \left(\frac{H_\epsilon(\phi(x))}{k_{fluid}} + \frac{1 - H_\epsilon(\phi(x))}{k_{solid}} \right)^{-1}$$

E. Hachem, H. Digonnet, E. Massoni, T. Coupez, Immersed volume method for solving natural convection, conduction and radiation of a hat-shaped disk inside a 3d enclosure, International Journal of numerical methods for heat & fluid flow (2012).

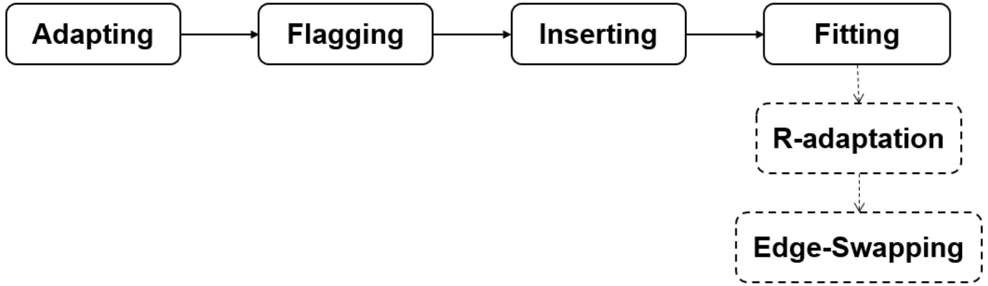
Immersed Volume Method

- Mixing laws for thermal properties
  - Advantages : Suitable for most of tetrahedral meshes
  - Drawbacks : the ε parameters should be related to the mesh size.
    - What to choose when you have different mesh sizes ?
    - High impact on the results if not well defined

How to remove mixing laws

- Fitted Meshes
  - Mesh elements are only in one region (fluid, loads, …)
  - No need to mix thermo-physical properties

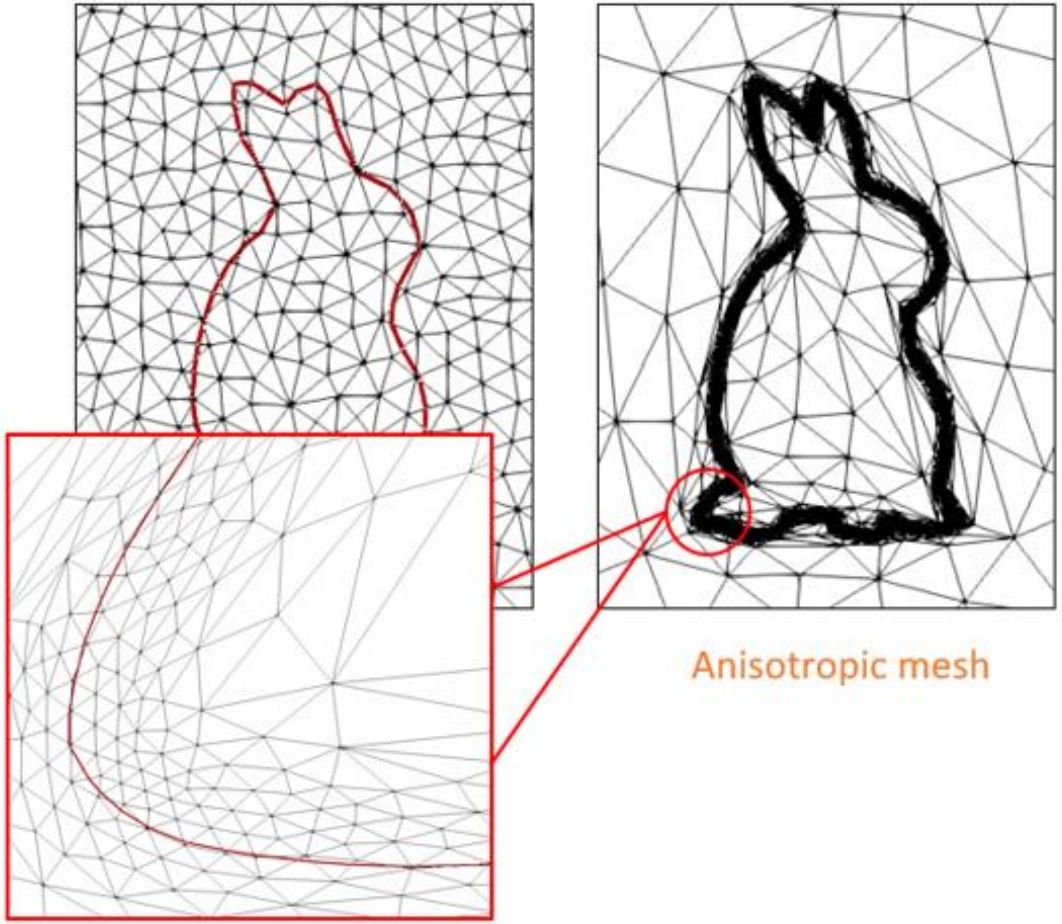
- How to obtain fitted meshes



Adapting → **Flagging** → **Inserting** → **Fitting**

R-adaptation

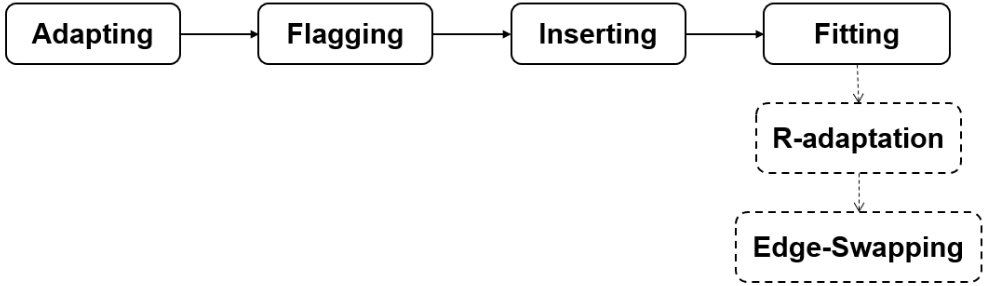
Edge-Swapping



S. EL Aouad, Numerical and parallel modeling of anisotropic fitted mesh for industrial quenching applications, Thèse de doctorat Mathématiques numériques, Calcul intensif et Données Université Paris sciences et lettres 2022

How to remove mixing laws

- How to obtain fitted meshes



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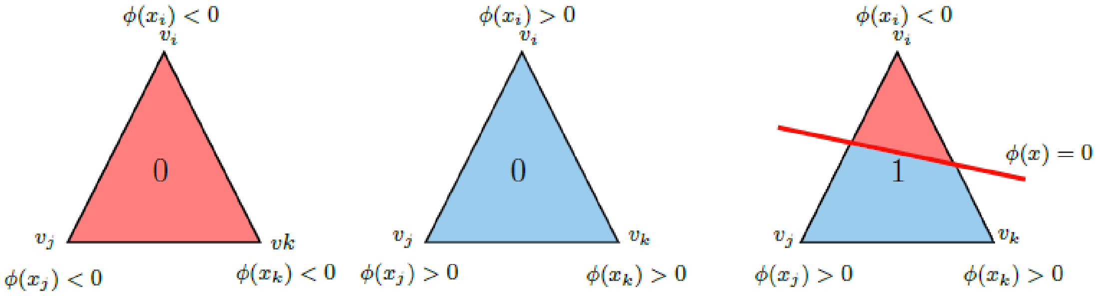
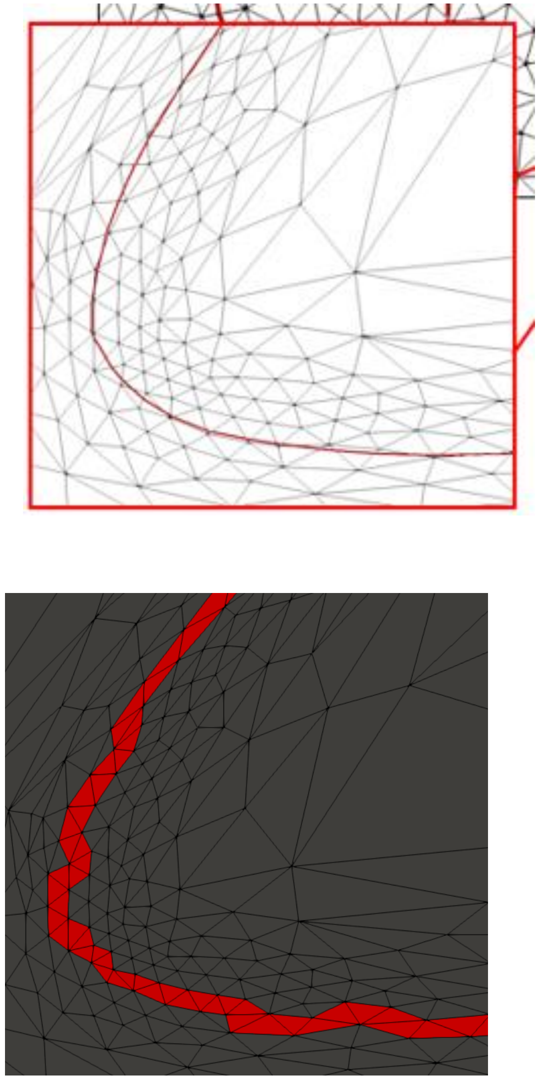
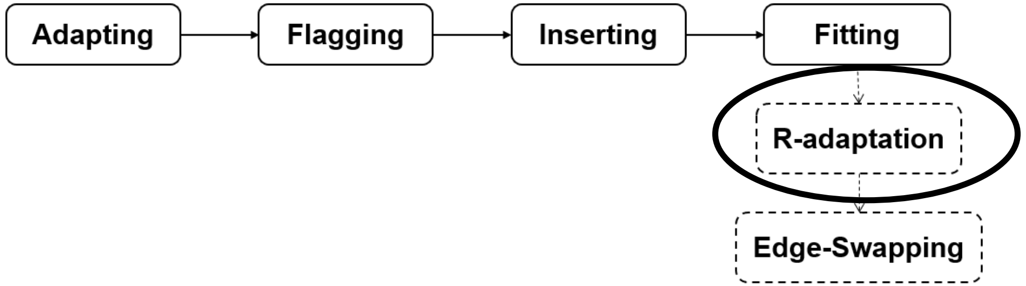


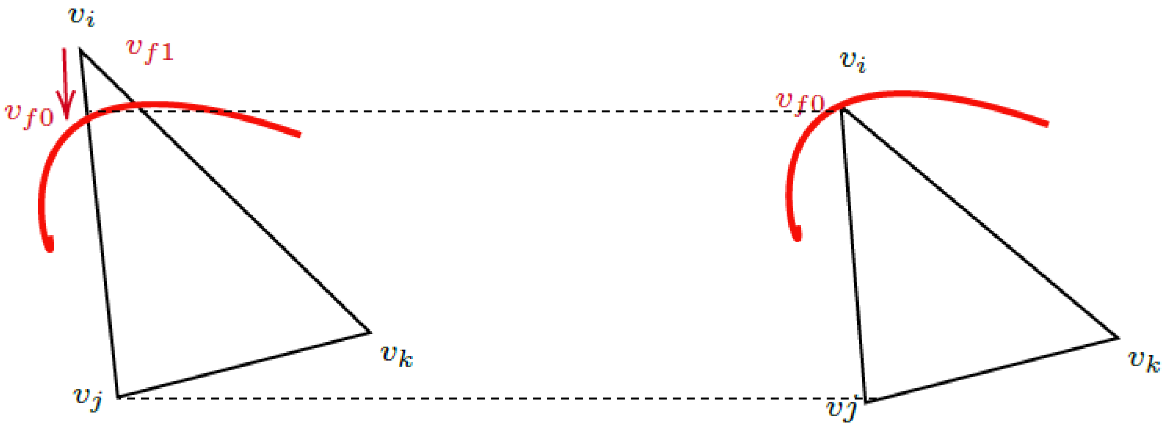


S. EL Aouad, Numerical and parallel modeling of anisotropic fitted mesh for industrial quenching applications, Thèse de doctorat Mathématiques numériques, Calcul intensif et Données Université Paris sciences et lettres 2022

How to remove mixing laws

- How to obtain fitted meshes





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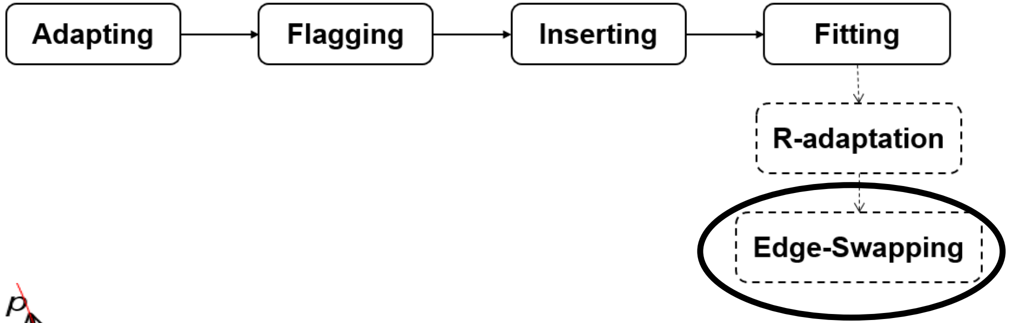
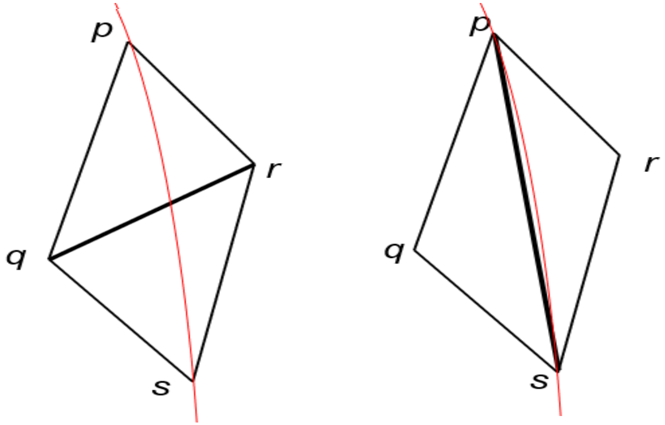
How to remove mixing laws

- How to obtain fitted meshes


Adapting → **Flagging** → **Inserting** → **Fitting**

R-adaptation

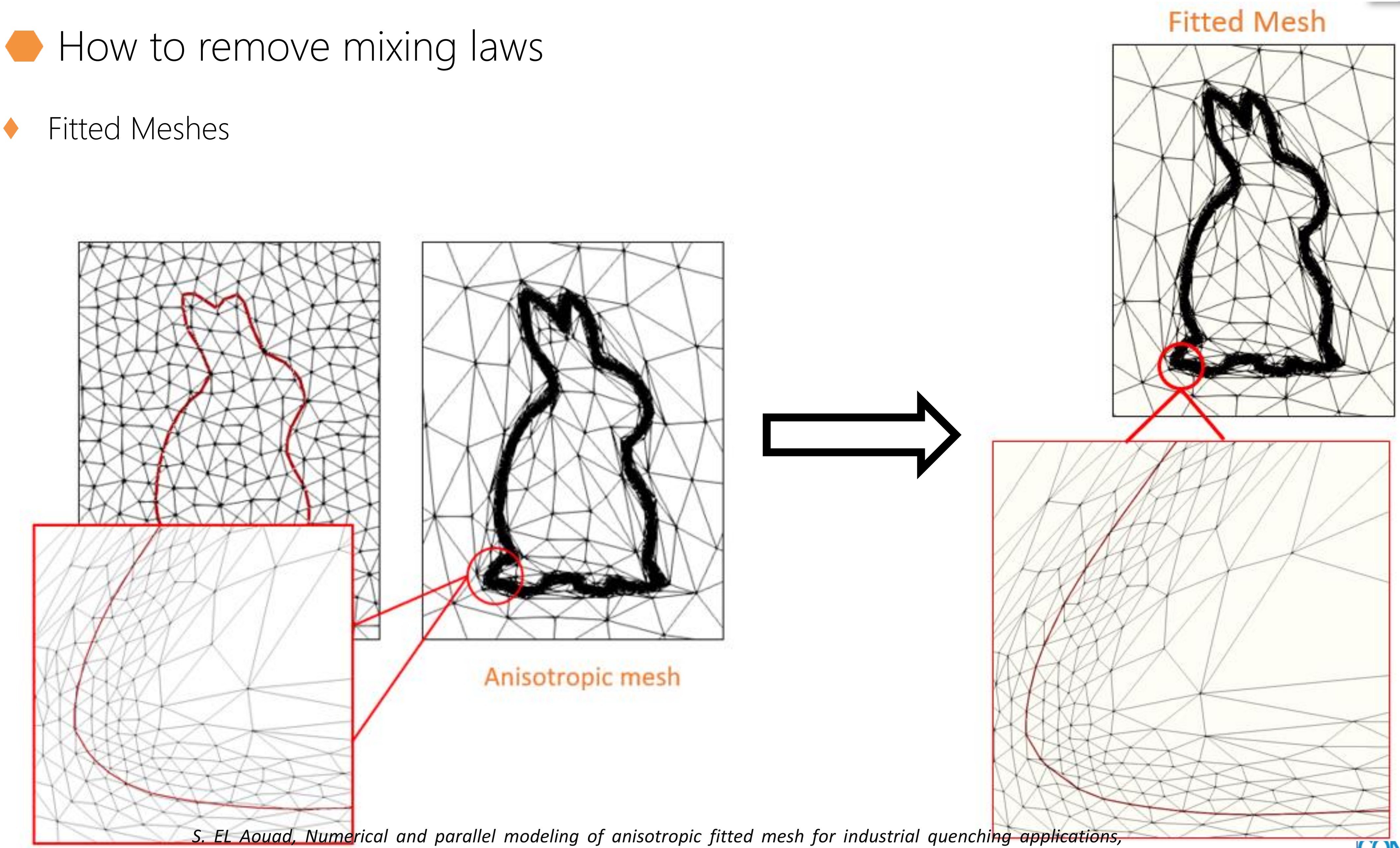
Edge-Swapping



El Aouad, S., Larcher, A., & Hachem, E. (2022). Anisotropic adaptive body-fitted meshes for CFD. Computer Methods in Applied Mechanics and Engineering, 400, 115562

How to remove mixing laws

- Fitted Meshes

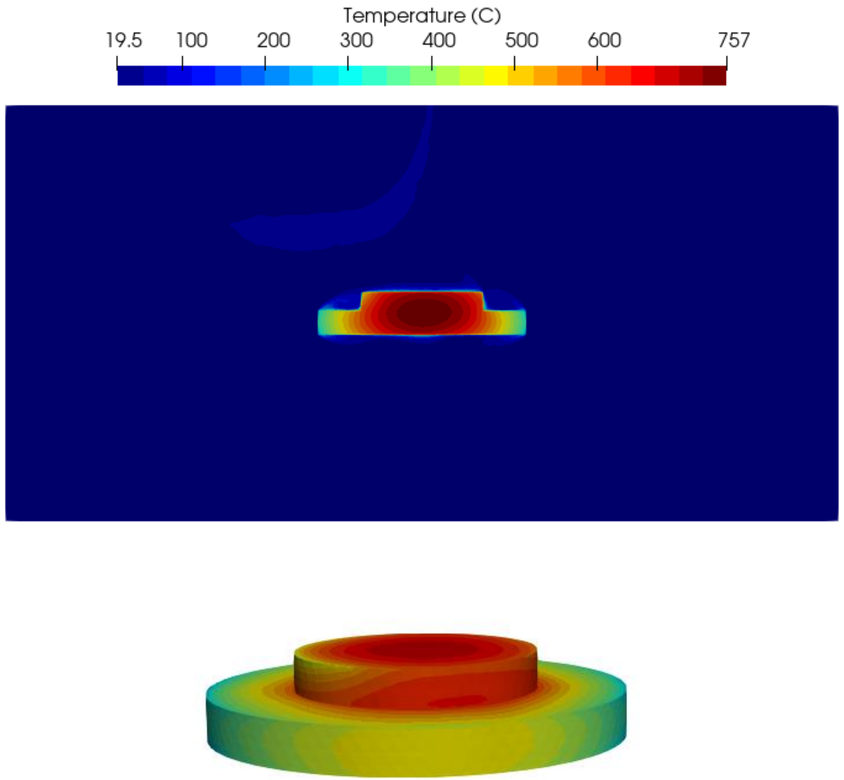


S. EL Aouad, Numerical and parallel modeling of anisotropic fitted mesh for industrial quenching applications, Thèse de doctorat Mathématiques numériques, Calcul intensif et Données Université Paris sciences et lettres 2022

qobeo-AIR® : software principles

- Thermal Computation
- With or without Radiation
  by activating **S2S model**
  - S2S model take into account "obstruction"
- **PID regulation** of the thermal resistance
- Thermal solver applied on the **whole domain**
  (gas + load(s))
  - **Contact** between different loads is also considered

Temperature evolution



qobeo-AIR® : software principles

- S2S radiation model : Surface to Surface
  - Radiosity equation

$$J_i = \varepsilon_i \sigma \, T_i^4 + (1-\varepsilon_i) \sum_j F_{ji} J_j$$

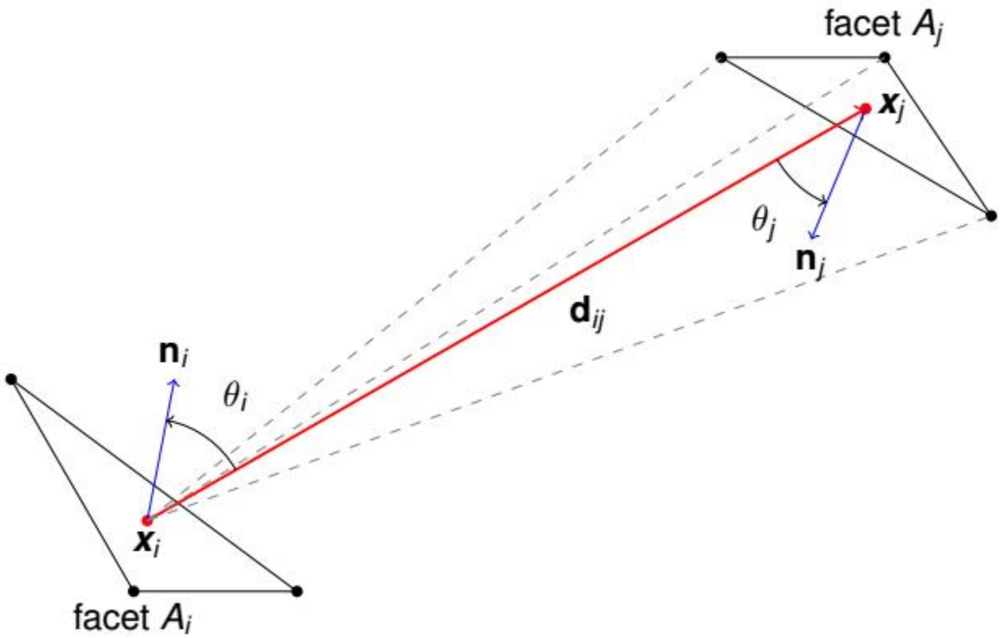
emitted ↓   ↓ reflected

  - The view factors

$$F_{ij} = |A_j| \frac{cos(\vartheta_i)\, cos(\vartheta_j)}{\pi |d_{ij}|^2}$$

  - Radiative flux

$$Q_i = |A_i| \frac{\varepsilon_i}{1-\varepsilon_i} (\sigma T_i^4 - J_i)$$

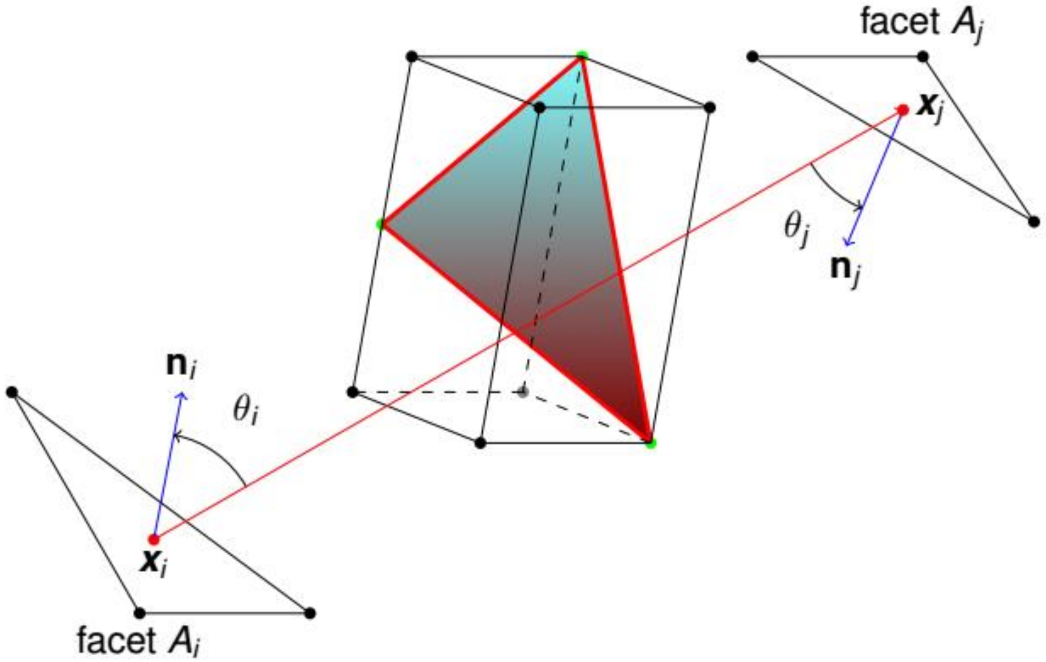


R. Gerard, Fast, flexible Surface to Surface thermal radiative transfer for sintering applications, Thèse de doctorat Mathématiques numériques, Calcul intensif et Données Université Paris sciences et lettres 2022

qobeo-AIR® : software principles

S2S radiation model : Surface to Surface

- Compute the a priori visibility of pairs of facets (A_i, A_j) by half-plane criterion
- Compute the obstruction for pairs of facets (A_i, A_j) of the reduced subset



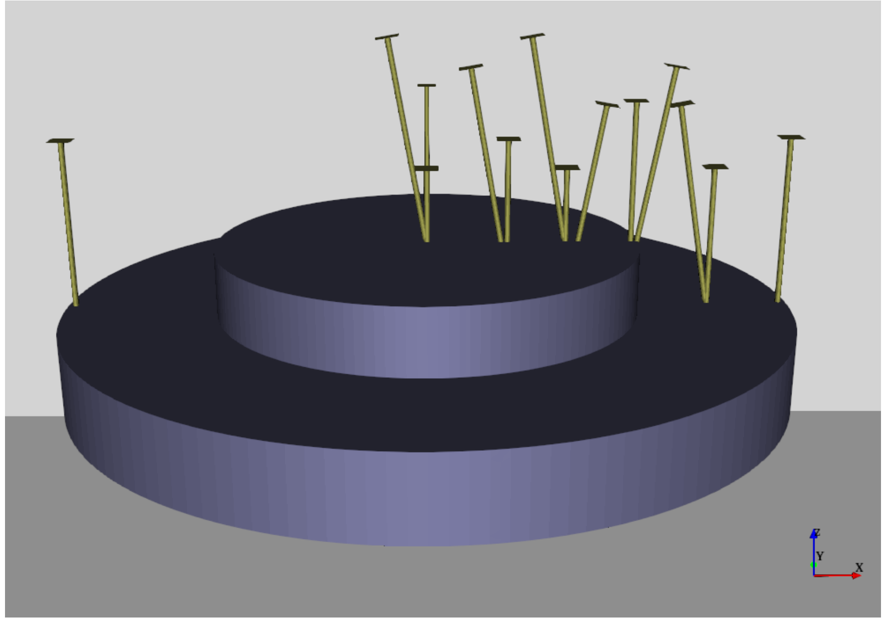
- Complexity issues : segment-tree for ray-box collisions.

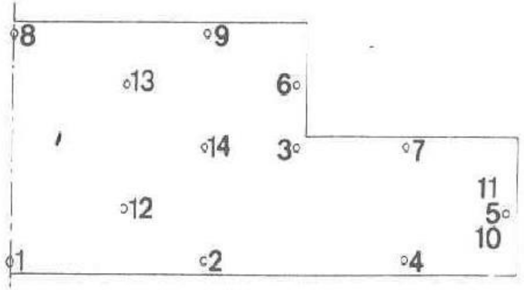
qobeo-AIR® : software principles

- S2S radiation model : Experimental validation test case
  - Provided by Safran

Resources	Type	Parameters	Position
Load	Disque Chapeau	R_{small}=0.145m, H_{small}=0.05m, R_{large}=0.25m, H_{large}=0.055m,	(0,0,0)

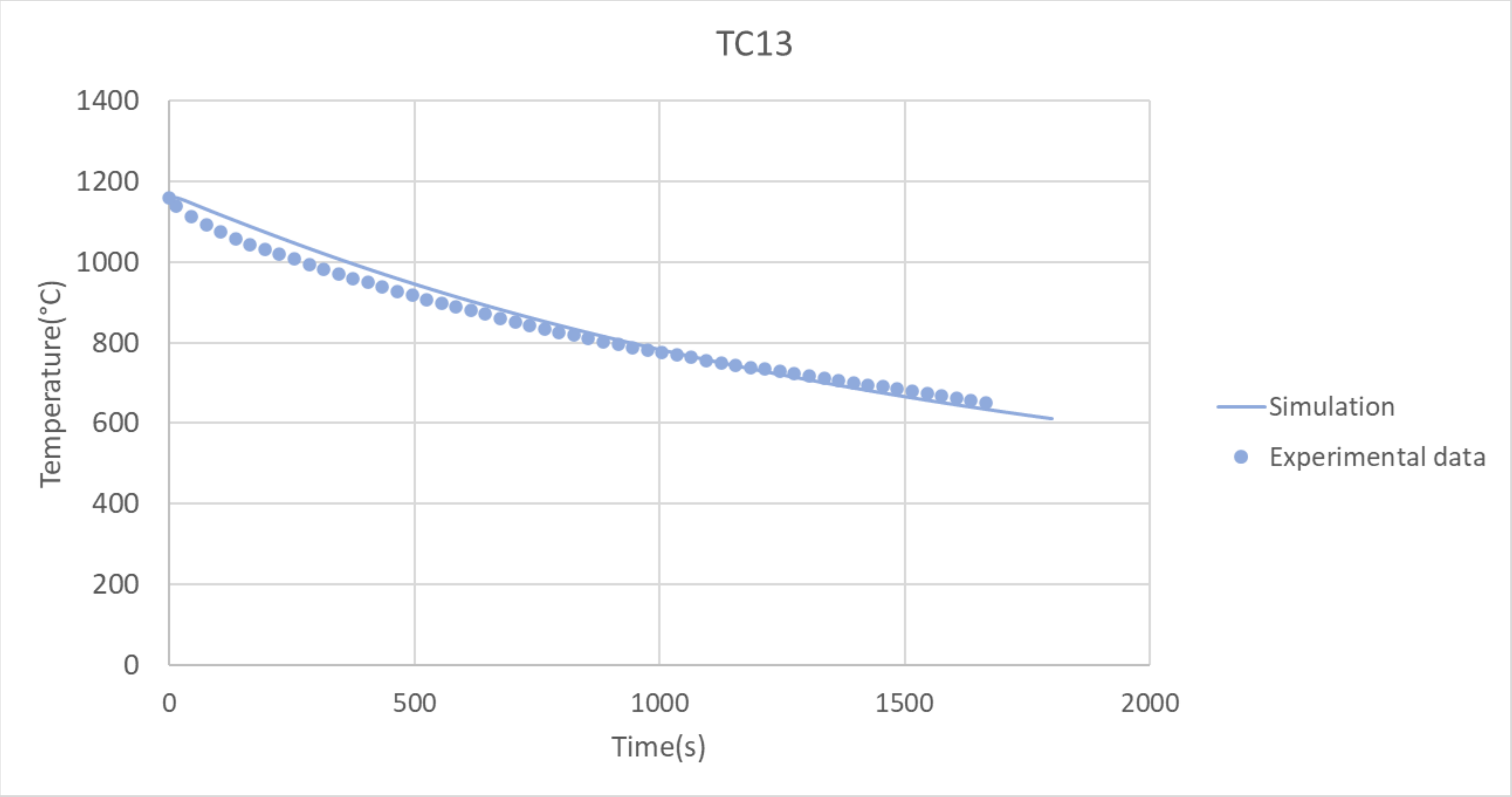
	Load
Material	Inco718
Temperature	1160°C
Emissivity	0,717

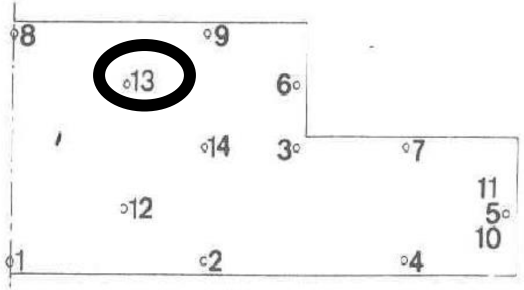




qobeo-AIR® : software principles

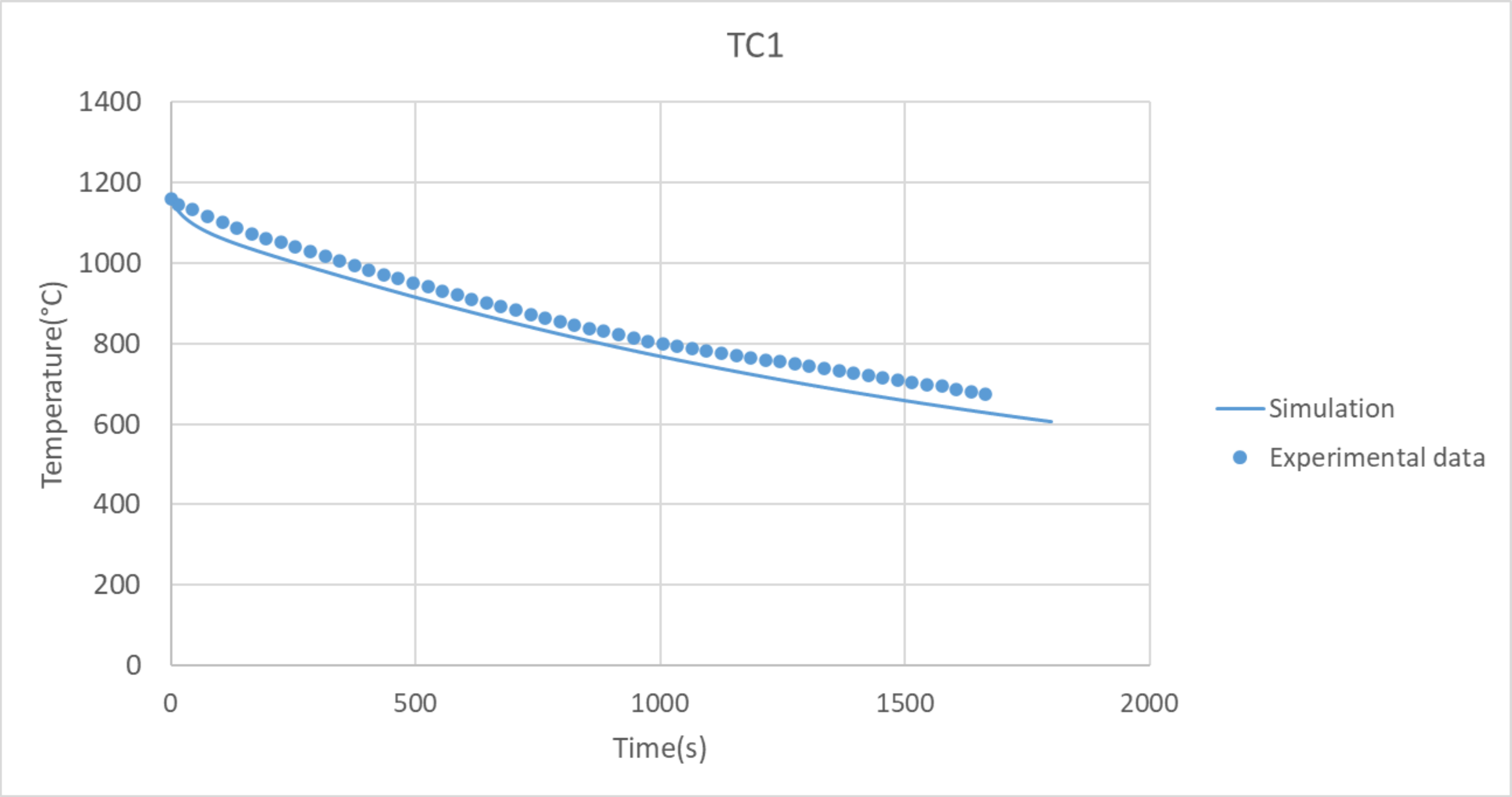
- S2S radiation model : Experimental validation test case

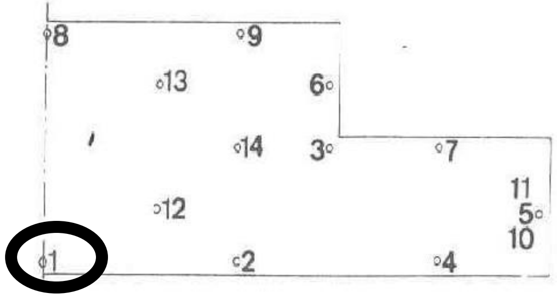




qobeo-AIR® : software principles

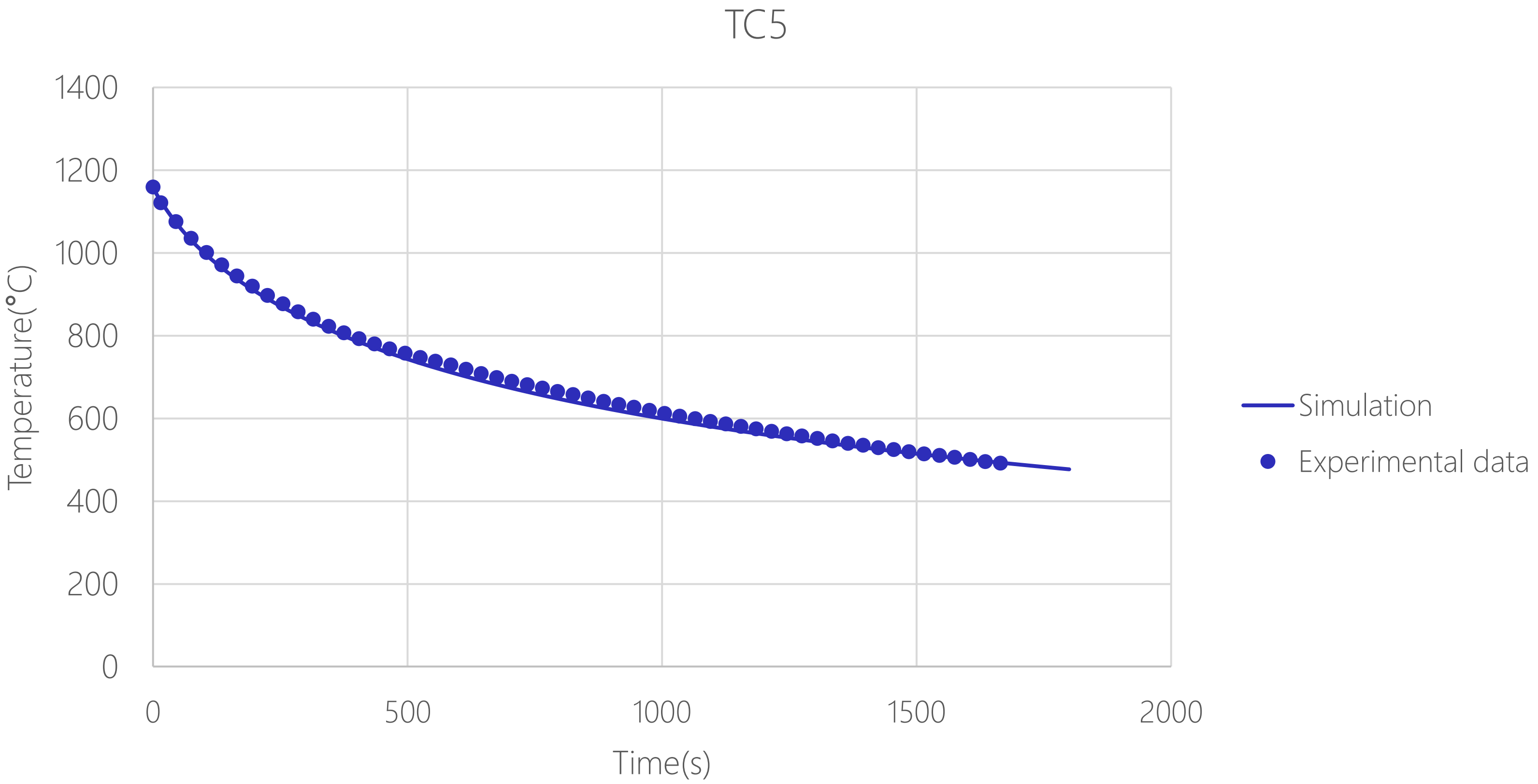
- S2S radiation model : Experimental validation test case
  - The "support" is neglected in the simulation.

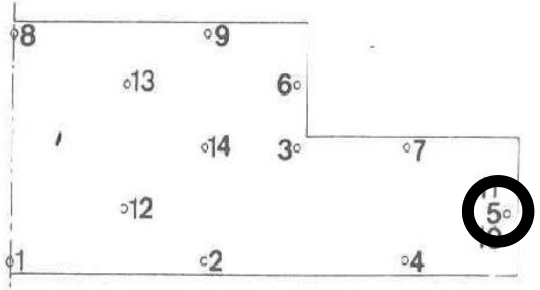




qobeo-AIR® : software principles

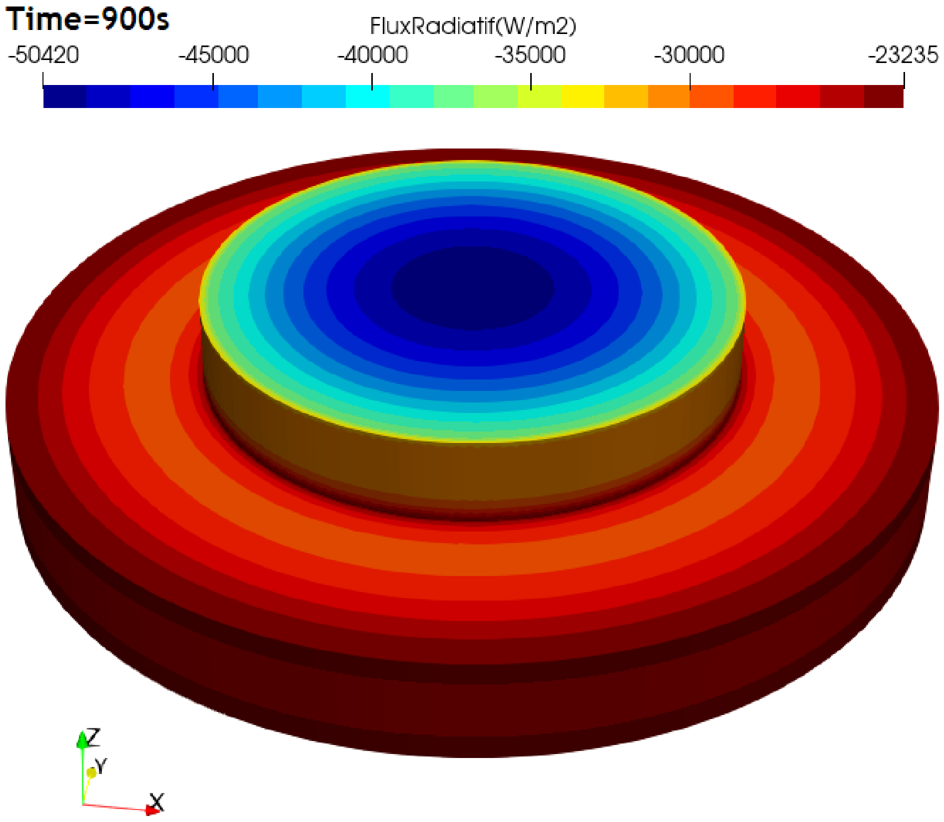
S2S radiation model : Experimental validation test case

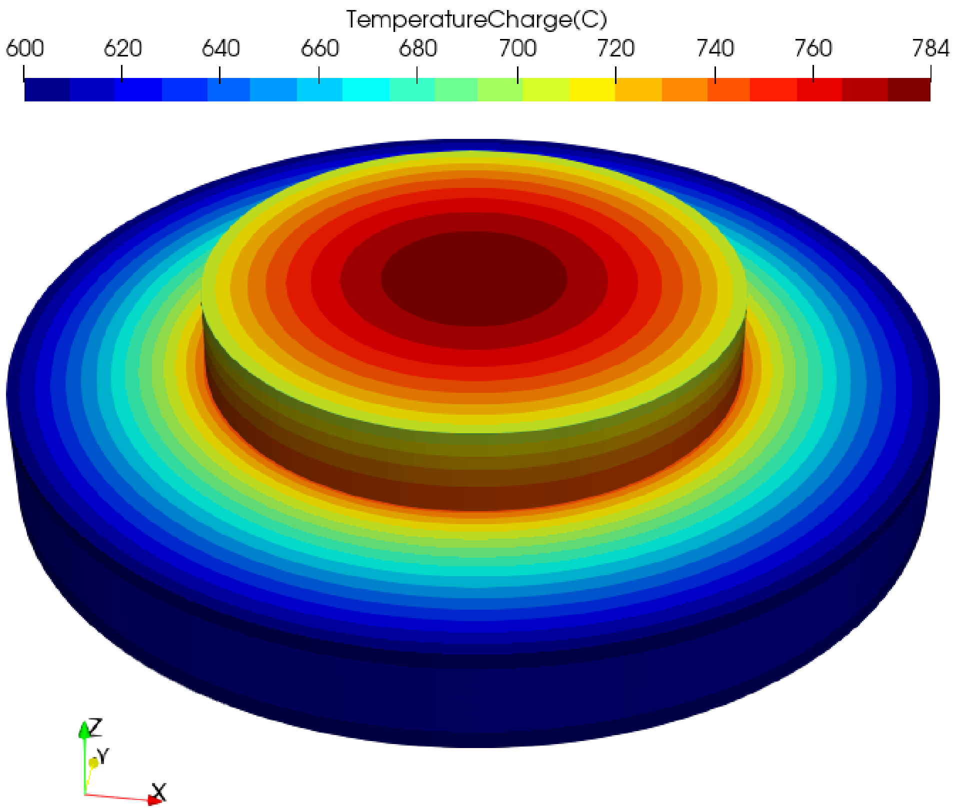




qobeo-AIR® : software principles

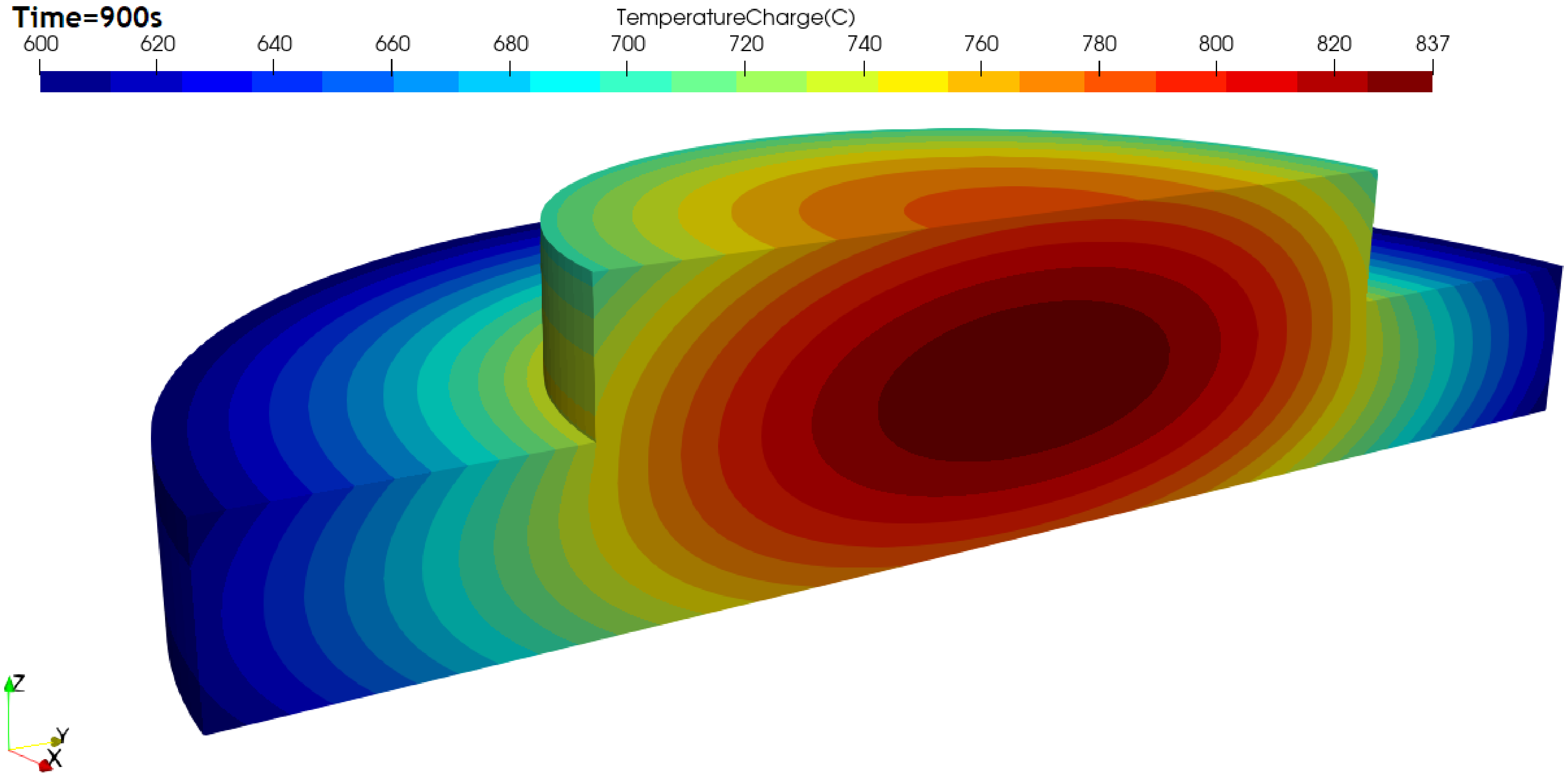
- S2S radiation model : Experimental validation test case



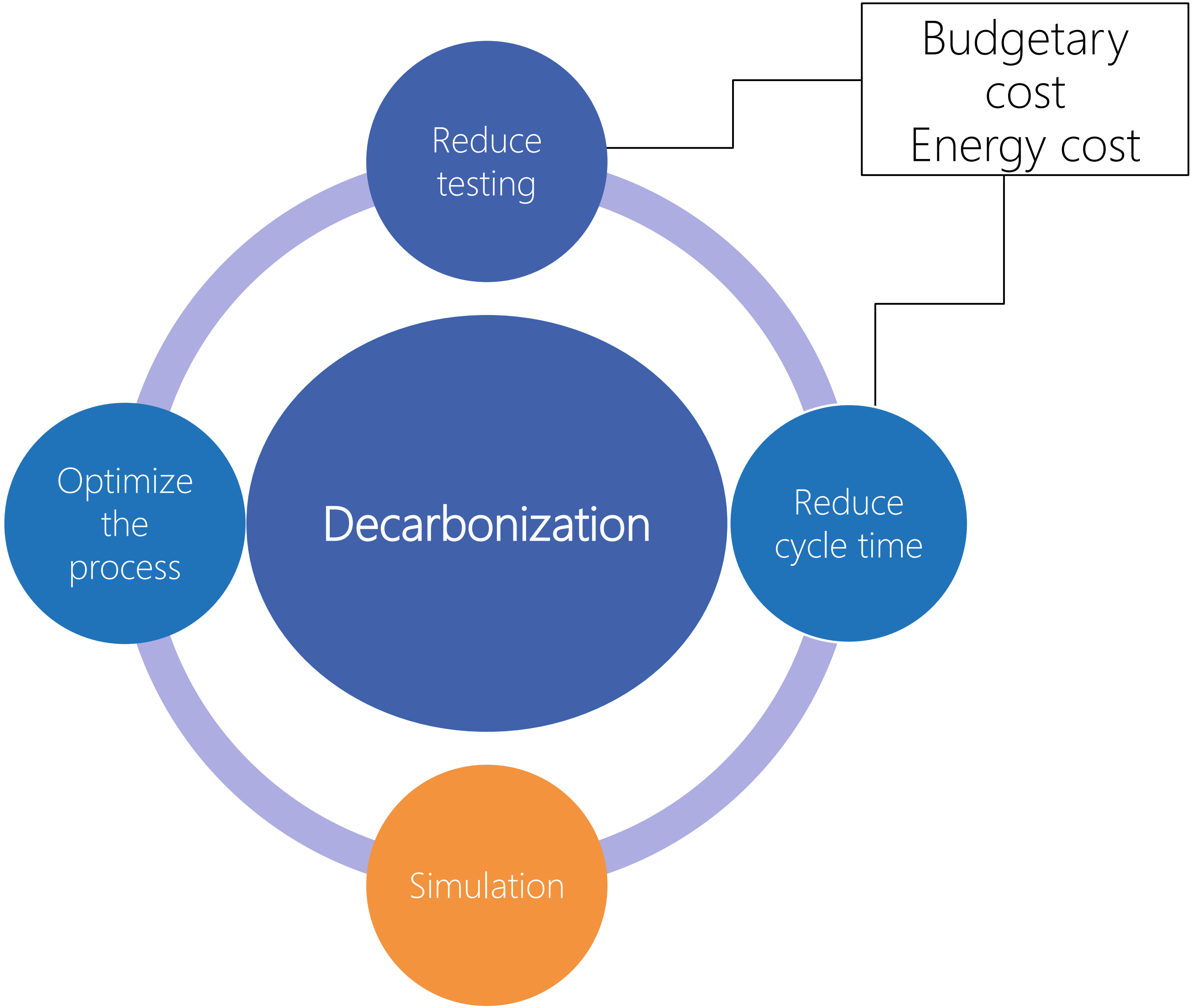


qobeo-AIR® : software principles

- S2S radiation model : Experimental validation test case



Context & objectives



Budgetary cost
Energy cost

Reduce testing

Optimize the process

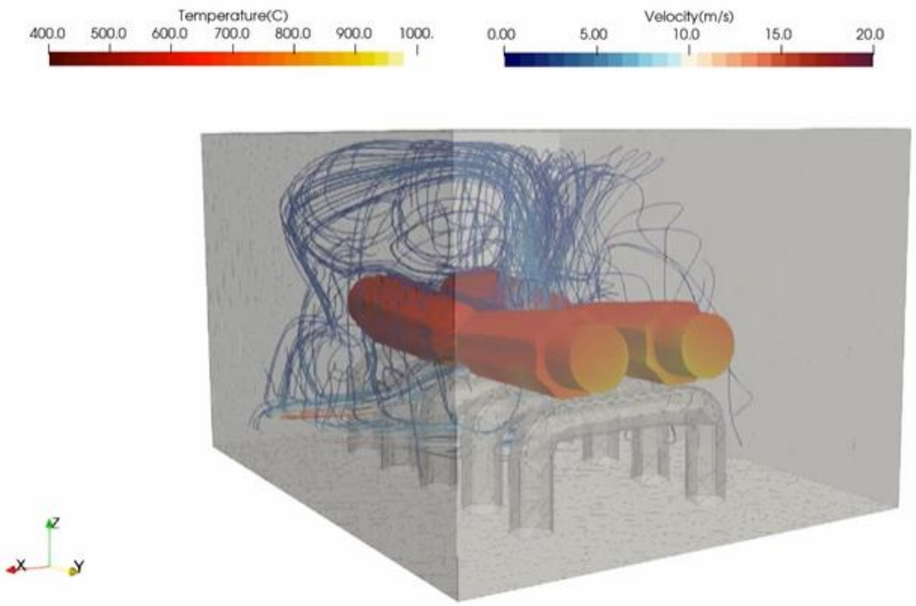
Decarbonization

Reduce cycle time

Simulation

Analysis of a furnace with ingot loading

- How to anticipate heating times?
- How to consider the impact of different process scenarios on the heating of the pieces?



Our approach

1

- Reference Simulation: a gas furnace (qobeo-AIR®)
  - Loading of 4 ingots

2

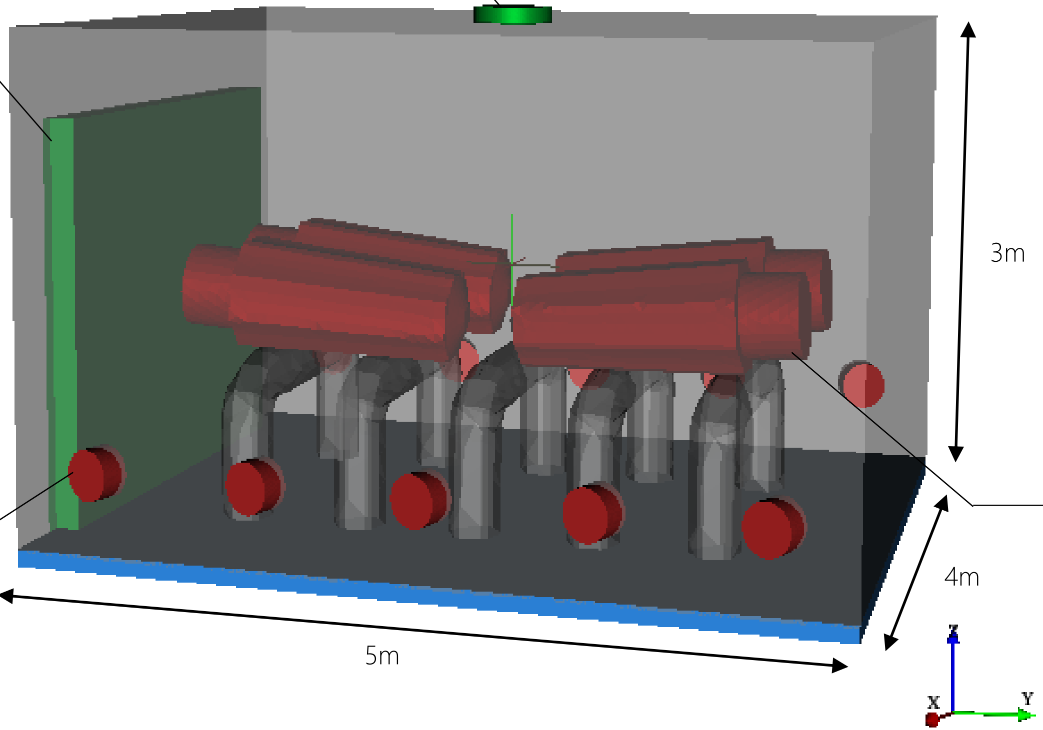
- Simulation & results
  - Heating 4 ingots
  - Replacement of the 1st heated ingot with a cold one

3

- Decarbonization: transitioning from gas to electric furnace
  - The main results

Case Implementation

- Gas furnace (4m x 5m x 3m) with air flow heating.



Exhaust hood

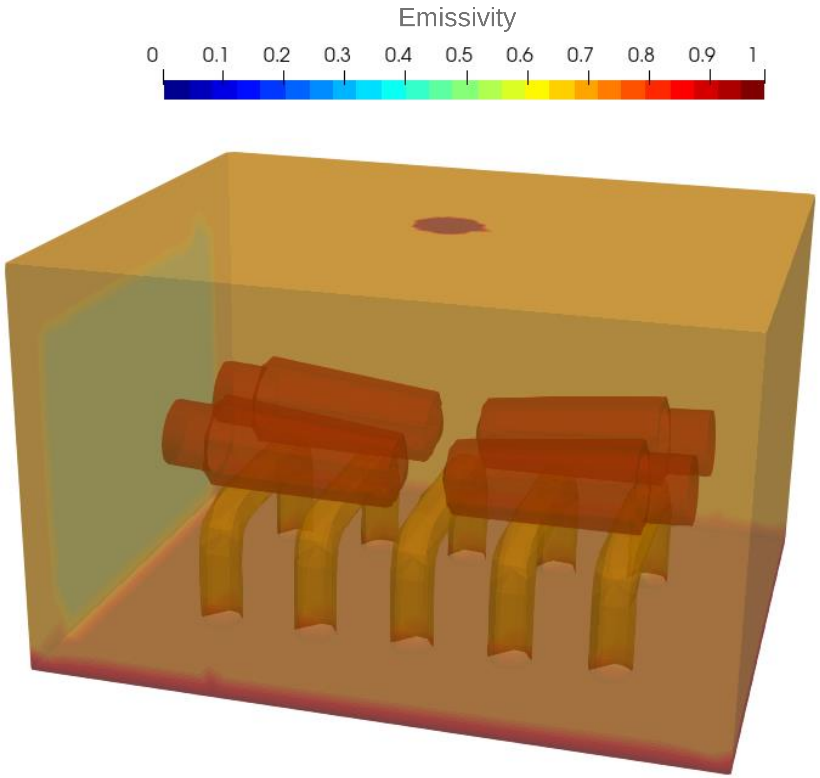
Furnace door
(3m x 0,2m x 5m)

4 ingots weighing 3.3 tons each, with $T_{initial} = 400°C$

10 burners blowing at $1280°C$ with $17m/s$ velocity. The burners reach their maximum flow rate after 1 minute from their start-up.

Case Implementation

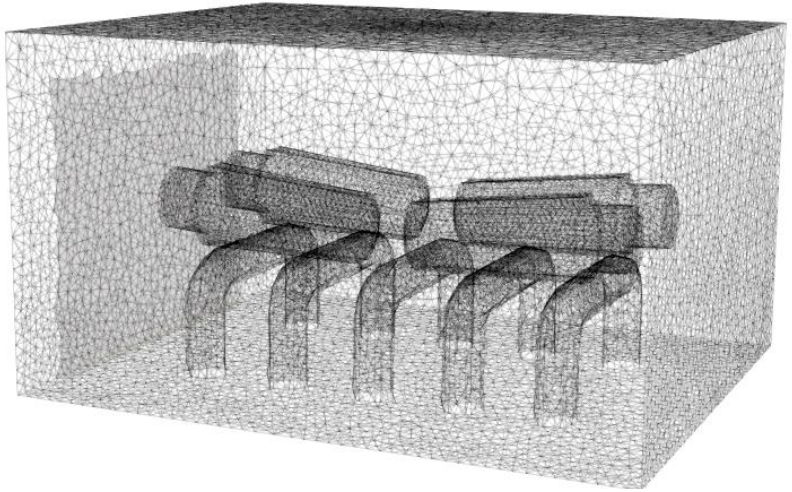
- Fourier boundary conditions are applied on:
  - Furnace walls: $h = 5\frac{W}{m^2.K}$; $T_{outside} = 50^{\circ}$; $\epsilon_{walls} = 0{,}7$.
  - Closed door: $h = 5\frac{W}{m^2.K}$; $T_{outside} = 50^{\circ}$; $\epsilon_{door} = 0{,}4$.
- After 4,4 hours, the 1st ingot is replaced with a "cold" one at $\mathbf{400°C}$.



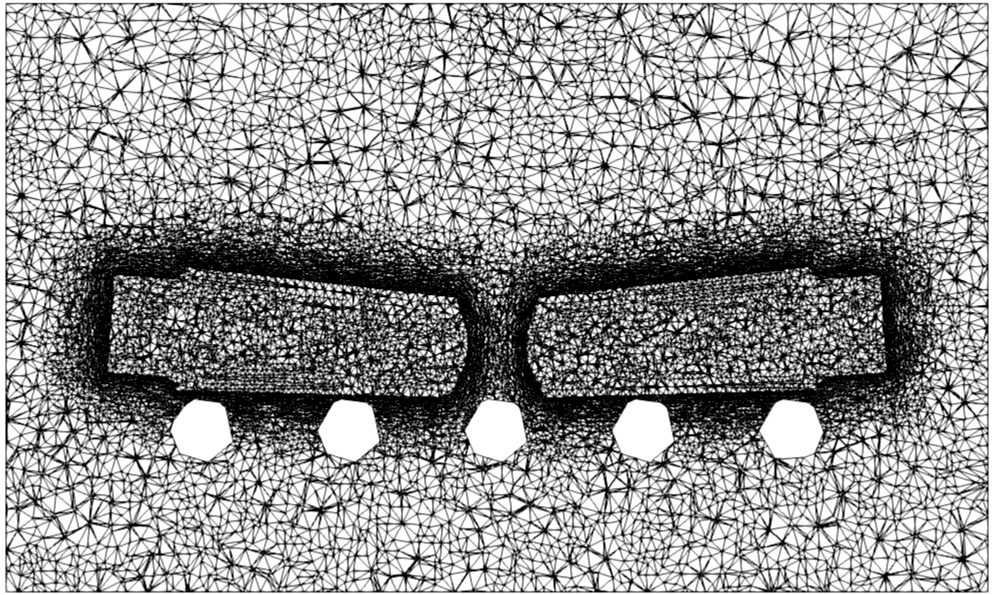
Visualization of different fields & thermal properties

Case Implementation

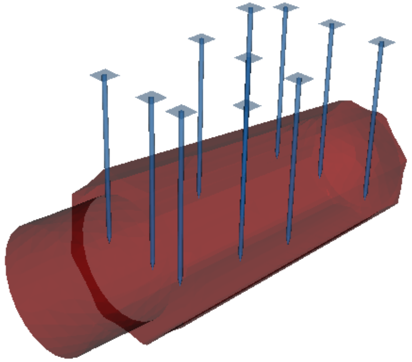
- Automatic generation of surface and volume mesh for enclosures and loads.



- Option to create a refined anisotropic mesh around the interfaces of the loads.



Simulation

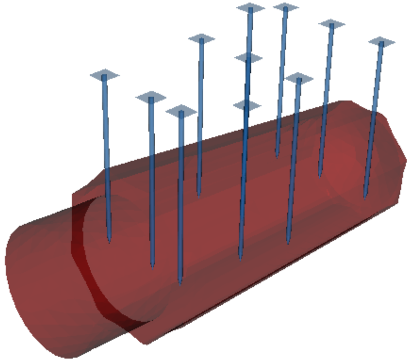


- Numerical sensors are added in each ingot.

- For each step, we solve:
  - For the first $30\ s$, with $\Delta t = 0{,}08\ s$:
    - Natural convection
    - Forced convection
    - Thermal calculation

- Computational cost (~1 month).

Simulation



- Numerical sensors are added in each ingot.

- Stabilized CFD
  - After the first seconds, we computed an averaged velocity on 25s of physical time: $\boldsymbol{V_m} = \frac{\boldsymbol{1}}{\boldsymbol{nb\_incr}} \sum_{\boldsymbol{i=1}}^{\boldsymbol{nb\_incr}} \boldsymbol{v_i}$ and we imposed this velocity field as constant for the remaining time.
  - For each step, we solve:
    - For the first $30\ s$, with $\Delta t = 0{,}08\ s$:
      - Natural convection
      - Forced convection
      - Thermal calculation
    - For the remaining calculation, thermal analysis is performed using the average velocity with $\Delta t = 0{,}25\ s$, which helps reduce drastically the computational cost (~1 day vs 1 month).

Results – Heating 4 ingots

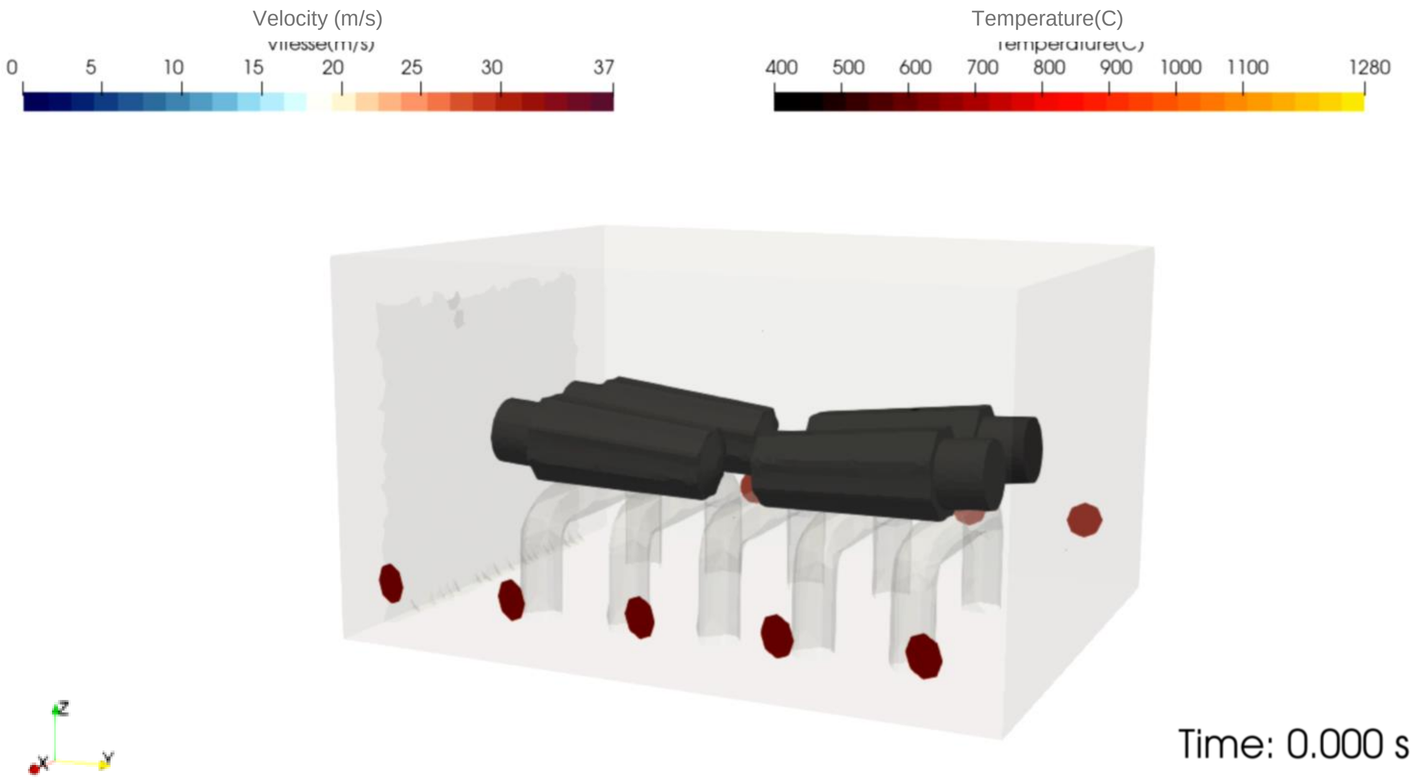
- Computational cost
  - Full simulation

	Time step	Number of cores	Calculation duration
From 0 to 4,4 hours:	0,08 s	32 cores (@3,6 GHz, 2022)	~ 1 month

  - Simulation with stabilized CFD

	Time step	Number of cores	Calculation duration
From 0 to 30 s:	0,08 s	32 cores (@3,6 GHz, 2022)	~ 8 hours
From 30 s to 4,4hours:	0,25 s	32 cores (@3,6 GHz, 2022)	~ 20 hours

Results – Heating 4 ingots

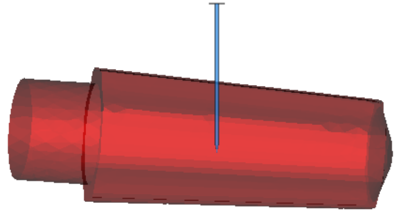


Obtained velocity & temperature fields.

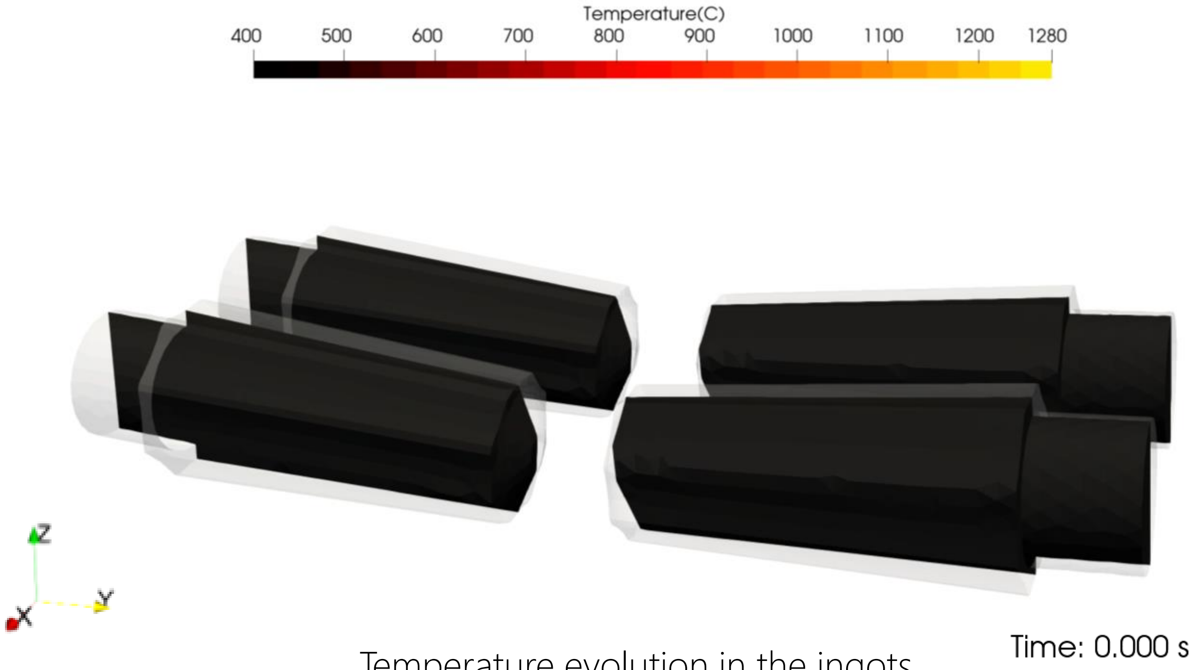
- Resolution of natural convection, forced convection, and radiation.
- The burners reach their maximal flow rate after 5 seconds.
- Stable velocity field is achieved after 30 seconds.

Results – Heating 4 ingots

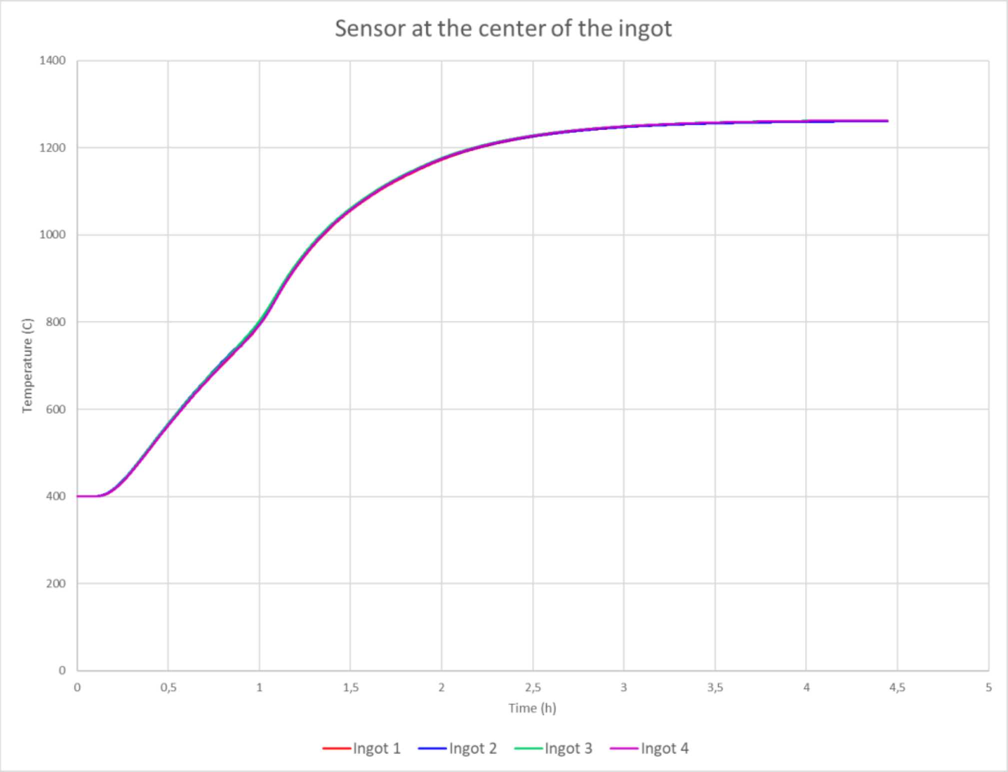
- Temperature evolution



Position of the numerical sensor at the center of each ingot



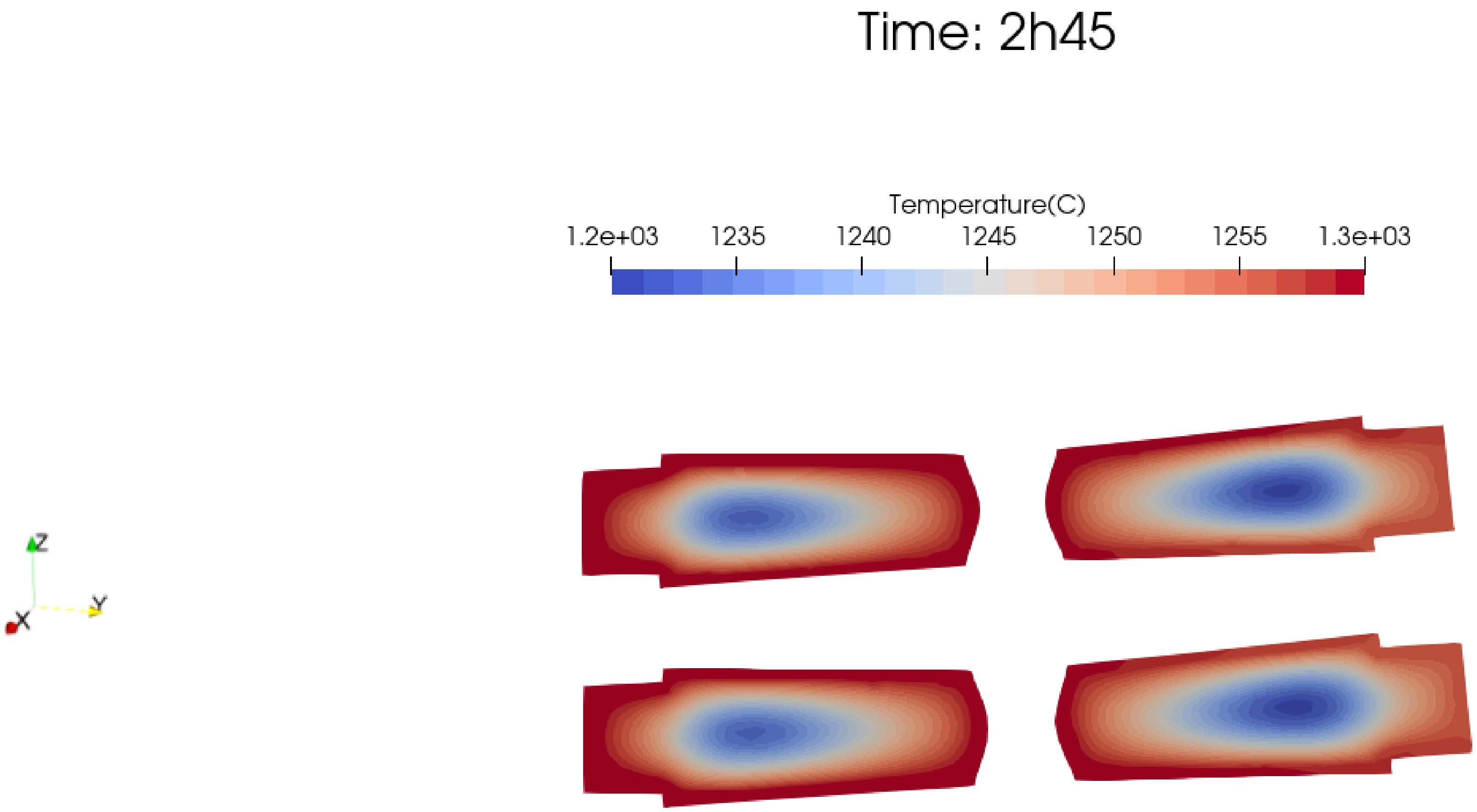
Temperature evolution in the ingots



Optimization of cycle time: Homogeneous temperature achieved in 3.5 hours instead of 4.4 hours.

Results – Heating 4 ingots

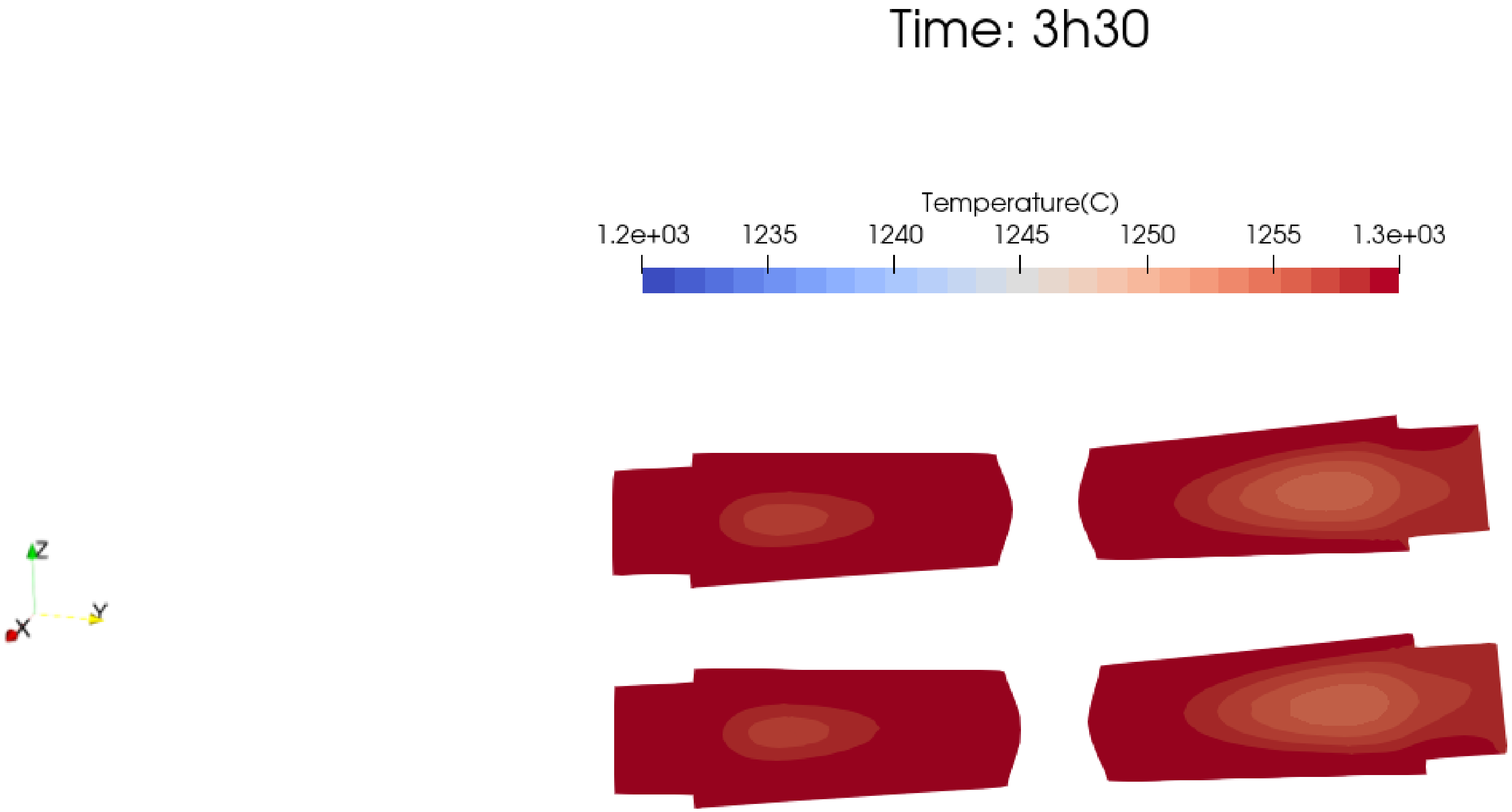
- Temperature evolution



~30 °C between minimum and maximum

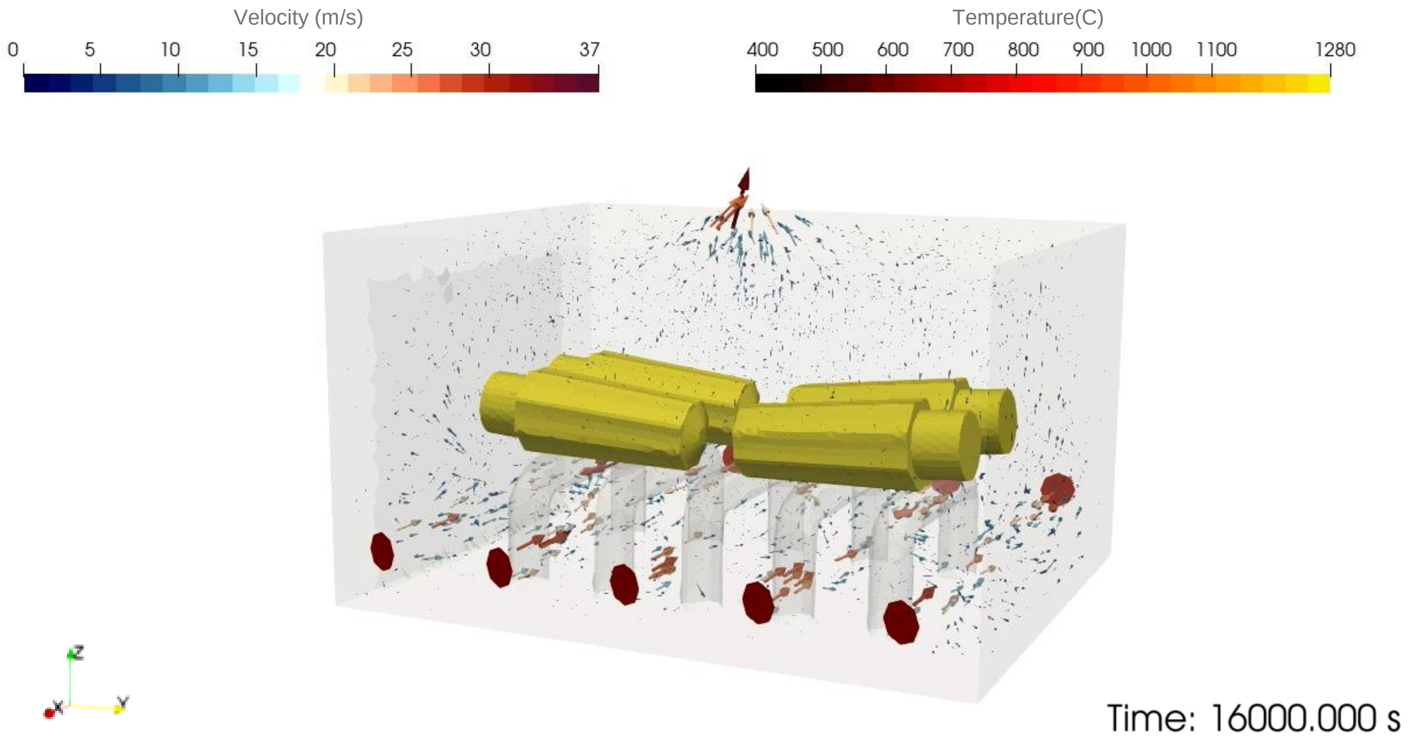
Results – Heating 4 ingots

- Temperature evolution



~5 °C between minimum and maximum

Results – Replacement of the 1st ingot

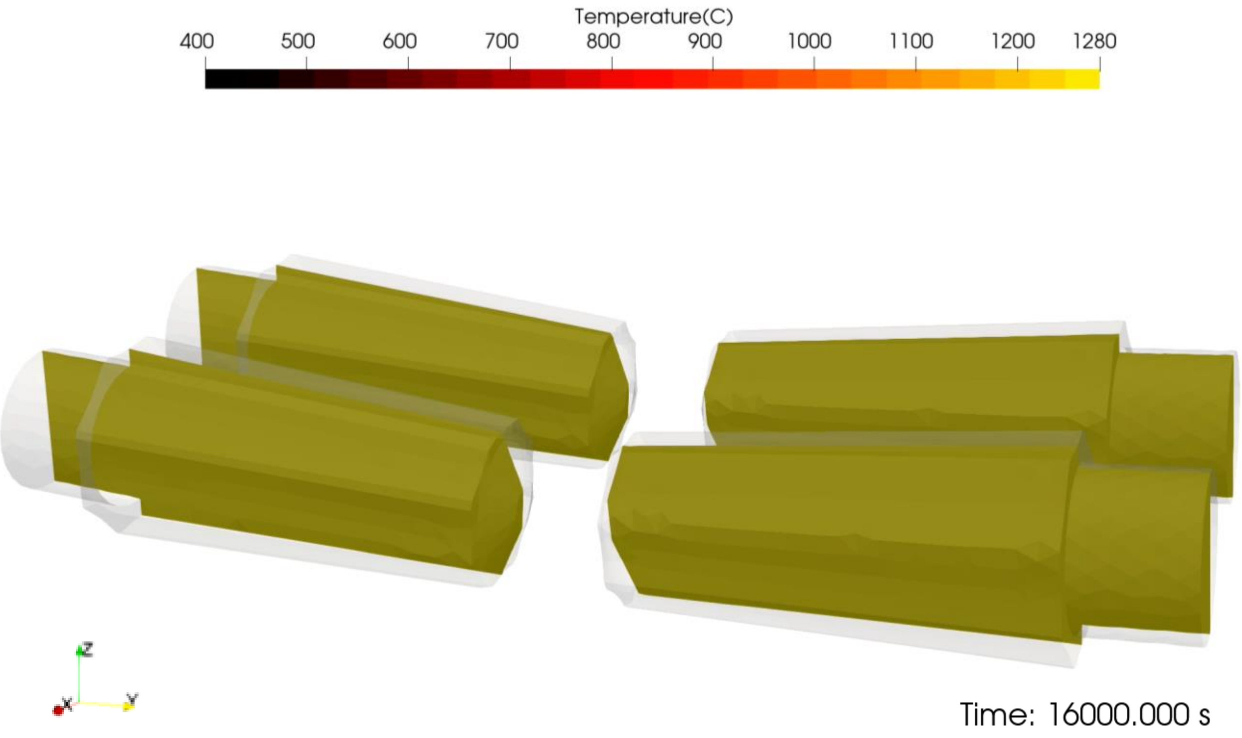


Obtained velocity & temperature fields.

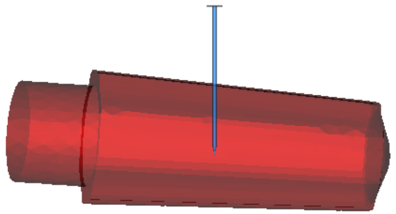
- A heated ingot is replaced by another one at 400°C.
- Resolution of natural convection, forced convection, and radiation.
- The average velocity field is calculated for 100 increments after 10 seconds after the replacement.
- Resolution of the thermal solver for the remainder of the simulation.

Results – Replacement of the 1st ingot

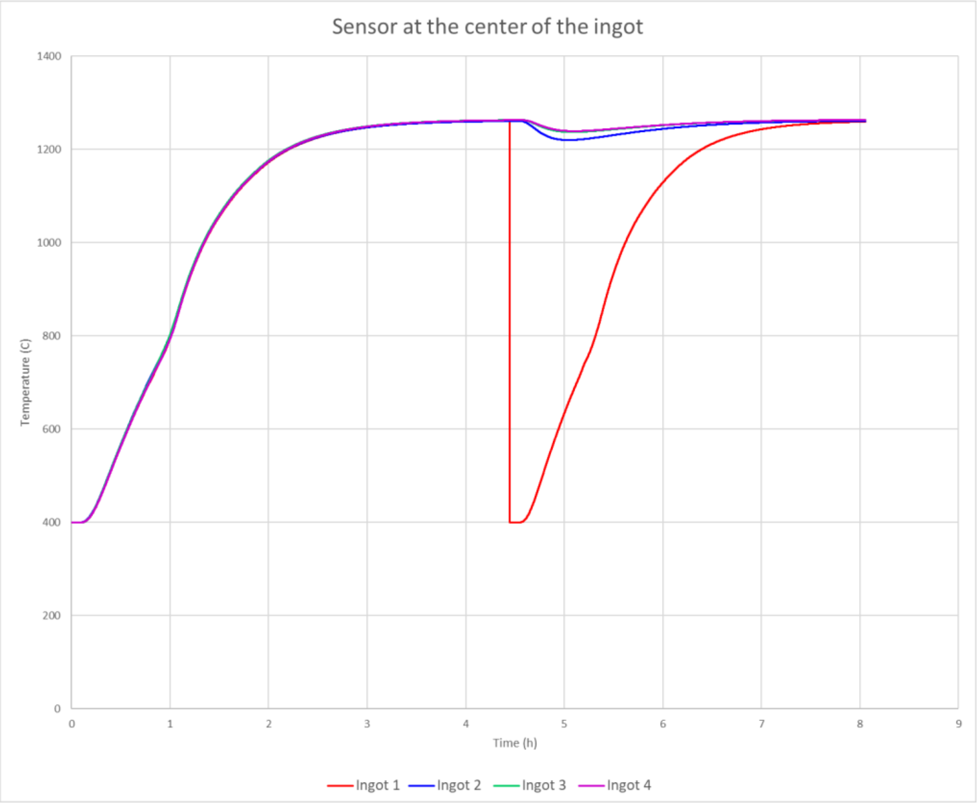
Temperature Evolution



Temperature evolution in the ingots

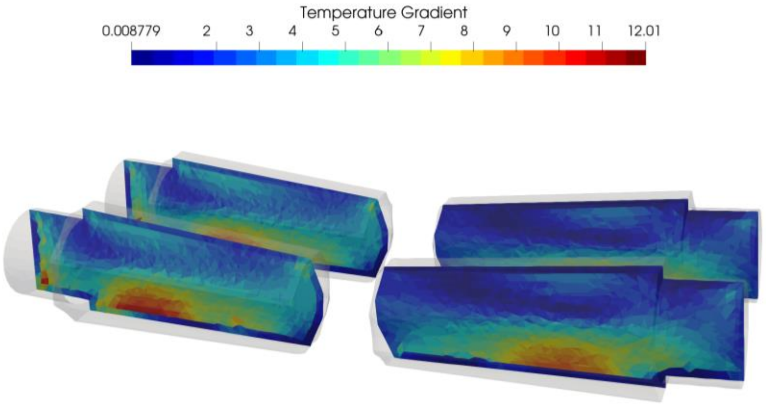


Position of the numerical sensor at the center of each ingot

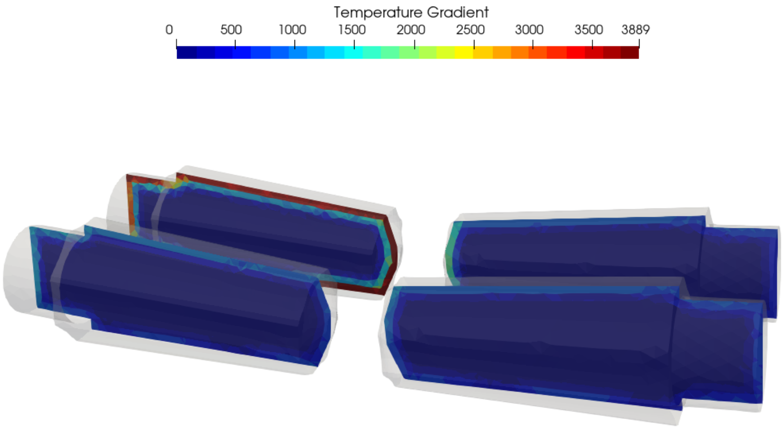


Results – Replacement of the 1st ingot

- The replacement effect on the adjacent ingots

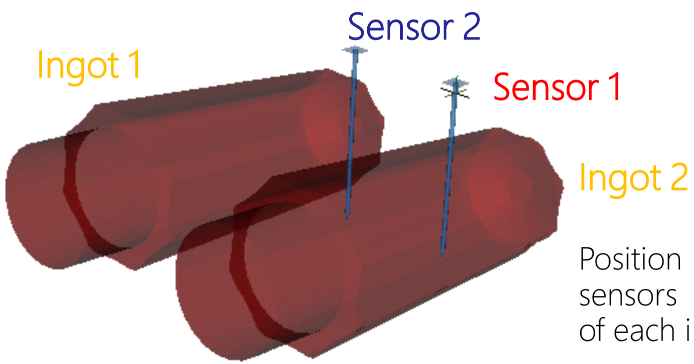


The temperature gradient in the ingots just before replacement at **4.4 hours**.

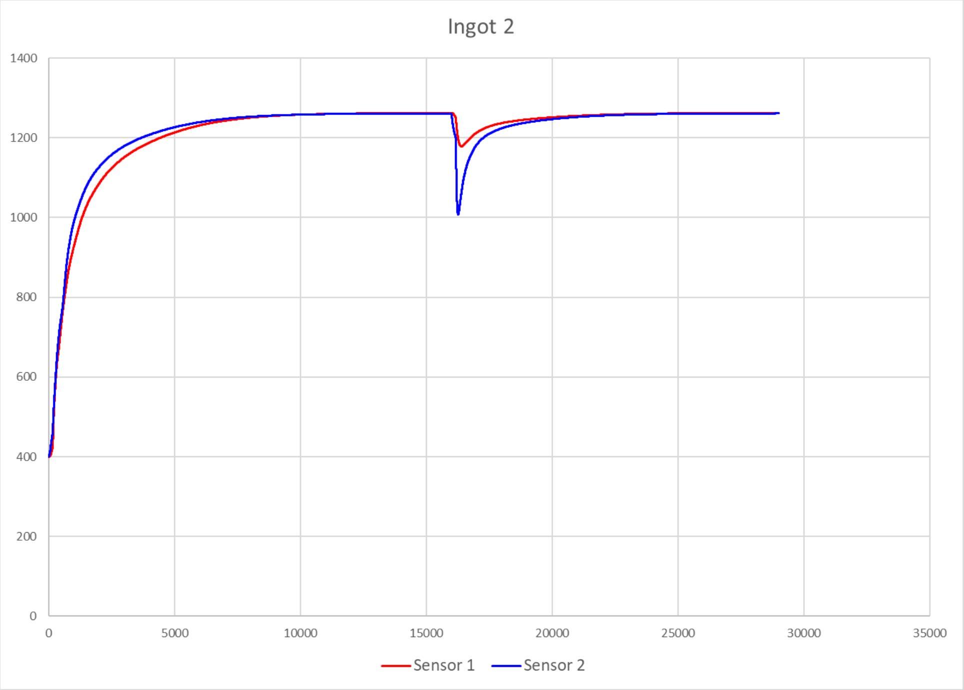


The temperature gradient* in the ingots after replacement at **4.5 hours**.

* Change of scale

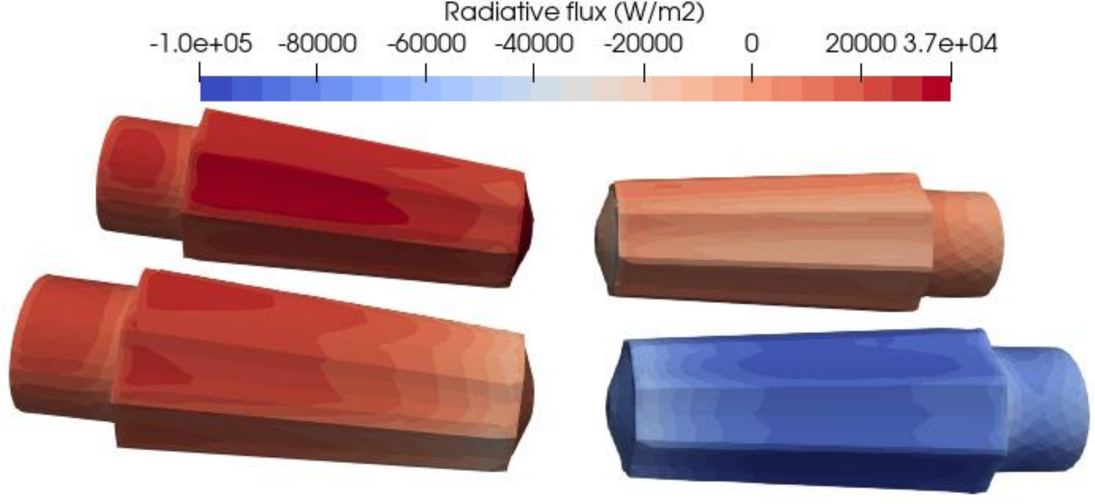


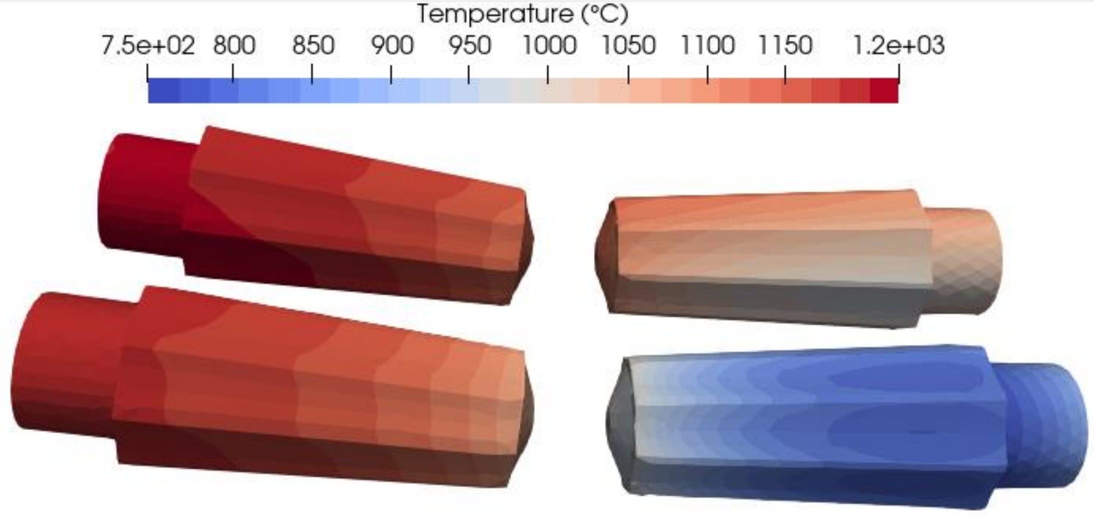
Position of the numerical sensors near the interface of each ingot



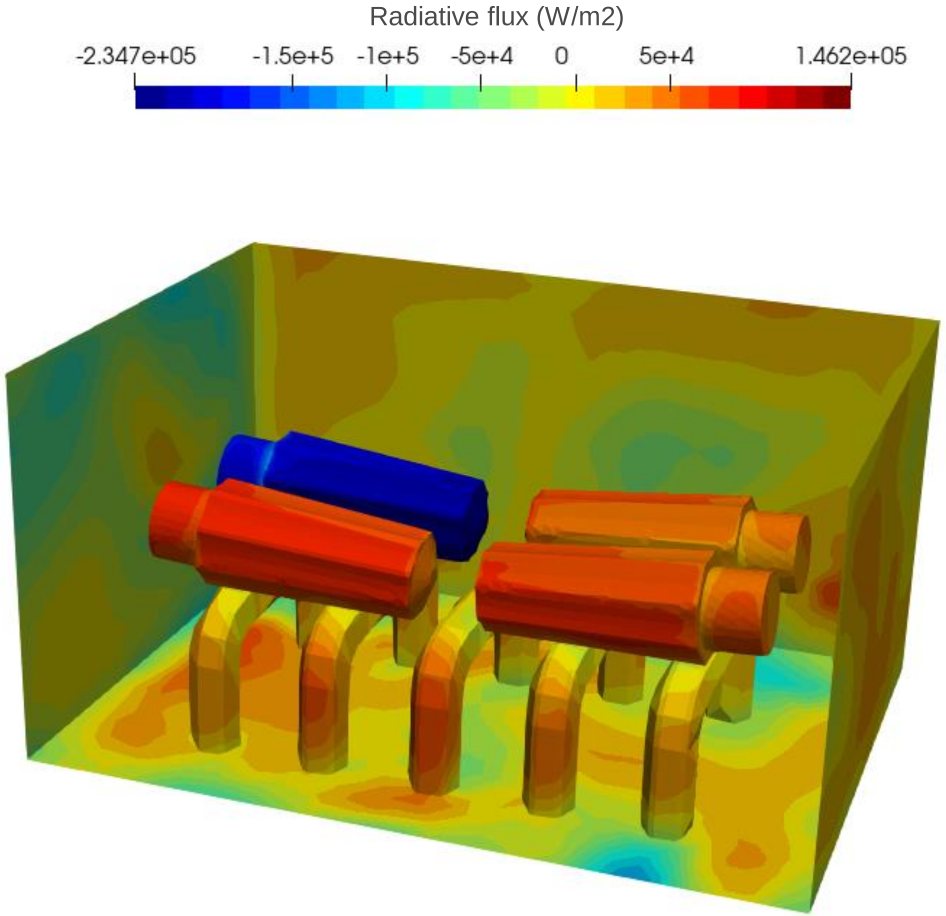
Results – Replacement of the 1st ingot

- The replacement effect on the adjacent ingots





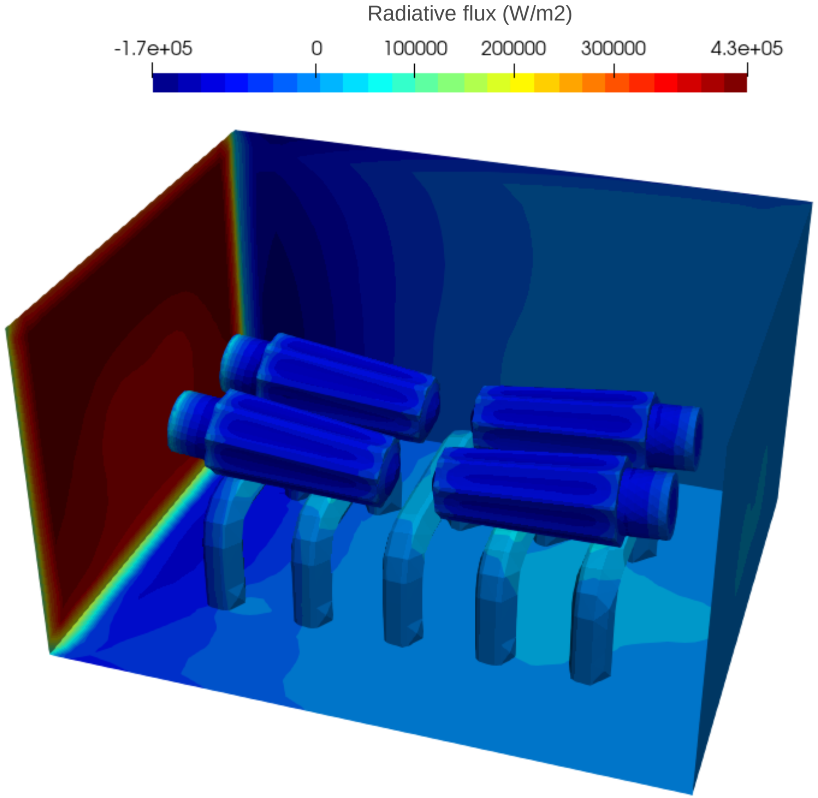
Results – Replacement of the 1st ingot



- Calculation of radiative flux and its evolution during the simulation.

Decarbonization: transitioning from gas to electric furnace

- With qobeo®, the simulation of ingots in an electric furnace can also be performed :

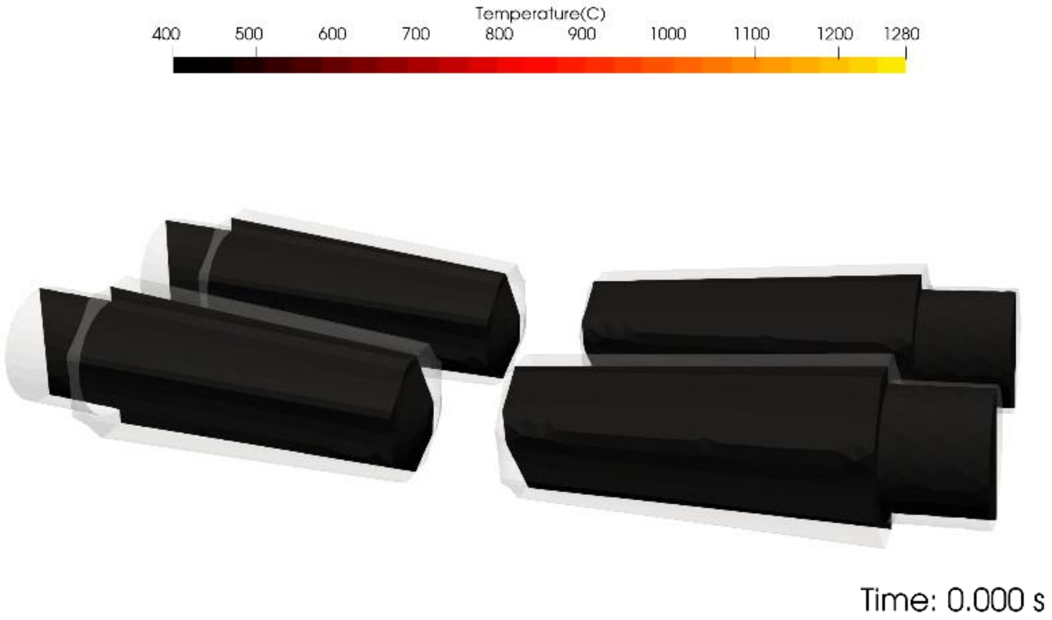


- Electric thermal resistances can be considered.
  - Furnace walls: $T_{walls} = 1200^{\circ}C$; $\epsilon_{walls} = 0{,}7$.
  - Fourier boundary conditions are applied on:
    - Closed door: $h = 5\frac{W}{m^2.K}$; $T_{outside} = 50^{\circ}$; $\epsilon_{door} = 0{,}4$.
- After 4,4 hours, the 1st ingot is replaced with a “cold” one at $400°C$.
- The radiative flux and its evolution can be calculated during the simulation.

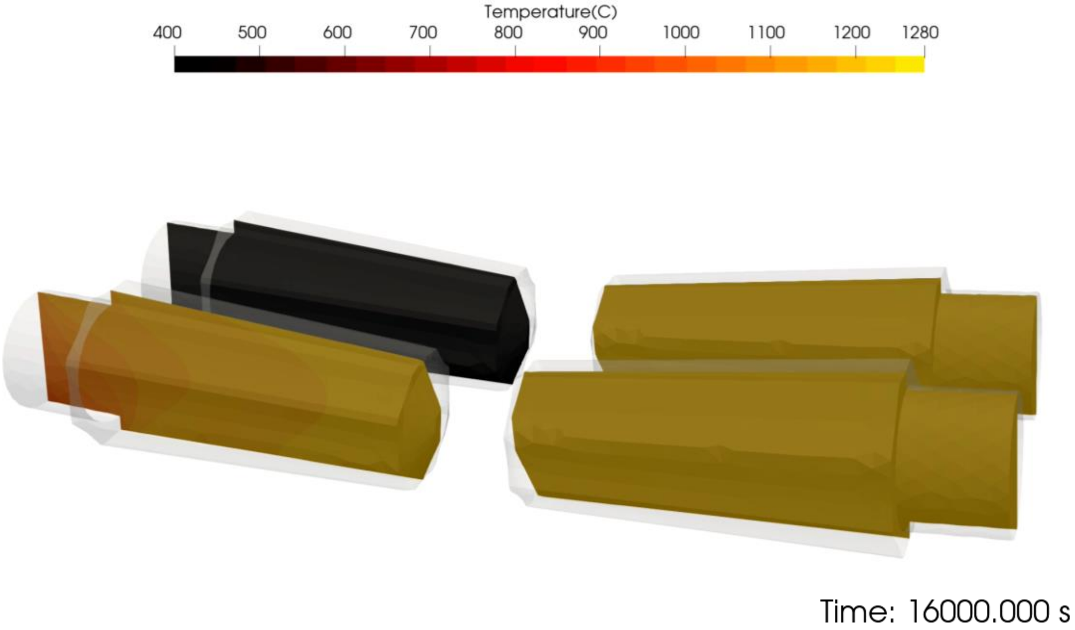
Decarbonization: transitioning from gas to electric furnace

Temperature Evolution

From 0 to 4,4 hours



From 4,4 hours to 8 hours



Fast Computation

Physical time	Number of cores	Calculation duration
8 hours	32 cores (@3,7 GHz)	~ 30 hours

Conclusion

- Simulate complex installations ✓
- Consider the physics’ complexity ✓
- Achieve optimal heating cycles ✓
- Reliable and fast numerical analysis ✓
- With qobeo®, the transition to decarbonization can be done in a smoother manner.

“It's always worth exploring numerical simulation to support your process optimization. ”

SCIENCES COMPUTERS CONSULTANTS

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