La maîtrise de l'innovation

CFD simulations of the temperature behaviour of bitumen mud with *Code_Saturne* V4.0

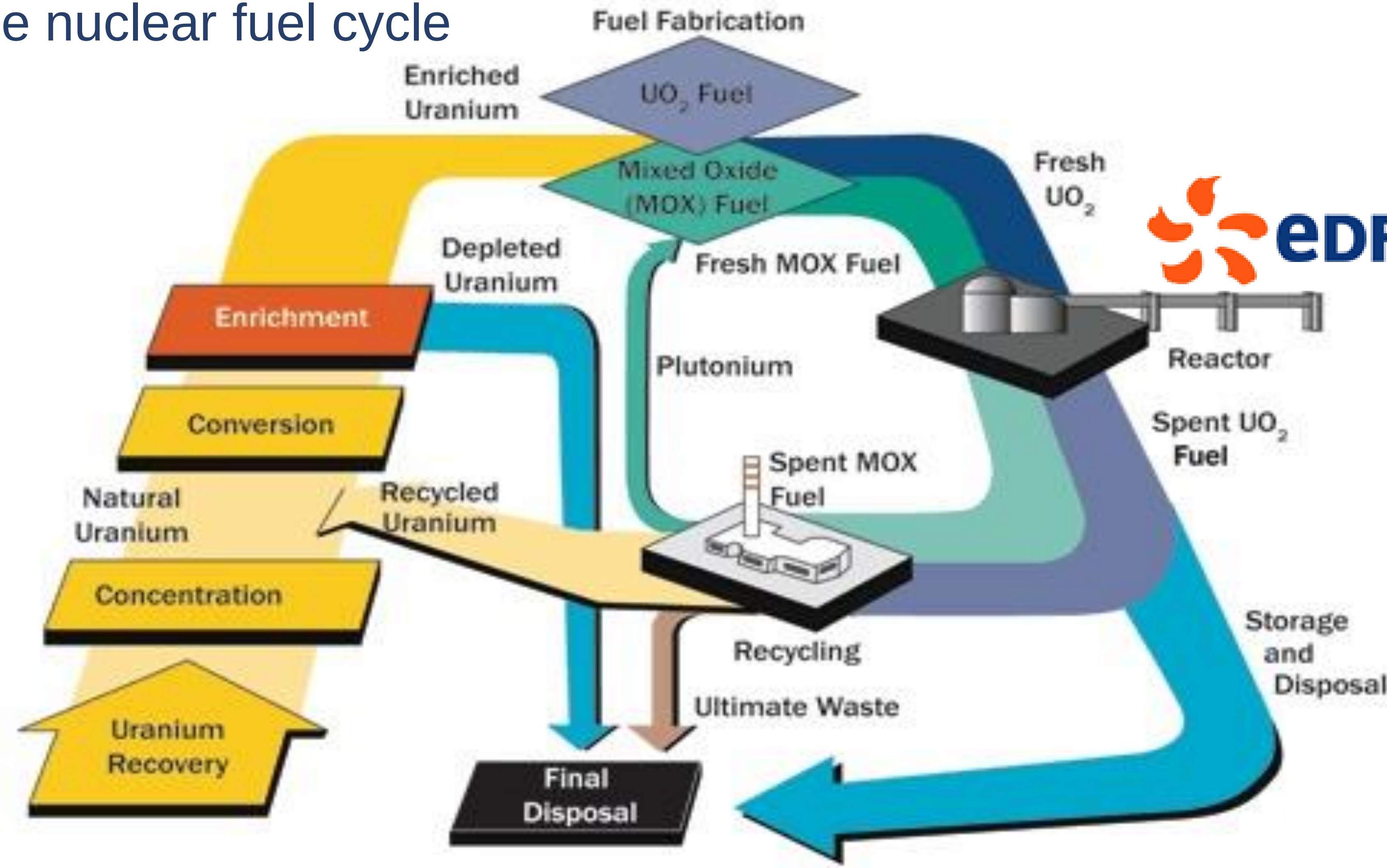
[April - 2015] – Study for EDF R&D & EDF DCN

Overview

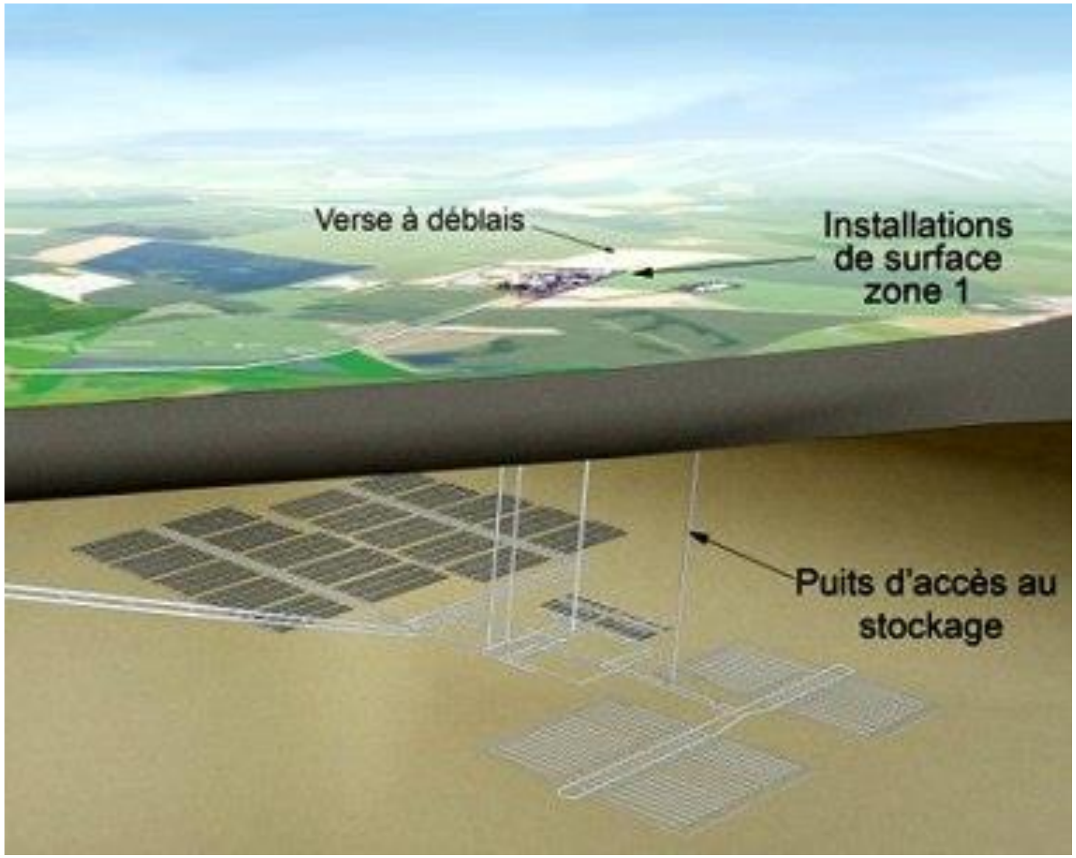
- Context
- Experimental
- Geometry and mesh
- Boundary conditions and Numerical parameters
- Physical properties
- CFD results *Code_Saturne* vs. experimental
- CFD results: barrel scale 1

Context

The nuclear fuel cycle



Context


Verse à déblais
Installations de surface zone 1
Puits d'accès au stockage

Context

Radioactive wastes in the form of dewatered sludge are incorporated in the bitumen. Bitumen is a derivative of crude oil.

Control of various risks is trough simulation and experimentation.

The goal is to contribute to the validation of containment nature of the mixture formed by the bitumen and dehydrated radioactive sludge

Experimental
Bitumen: medium-scales trial (2kg)

Before studying the behavior of bitumen in a drum, we try to reproduce the behavior of bitumen in a small pot of 2kg.

Exploitation of measurements from trials made by the CEA

Cylindrical pot

- similar to the shape
- preventing lateral heat losses
- radius sufficient for the establishment of the convection loops
- allow to observe the movement of the temperature front
- establishment of thermocouples

Experimental
Sensor measure

Changes in temperature over time within the coated subjected to an external heat flux is recorded with probes

Probes radius:

R_C = 0 (centrer)

R_I = 36.2 (internal)

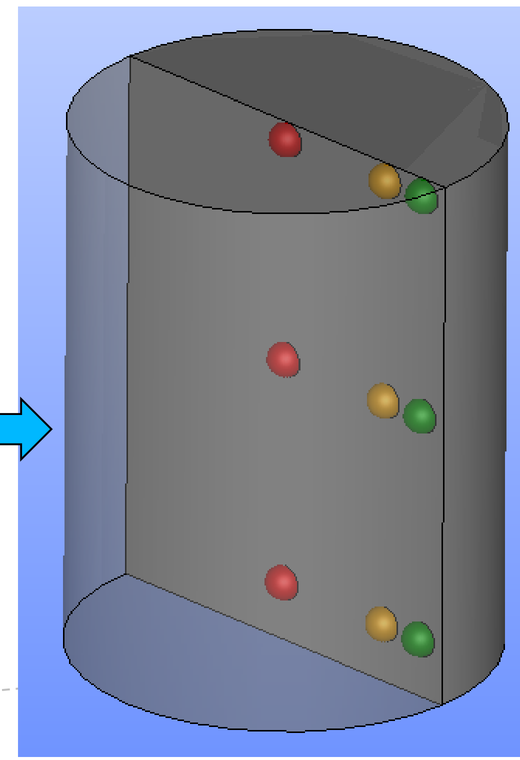
R_E = 49.5 (external)

Probes height:

H_H = 148 (top)

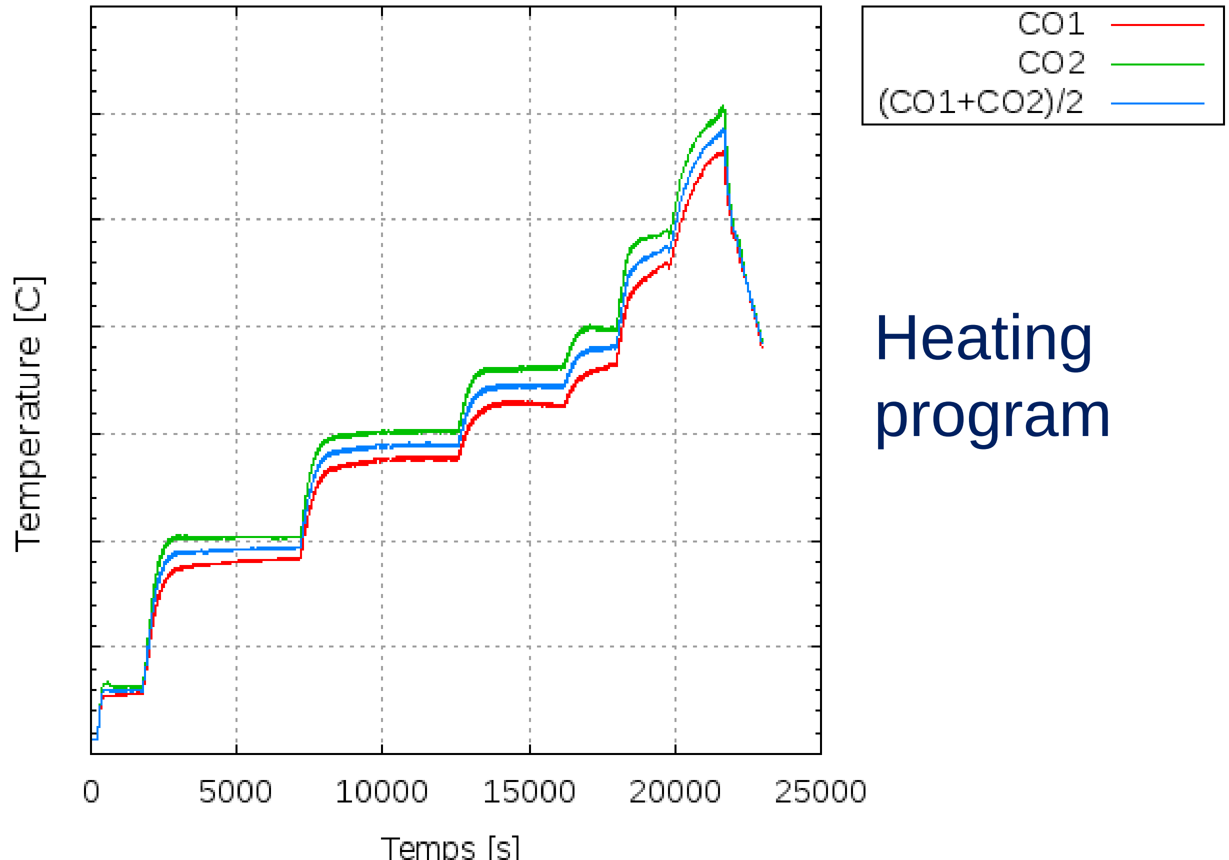
H_M = 83 (middle)

H_B = 17 (low)



Experimental
Temperature applied on the walls

A heating crown and a temperature control system is used for heating the vertical walls.



Heating program

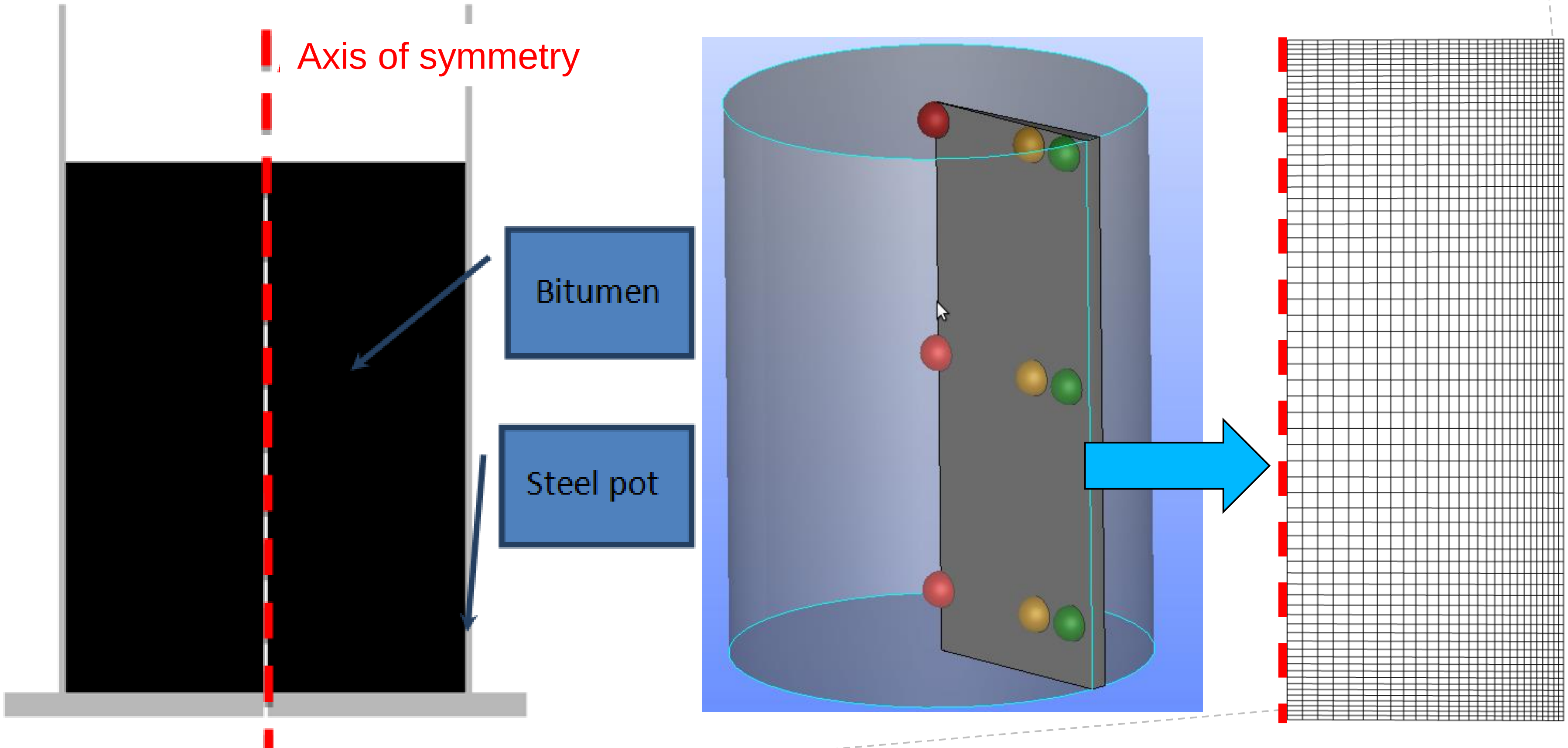
T measure CO1
T measure CO2

On wall for *Code_Saturne*
T = (CO1+CO2)/2

Geometry and mesh

Axisymmetrical bidimensional simulation

Dimension	[m]
Height	0.153
Radius	0.05725



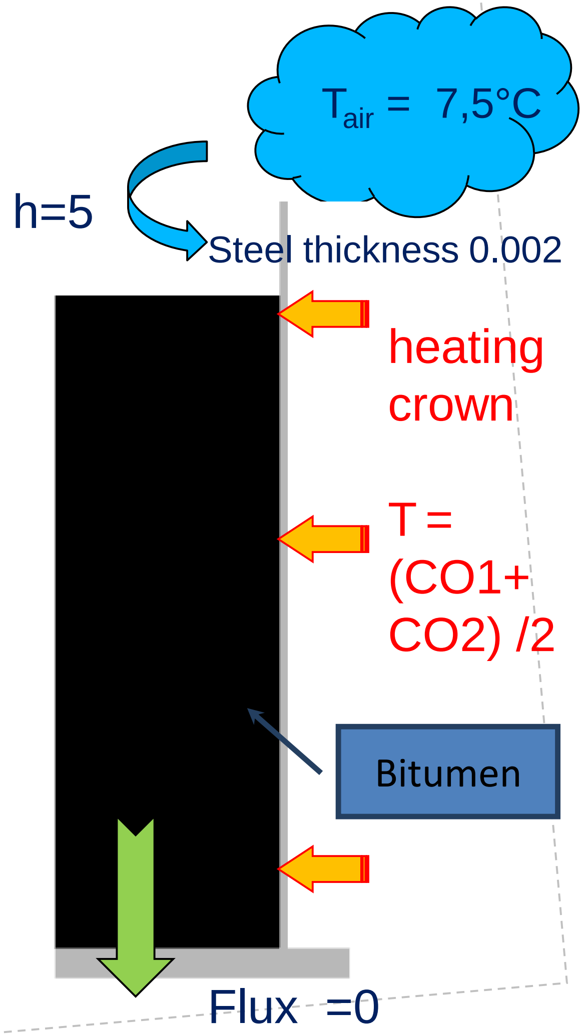
Boundary conditions and Numerical parameters

Axisymmetric 2D model created with version 4.0 of *Code_Saturne* takes into account the following parameters :

- physical properties of the bitumen
- convective exchange surface
- positioning of the heating bracelet
- room temperature
- thermal properties of pot
- source term (chemical kinetics)

A first boundary condition h=5 has been tested, then flux =0, the bottom of the barrel based on aerated concrete block insulation.

Although even lose heat by conduction with this concrete block, it is difficult to assess the loss.



Physical properties

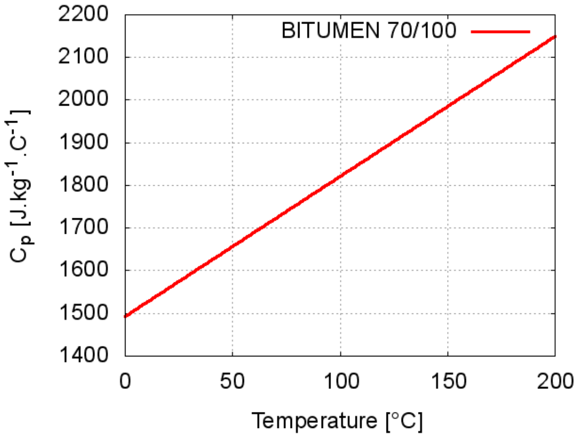
For the first calculations, the physical properties of the bitumen 70/100 was used

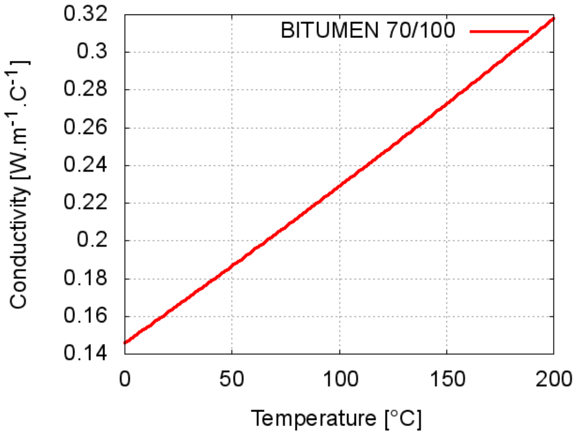
Specific heat Cp [J.kg^{-1}.C^{-1}]

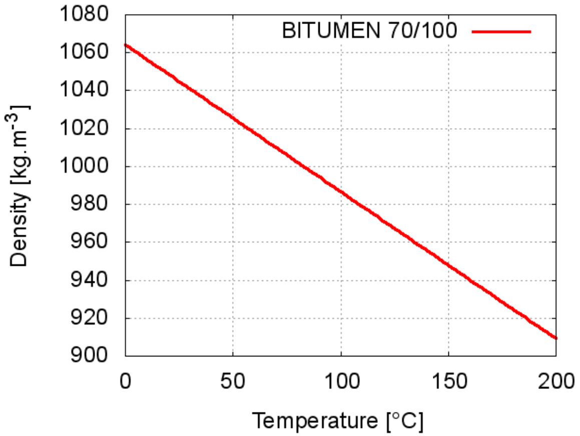
*3.29 * T + 1492*

Density ρ [kg.m^{-3}]

*1064.2 – 0.775 * T*







Thermal conductivity λ [W.m^{-1}.C^{-1}]

$3*10^{-7} * T^2 + 8 * 10^{-4} * T + 0.1459$

Physical properties

For the first calculations, the physical properties of the bitumen 70/100 was used

Viscosity [Pa.s]
Loi de Carreau-Yasuda

$$\mu(\dot{\gamma}) = \frac{\sigma}{\dot{\gamma}} + \mu_0 a_T [1 + (\tau a_T \dot{\gamma})^a]^{\frac{n-1}{a}}$$

$\sigma = 0.02\ Pa$

$\mu_0 = 2300\ Pa.s$

$\tau = 2.5\ 10^{-3}\ s$

$n = 0.37$

$a = 0.55$

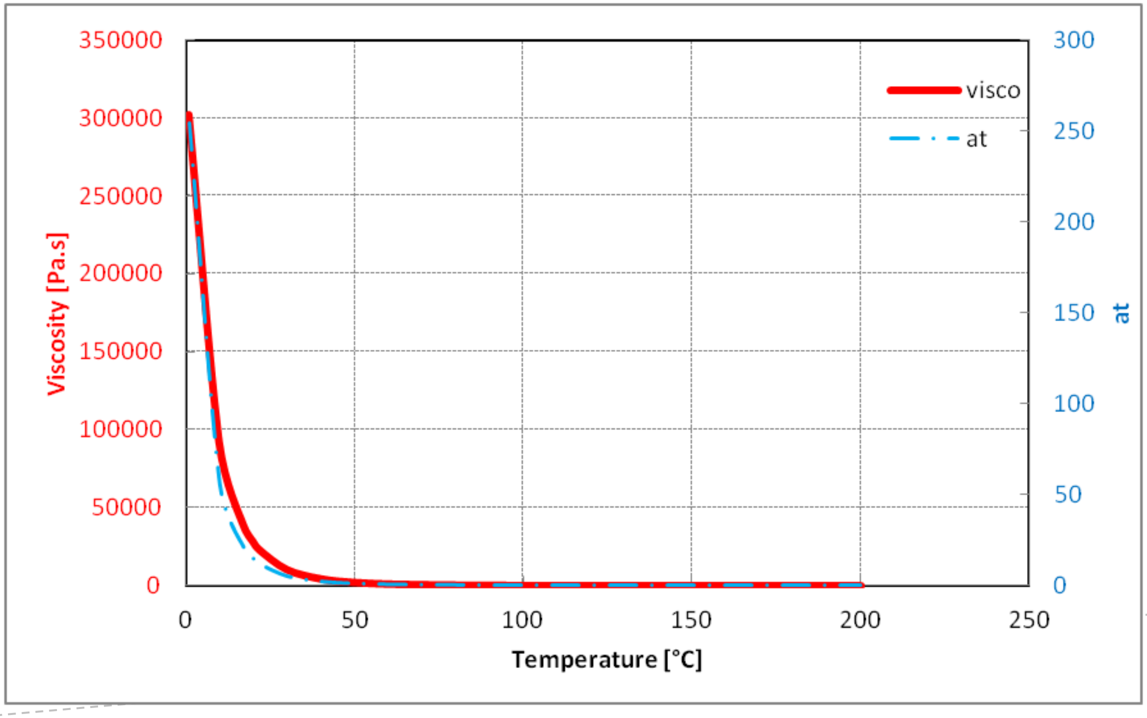
$C_1^0 = 8.16$

$C_2^0 = 121.2$

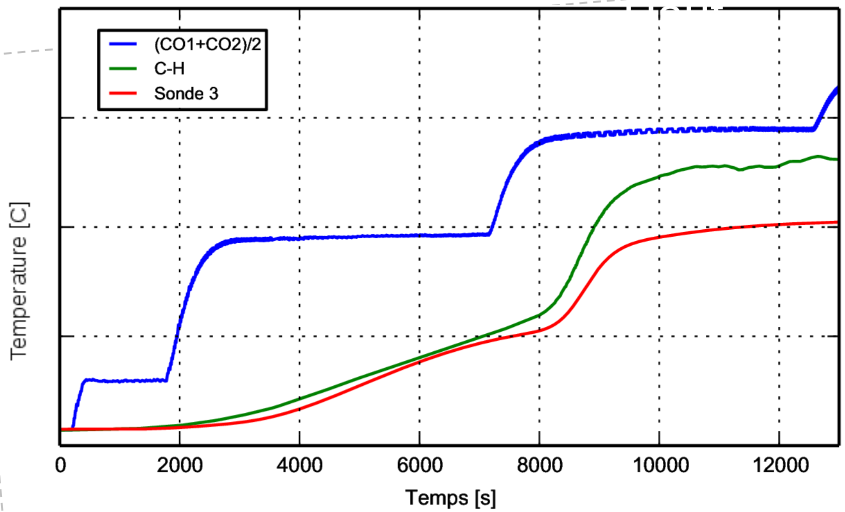
$T_{ref} = 50°C$

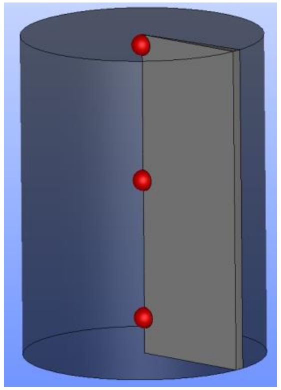
Coefficient of friction

$$a_T = e^{\left[\frac{-C_1^0 (T - T_{ref})}{C_2^0 + (T - T_{ref})}\right]}$$

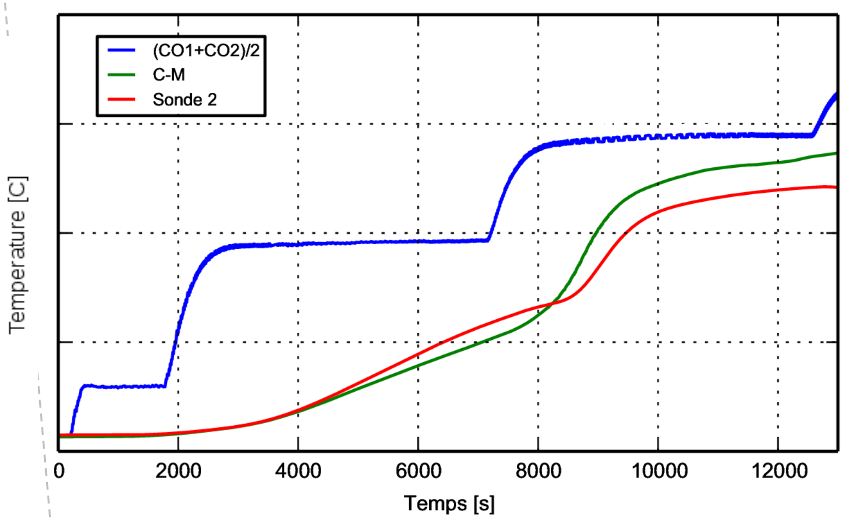


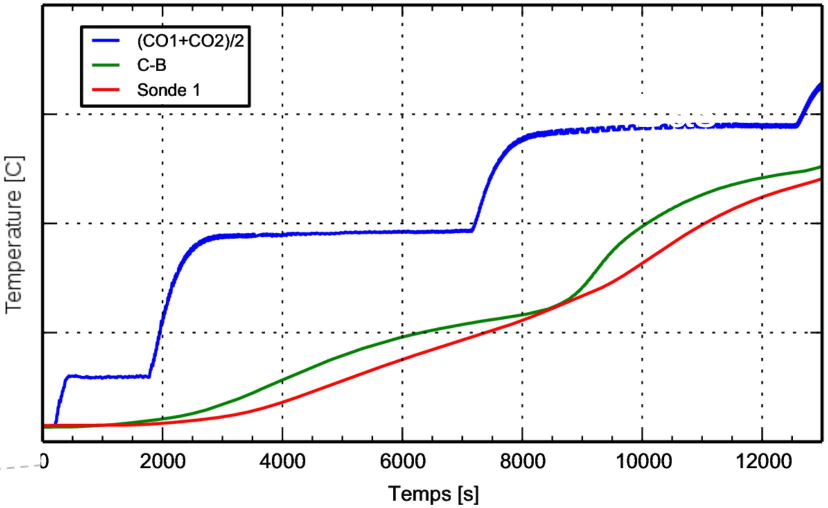
CFD results: *Code_Saturne* vs. experimental data



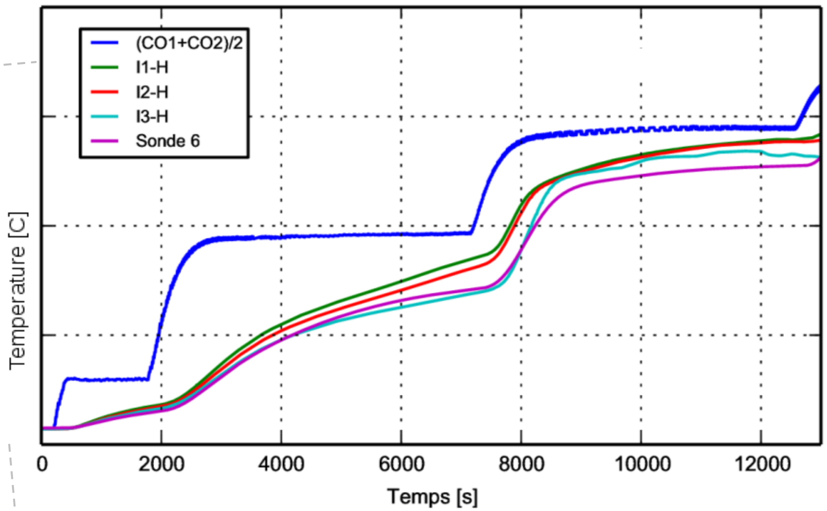


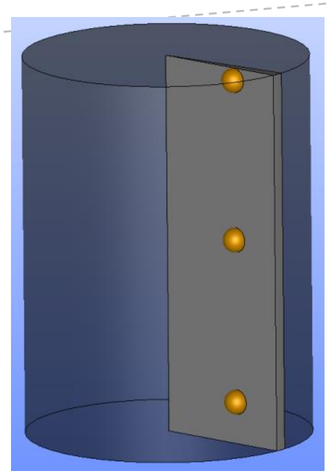
Changing the temperature at the centre



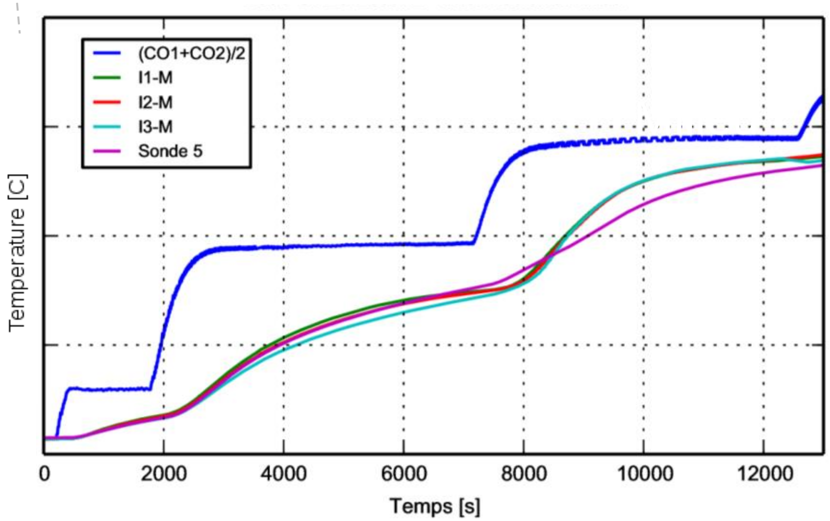


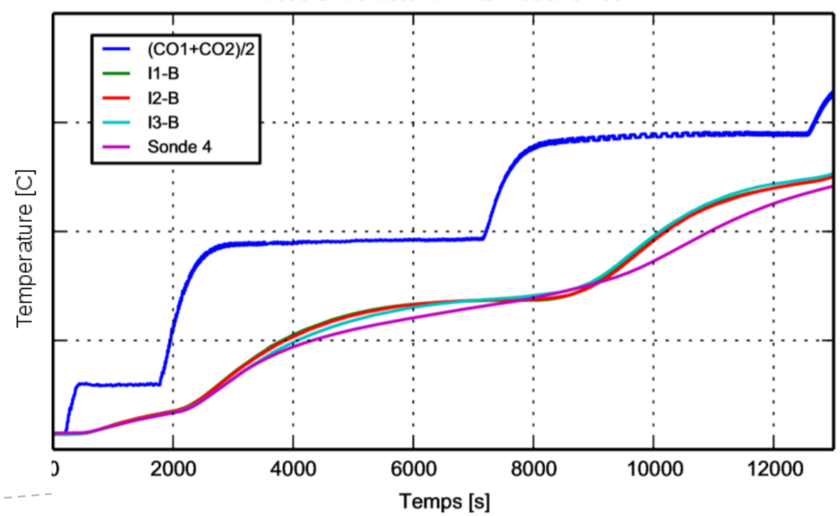
CFD results: *Code_Saturne* vs experimental data



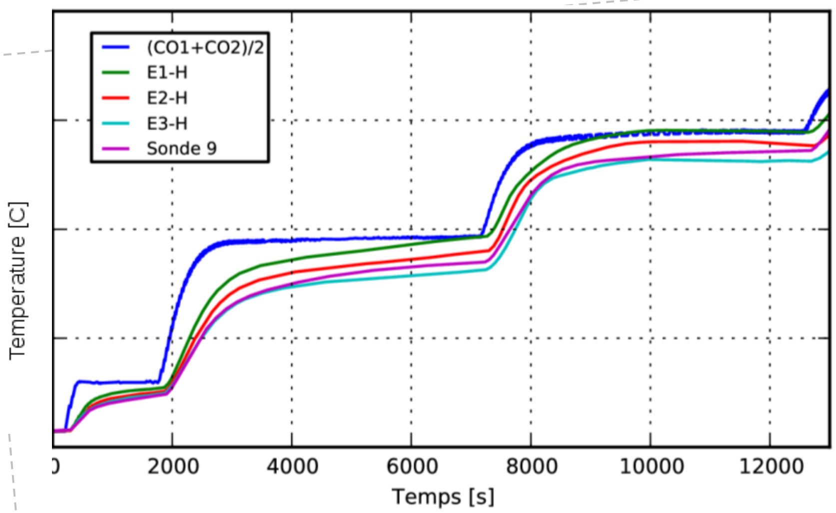


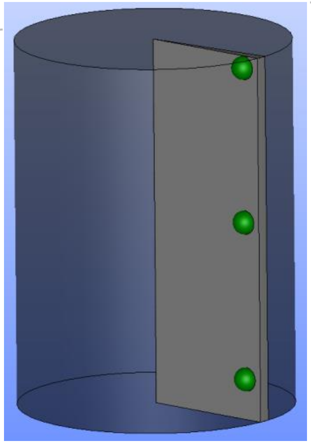
temperature changes in intermediate ring



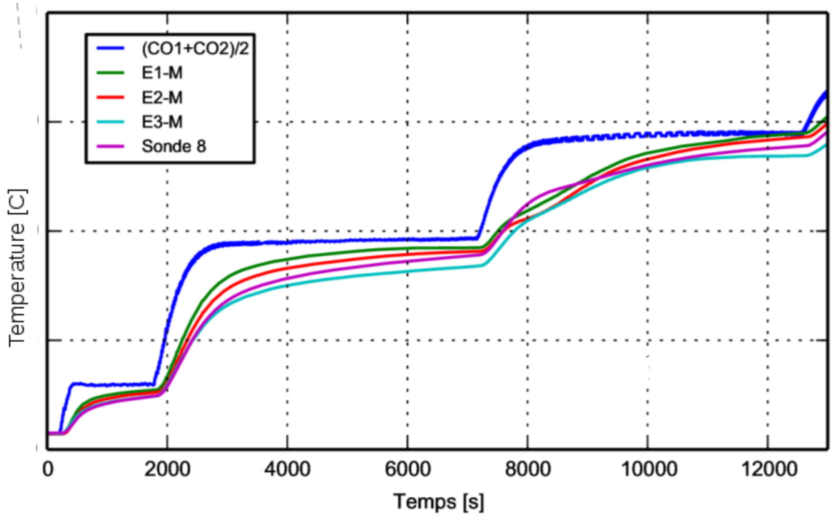


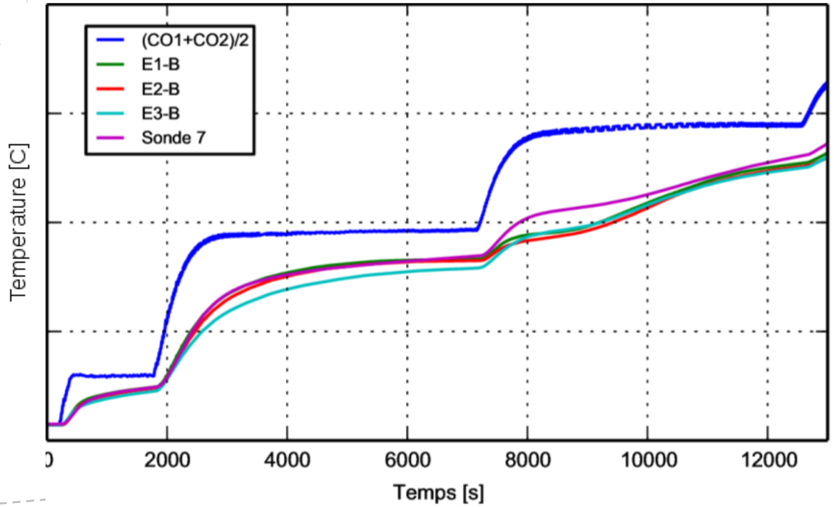
CFD results: *Code_Saturne* vs experimental data





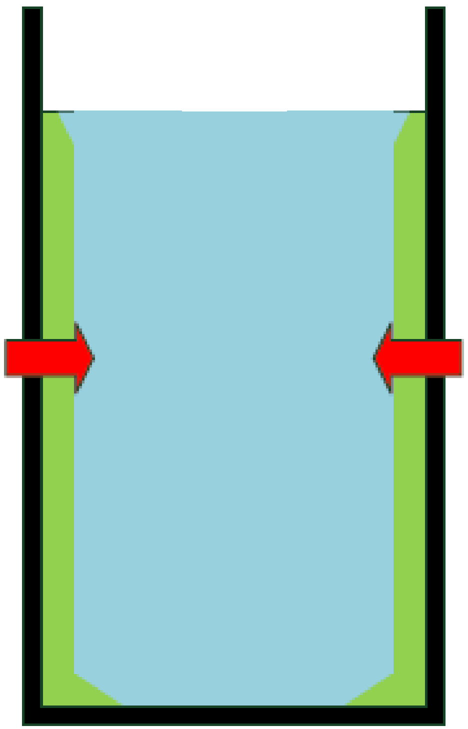
Evolution of the external ring temperature



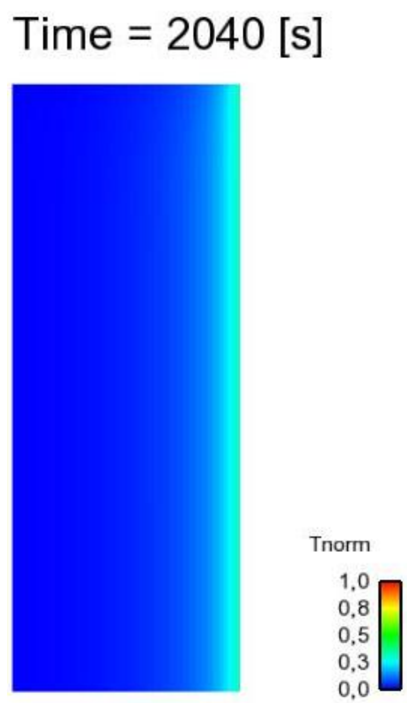


Analysis of the CFD results

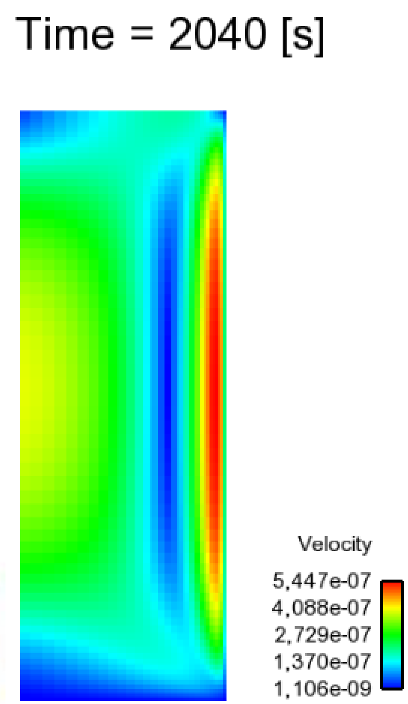
At low temperatures below the glass transition, the heat transfer takes place only by conduction.



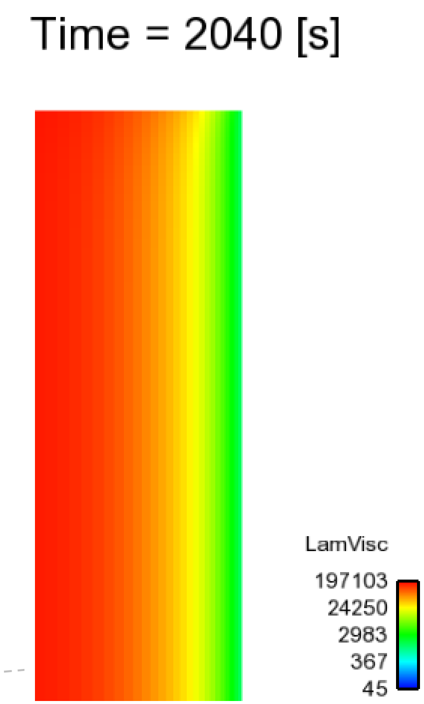
Temperature



Velocity

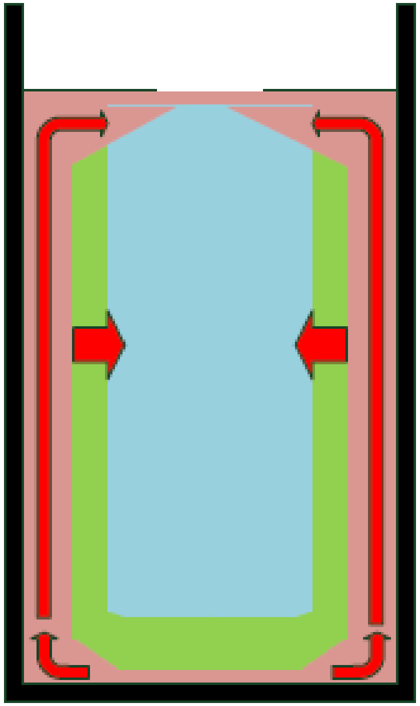


Viscosity



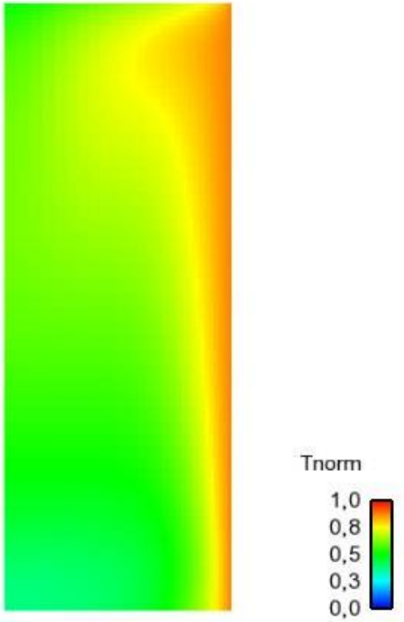
Analysis of the CFD results

Volumes subjected to temperature higher than the temperature of the glass transition. The fluid flows upwardly and cover the surface.



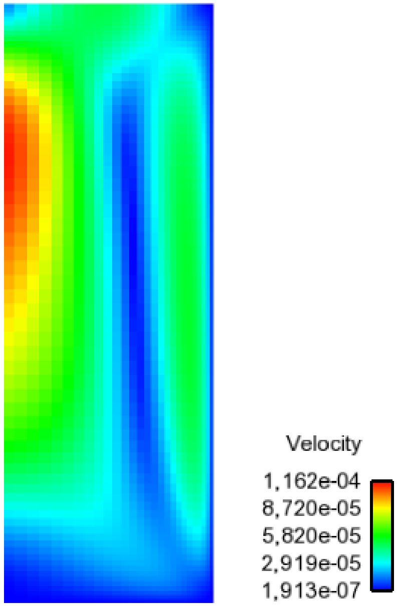
Temperature

Time = 9540 [s]



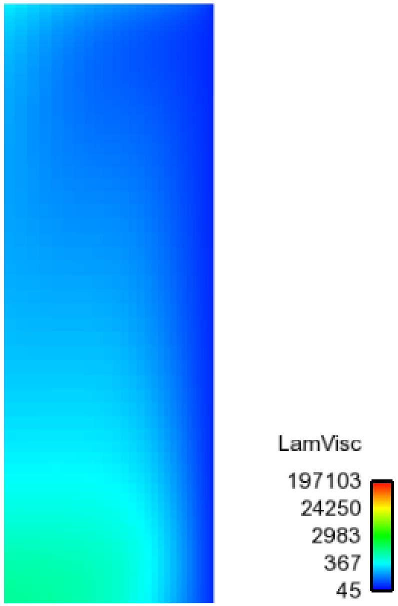
Velocity

Time = 9540 [s]



Viscosity

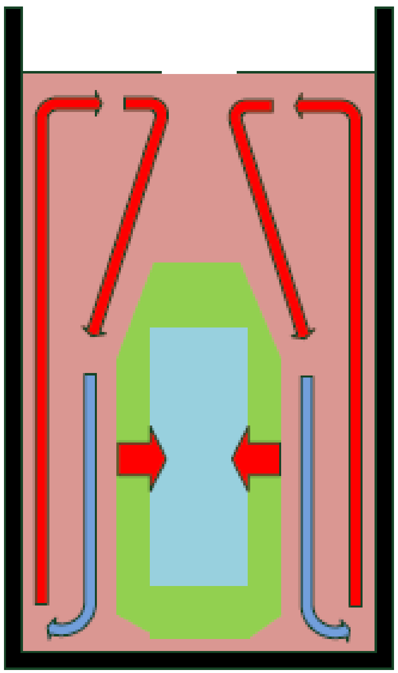
Time = 9540 [s]



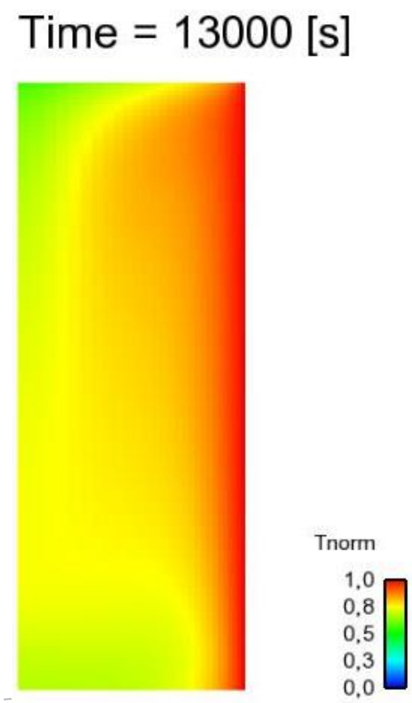
CFD results : Analysis of the results

The volumes with low viscosity is sufficient to allow thermal cycle of convection, near vertical walls.

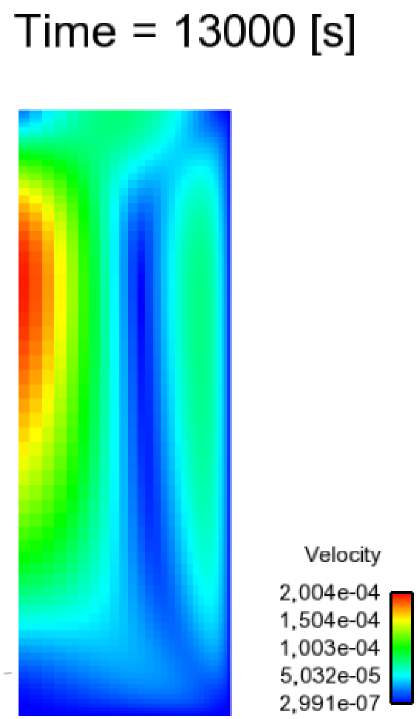
Exchanges in the heart of the matrix are always made by conduction.



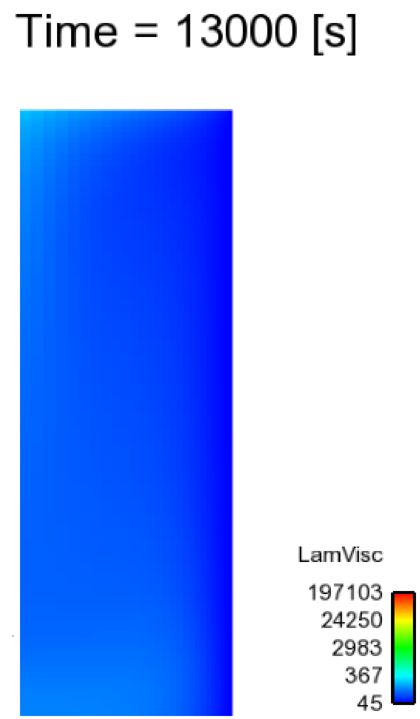
Temperature



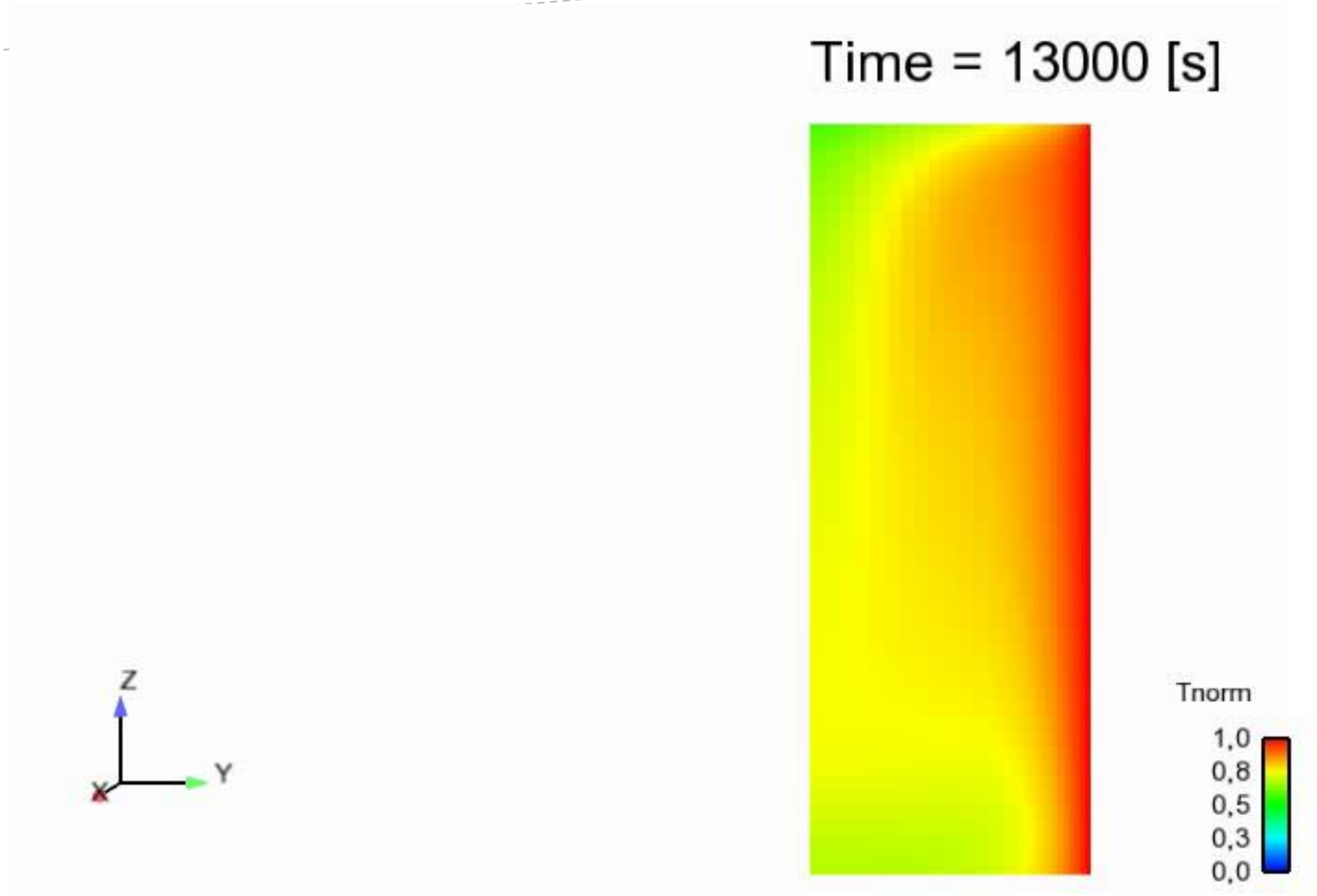
Velocity



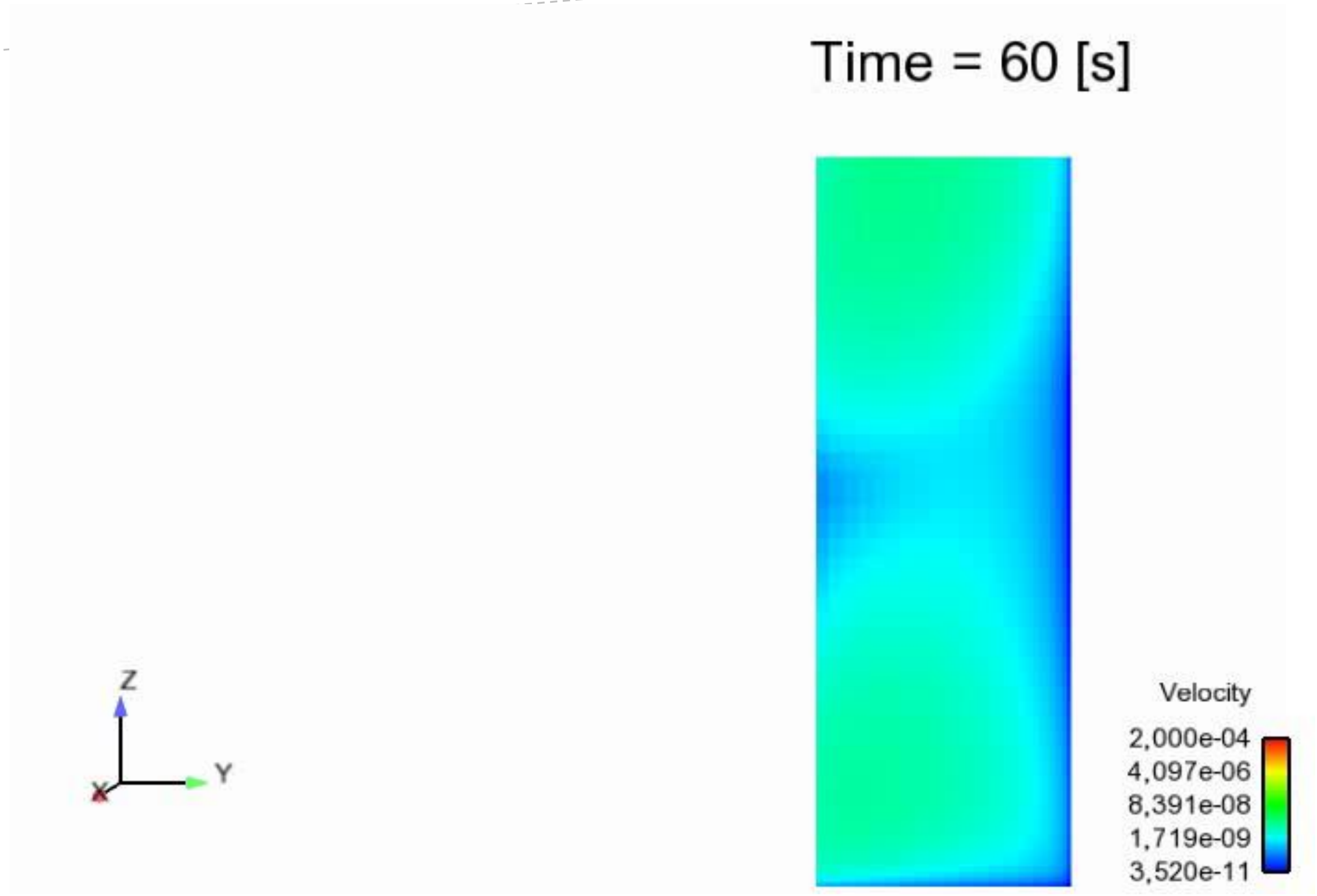
Viscosity



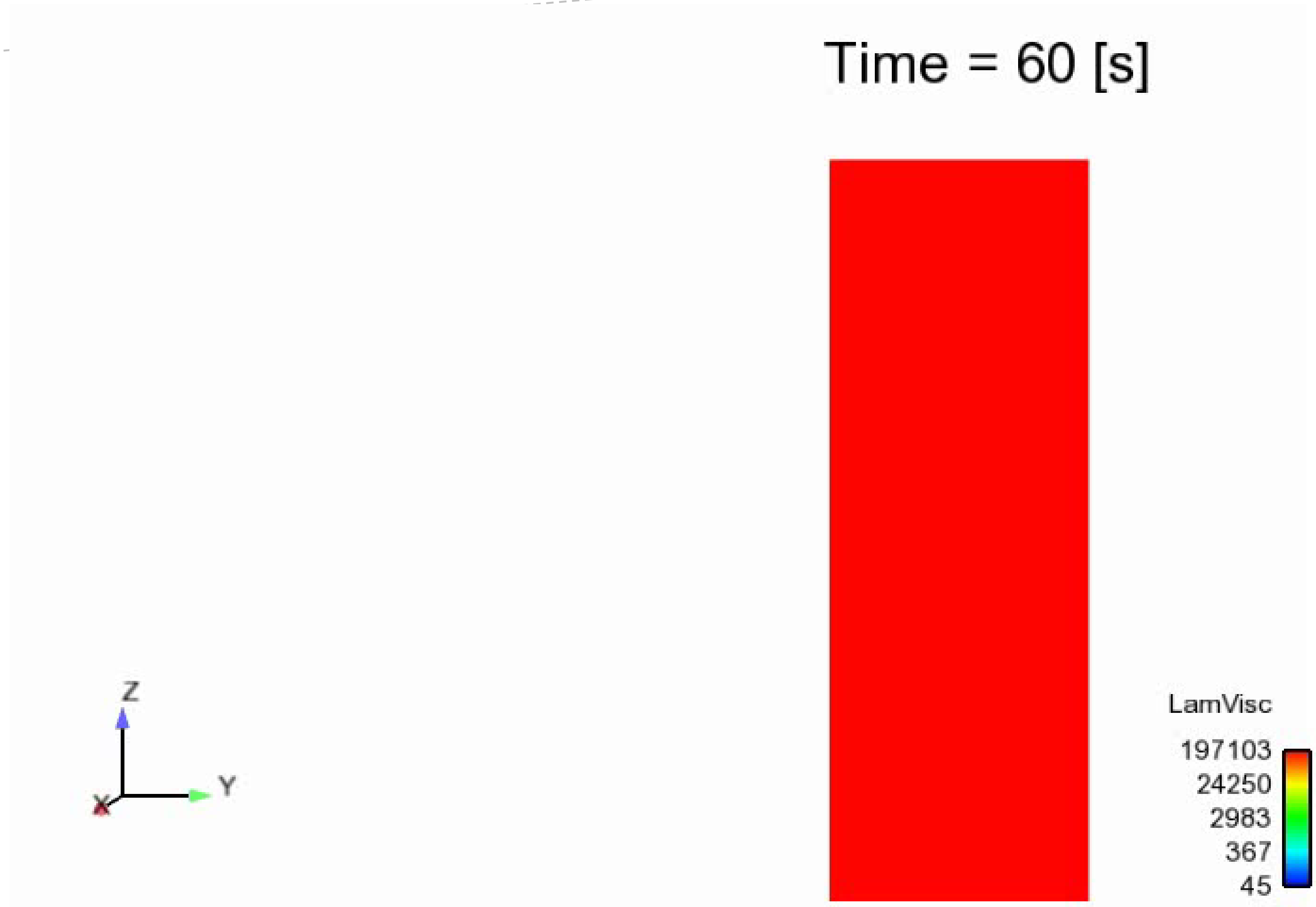
CFD results: video of the temperature field



CFD results: video of the velocity field



CFD results: video of the viscosity field



Consideration of a gradual release of chemical energy

Beyond a threshold temperature T_{onset} an exothermic chemical reaction provides heat to the bitumen volume. The thermal power P supplied by the chemical reaction is taken into account with a source of thermal power

Simplified kinetic equation $A \rightarrow B$

The rate of disappearance of species A $v = -\dfrac{d\,[A]}{dt}$ and $v = k\,[A]$

Transport equation of species A $\dfrac{\partial A}{\partial t} + \vec{u}.\overrightarrow{grad}A = D_m \Delta A - kA$

D_m mass diffusivity

k coefficient of the reaction rate (Arrhenius low) $k = Ae^{\frac{-E_a}{RT}}$

A frequency factor

Ea activation energy Arrhenius

R gas constant

Consideration of a gradual release of chemical energy

For a higher temperature T_{onset}, three types of law for the thermal power P

Law 1 : thermal power polynomial P function of time after an experimental curve

$$P = f(t)$$

Law 2 : thermal power P according to a Arrhenius law with the energy of activation Ea bitumen

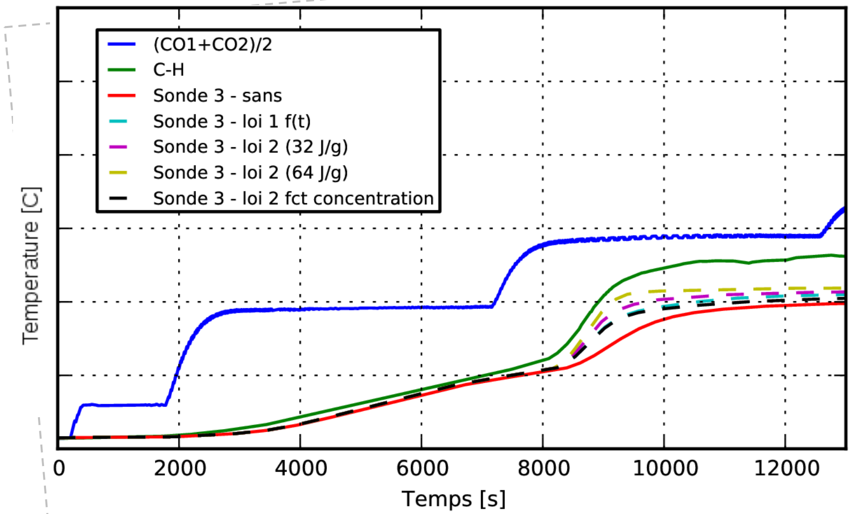
$$P = Ae^{\frac{-E_a}{RT}} \mathrm{V} \rho \, (-\, \Delta H_r)$$

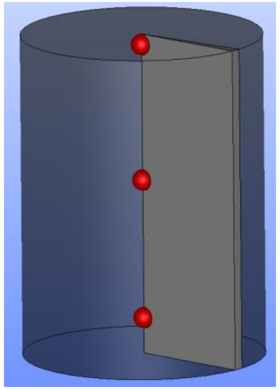
V volume, ρ density, $\Delta H_r < 0$ for exothermic chemical reaction

Law 3 : law 2 function concentration of species A

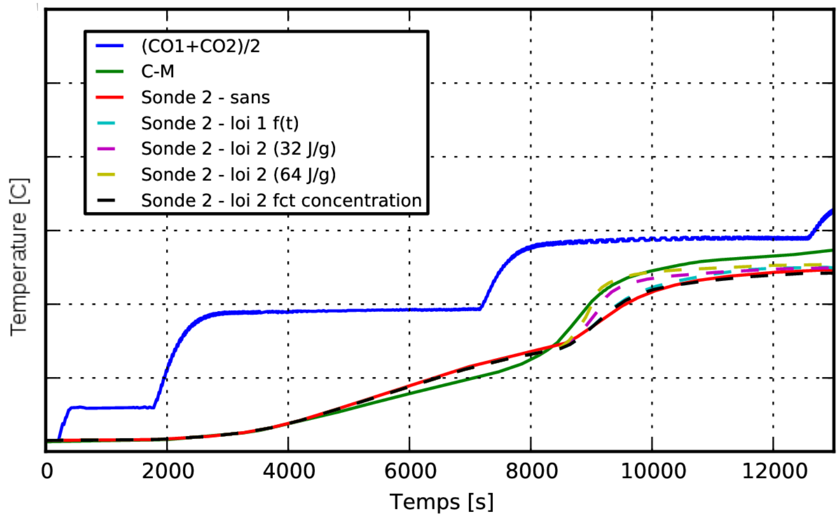
$$P = A \times e^{\frac{-E_a}{RT}} \times \mathrm{V} \times \rho \times \; (-\, \Delta H_r) \times [A]$$

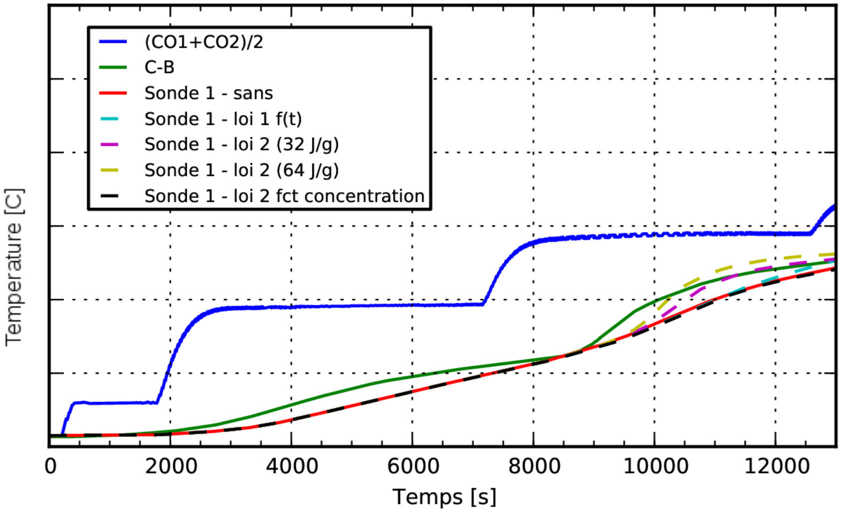
CFD results: *Code_Saturne* with thermal sources vs experimental data



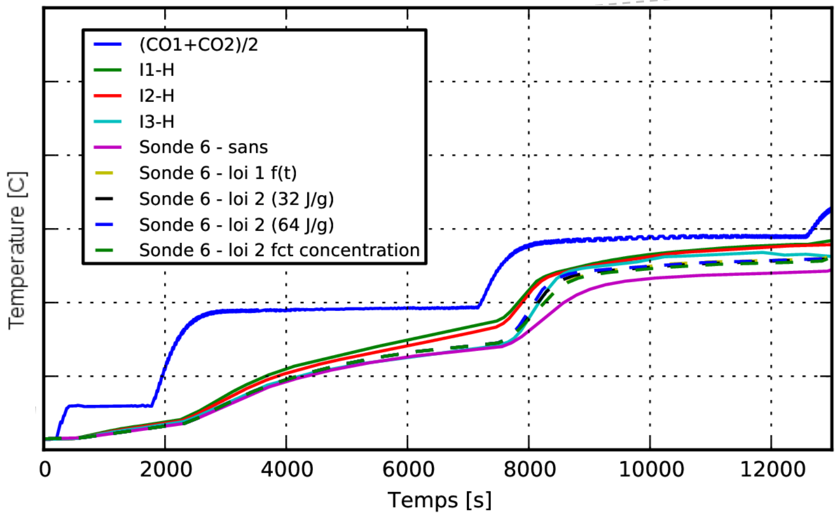


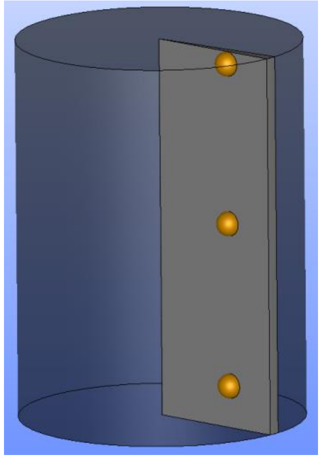
Changing the temperature at the center



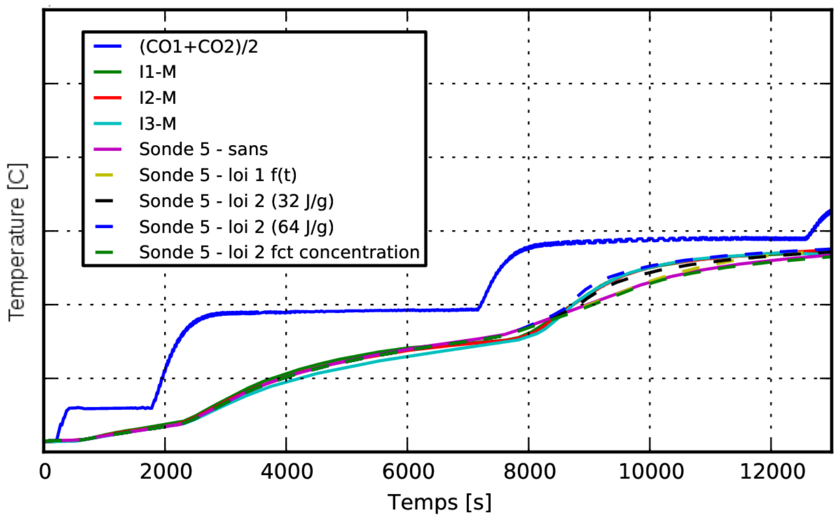


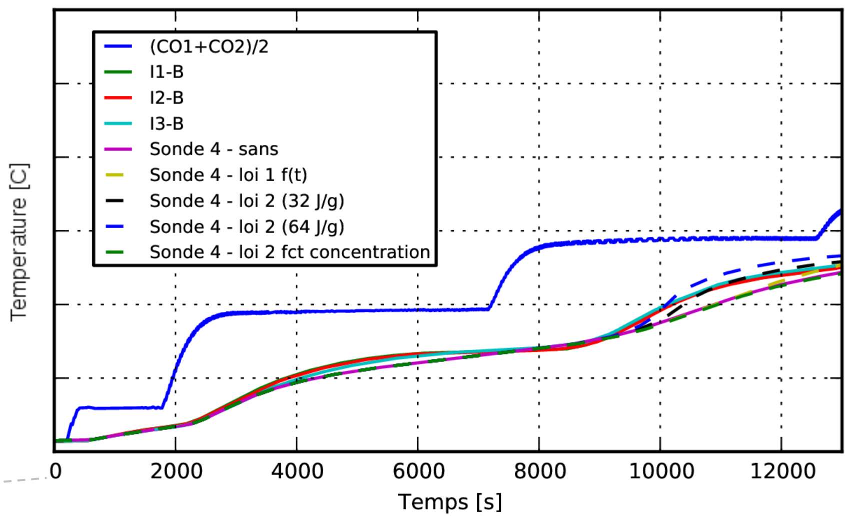
CFD results: *Code_Saturne* with thermal sources vs experimental data



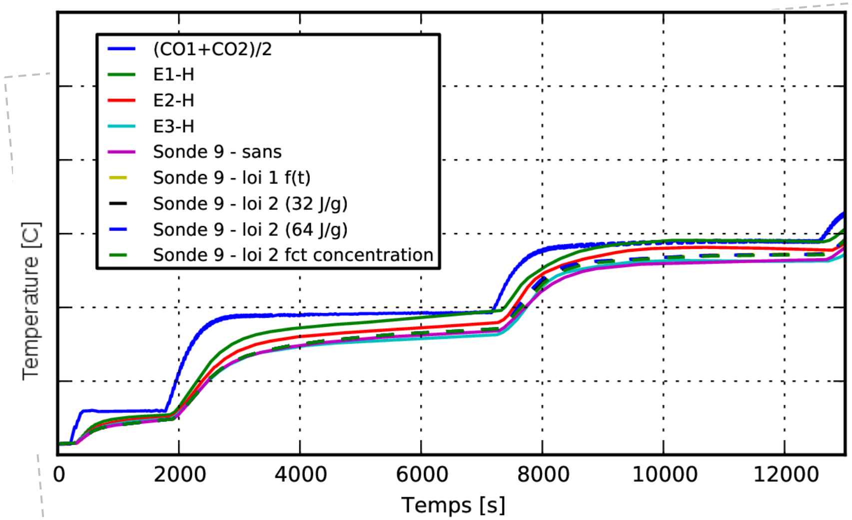


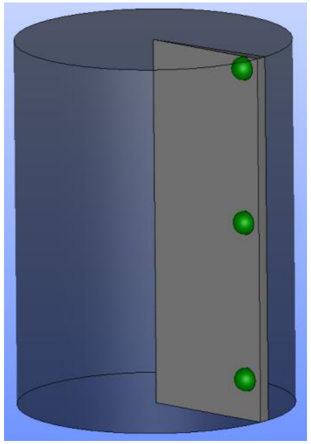
Temperature changes in intermediate ring



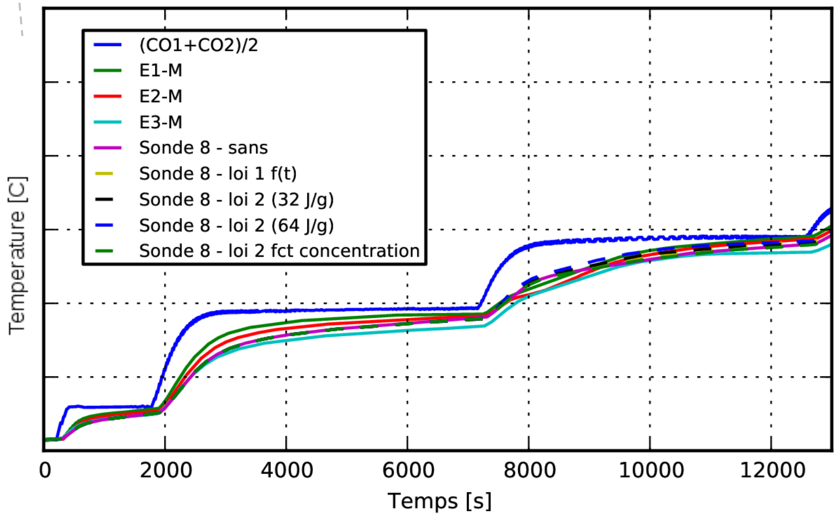


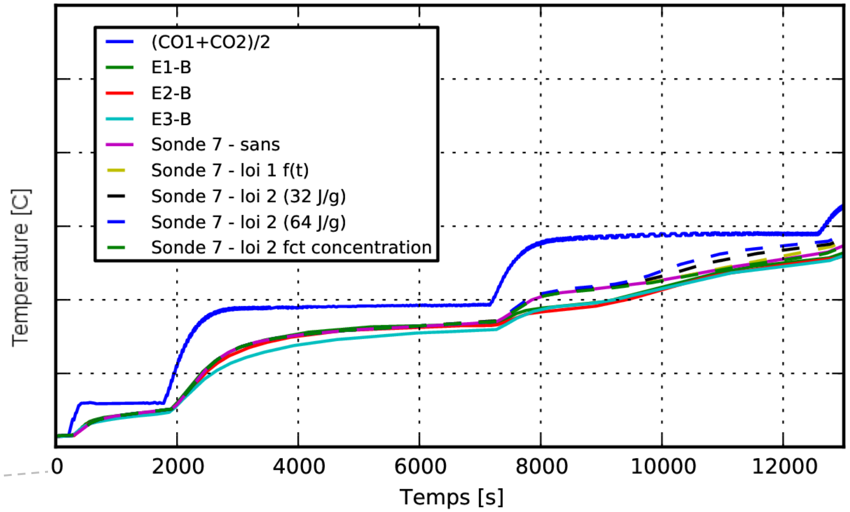
CFD results: *Code_Saturne* with thermal sources vs experimental data





Evolution of the external ring temperature



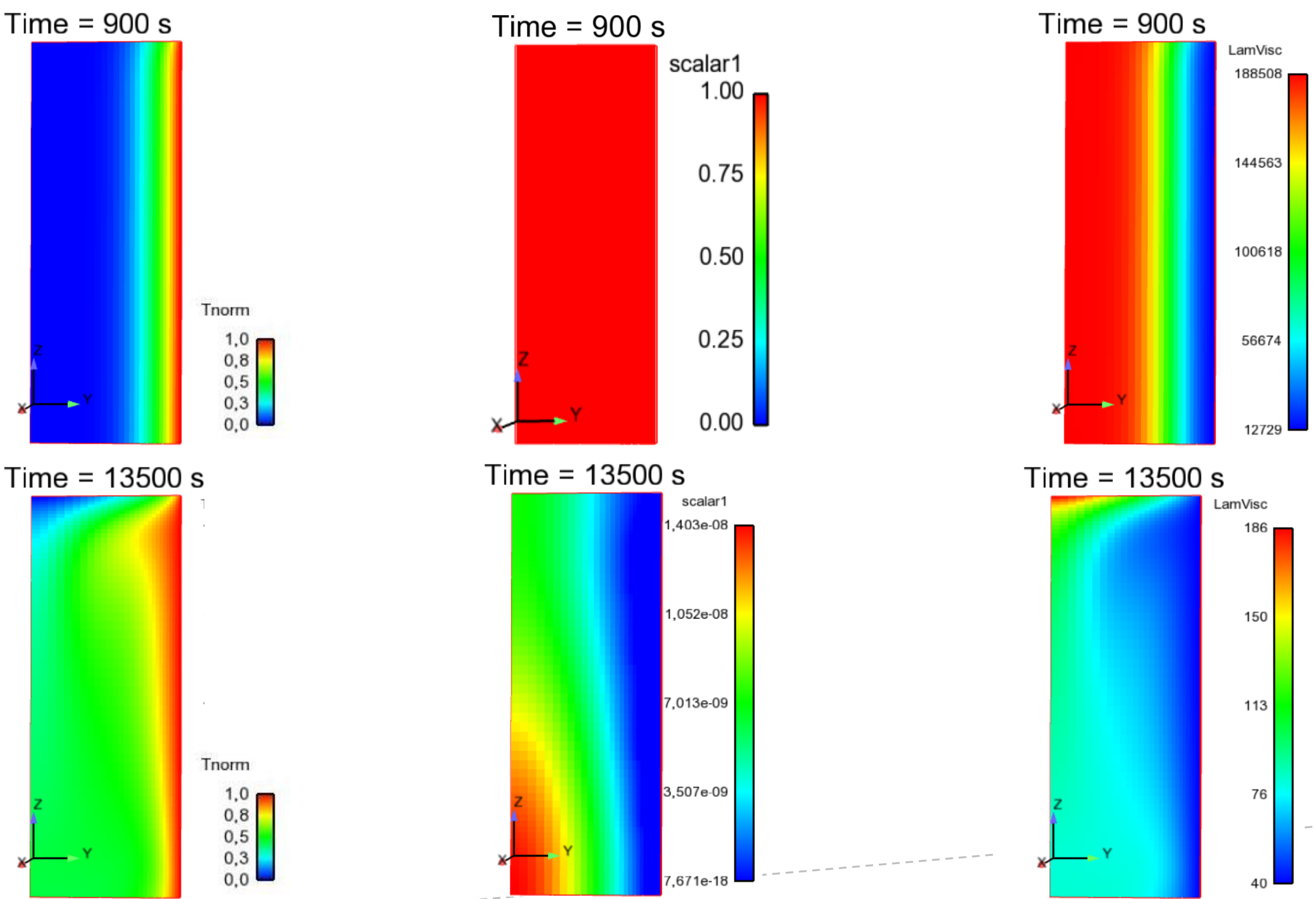


CFD results: *Code_Saturne* vs experimental data

Temperature

Concentration of the species [A]

Viscosity

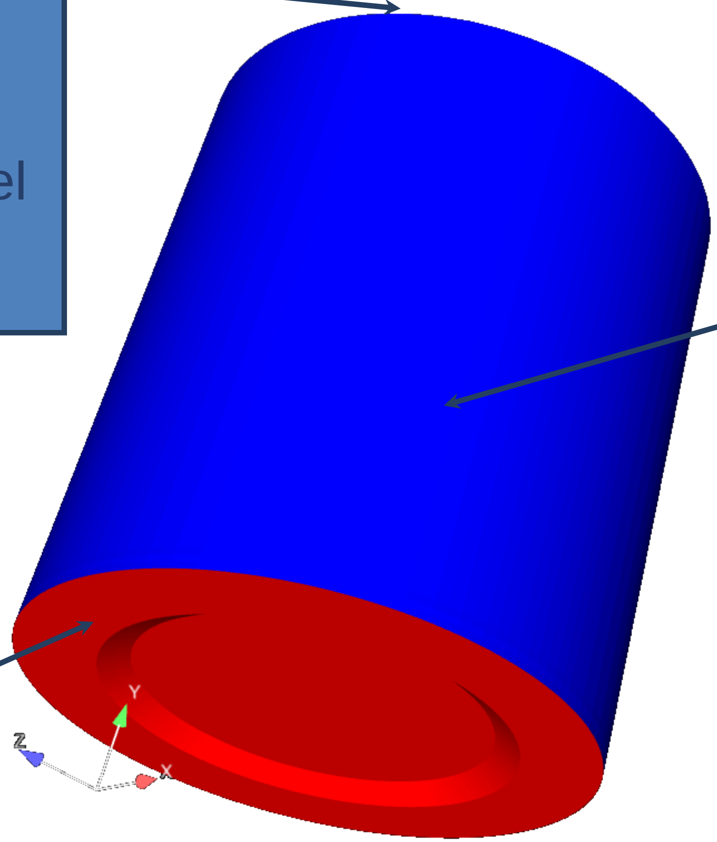


CFD results: barrel at scale 1

Constant boundary conditions over time

150 °C with h function to 20 cm of air and 2 mm of steel lid

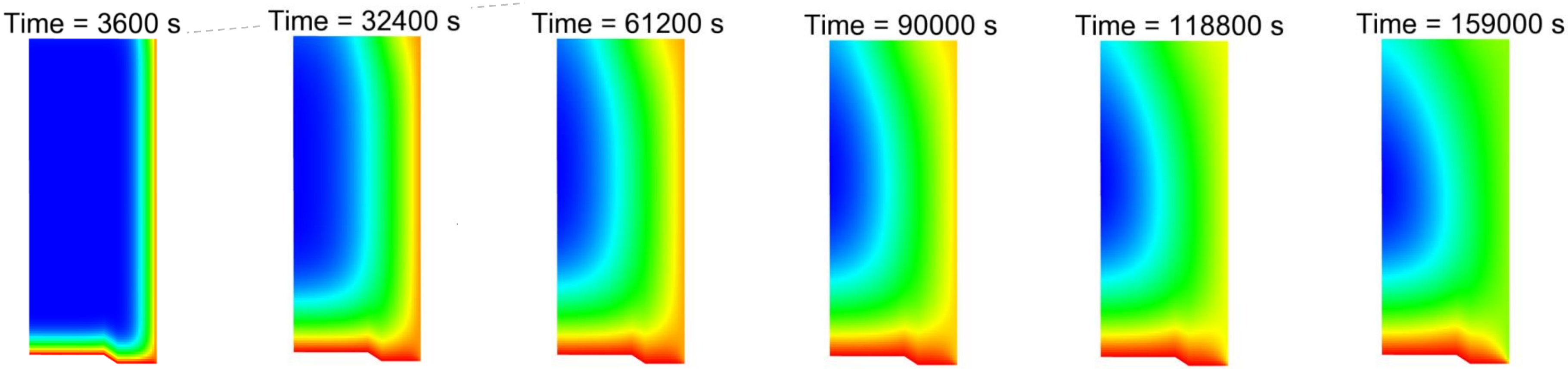
100 °C



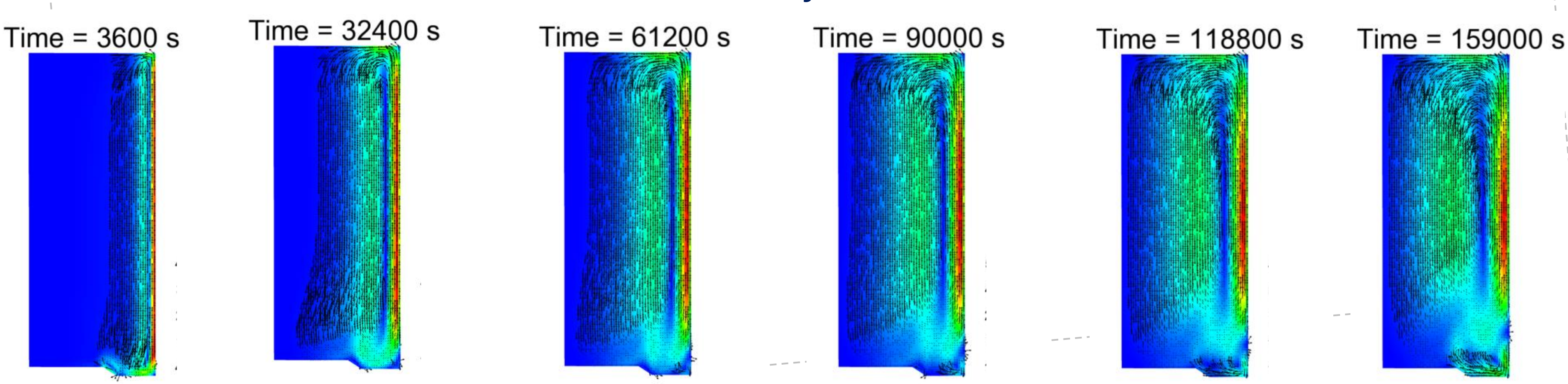
115 °C

CFD results

Temperature



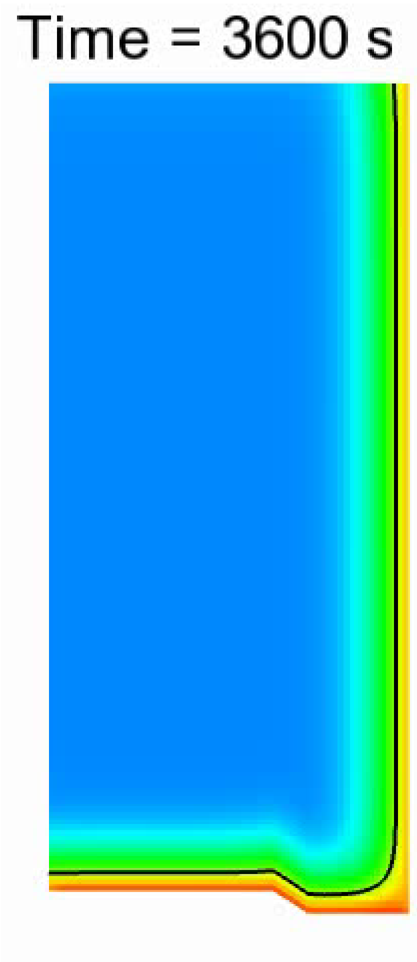
Velocity



CFD results : video

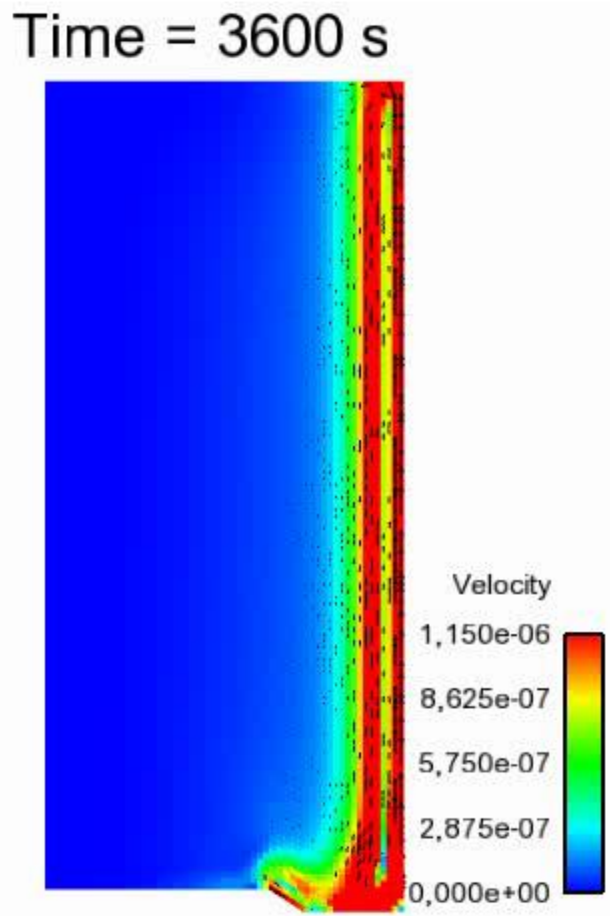
Constant boundary conditions over time

Temperature



Constant boundary conditions over time

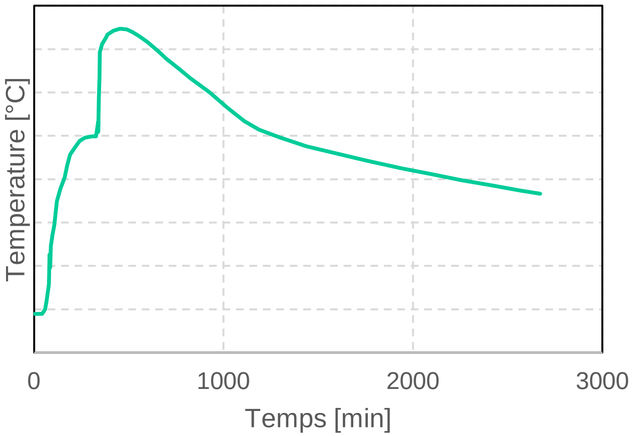
Velocity



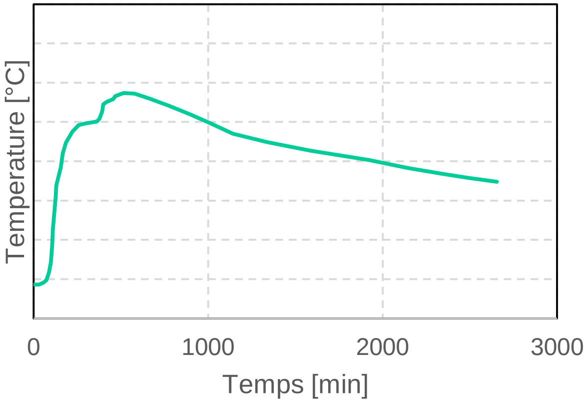
CFD results: barrel scale 1

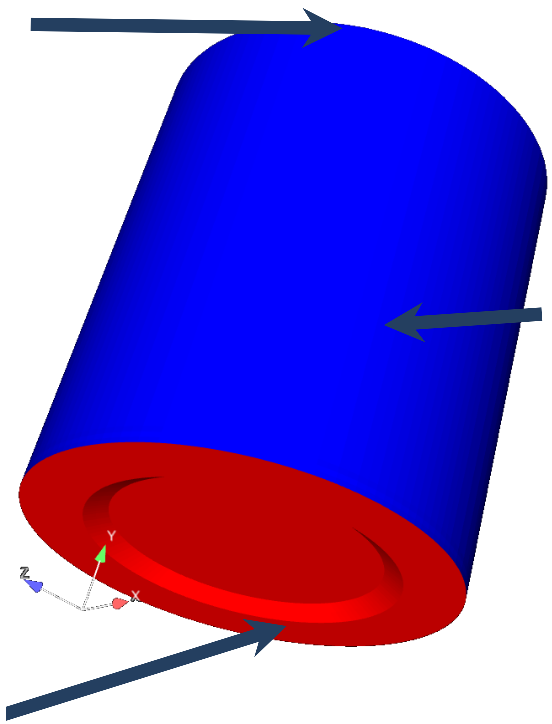
Variable boundary conditions over time

top

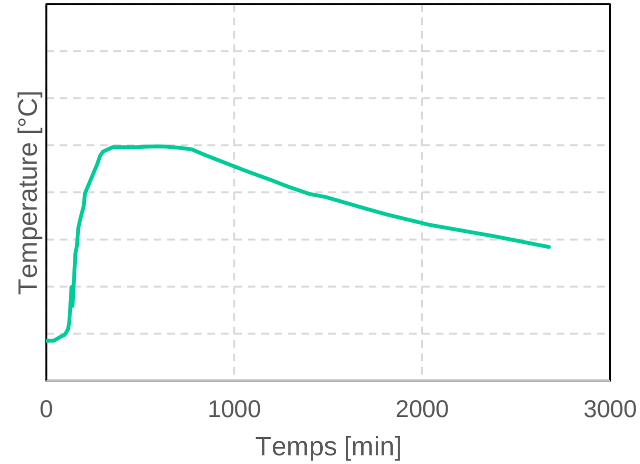


bottom



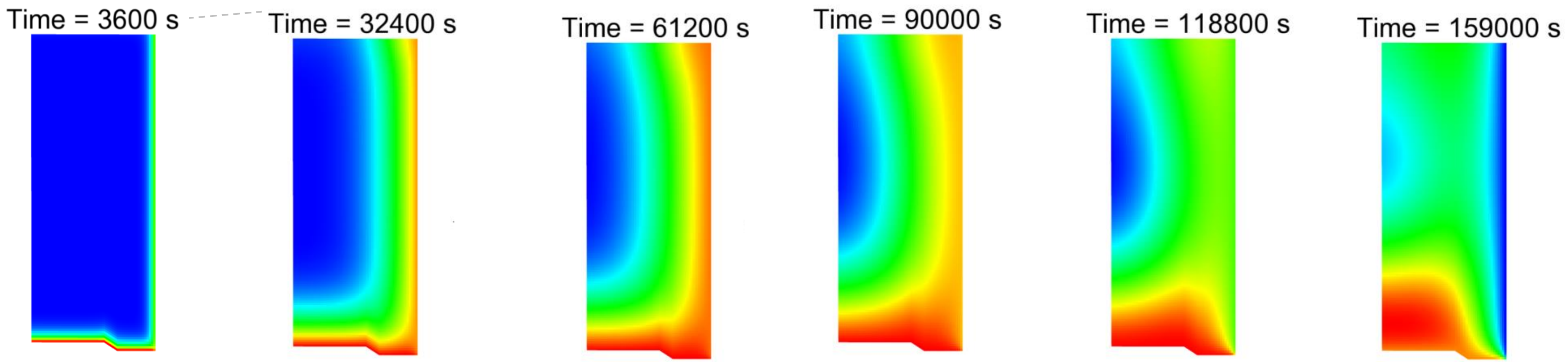


wall

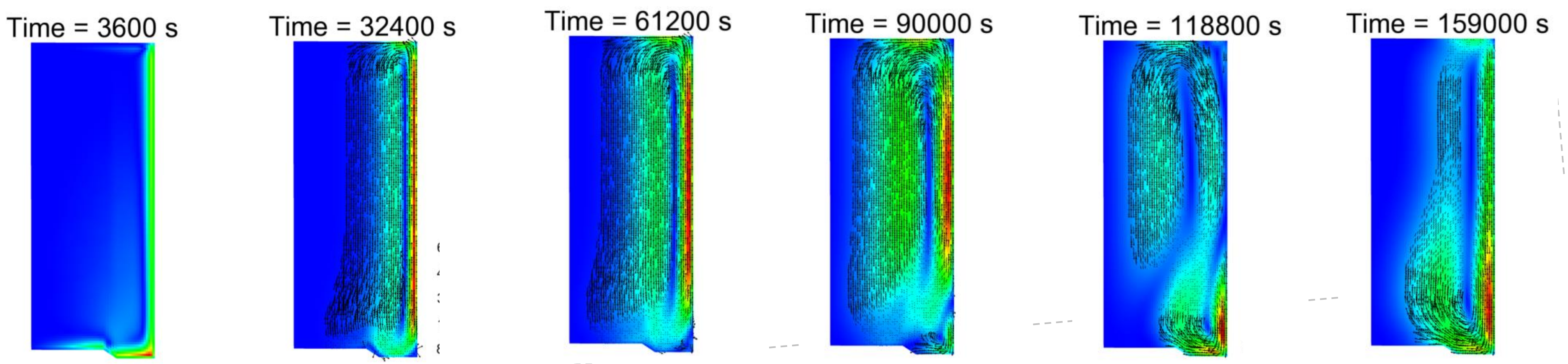


CFD results

Temperature



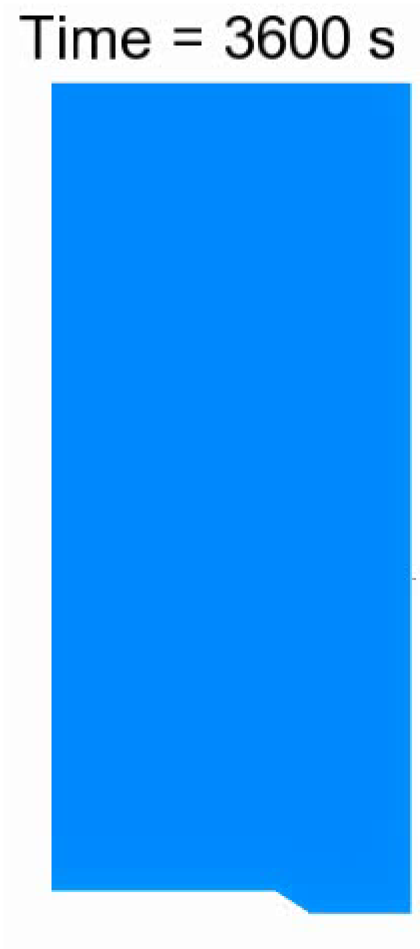
Velocity



CFD results: video

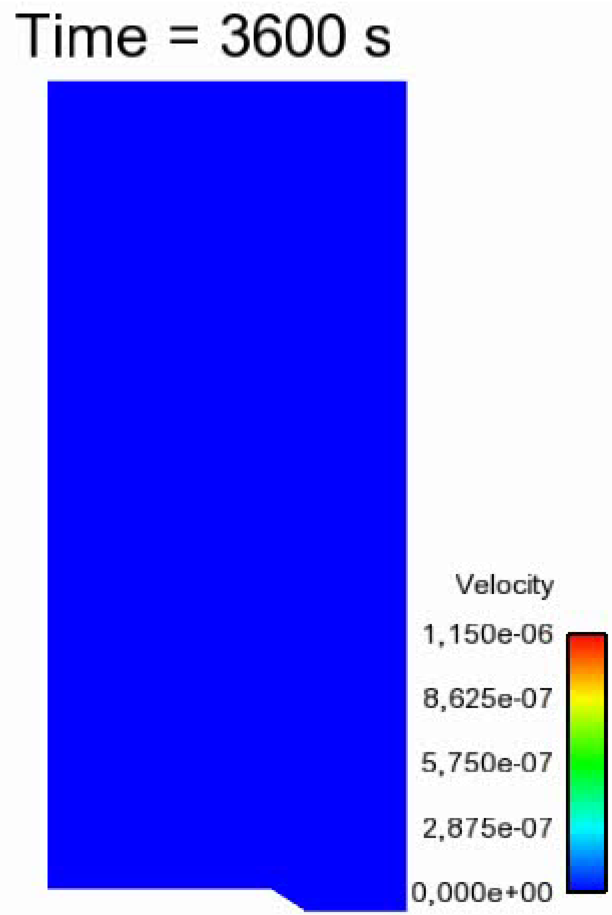
Variable boundary conditions over time

Temperature



Variable boundary conditions over time

Velocity



CONCLUSION

1) Summary of the case made validations

- Experimental data on several types of bitumen in a 2kg pot
- test case with the physical properties of the bitumen 70/100
- test cases with a first approach to physical properties of bitumen with radioactive sludge

2) Summary of the models produced

- model with a 2kg pot with 70/100 bitumen
- model with a 2kg pot with properties bitumen used for storage
- model with a 2kg pot including an exothermic reaction for bitumen (3 type of law)
- model with a barrel at scale 1

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3) The first fluid calculations were presented to CNE in January

END

THANK YOU FOUR ATTENTION

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