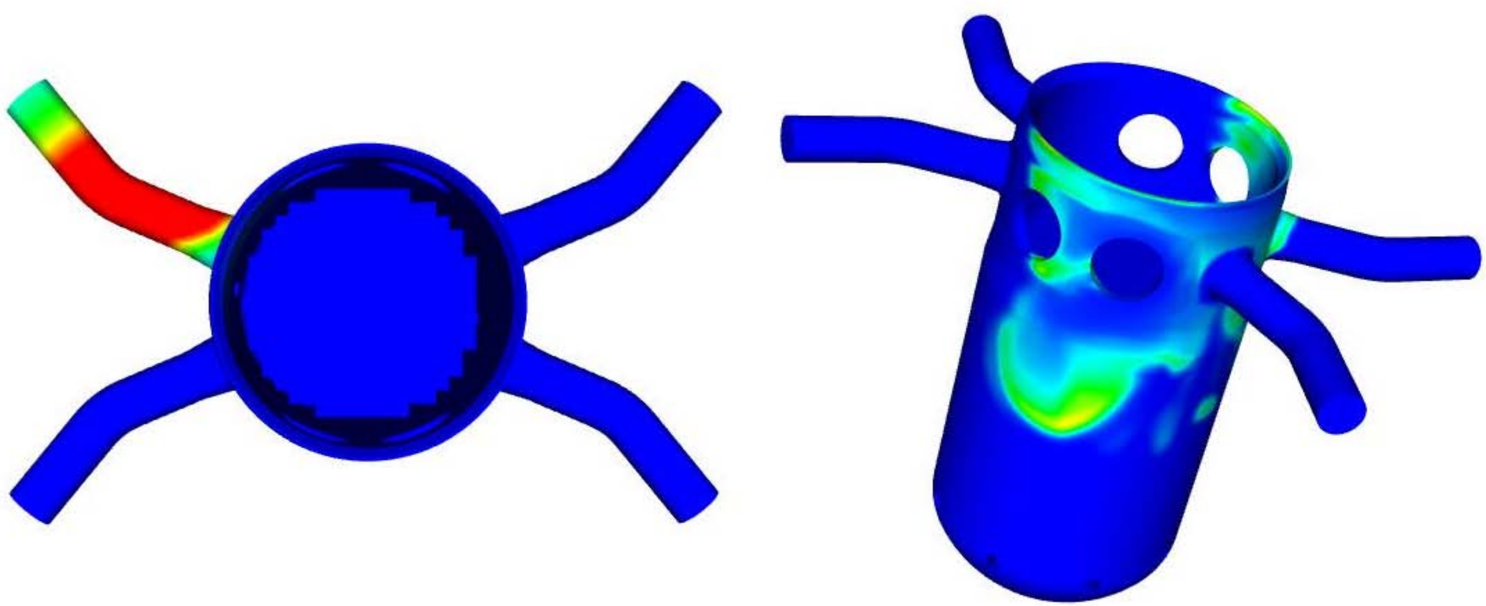
CFD simulations of the *JULIETTE 1/5th*-scale *PWR* model for external boron dilution studies with *Code_Saturne V3.0*

Franck LELONG EDF/SEPTEN/PR/THL

02 avril 2014

Contents



Industrial context

- Formation of diluted slug :
  - Pipes rupture of heat exchanger on the seal water injection circuit.

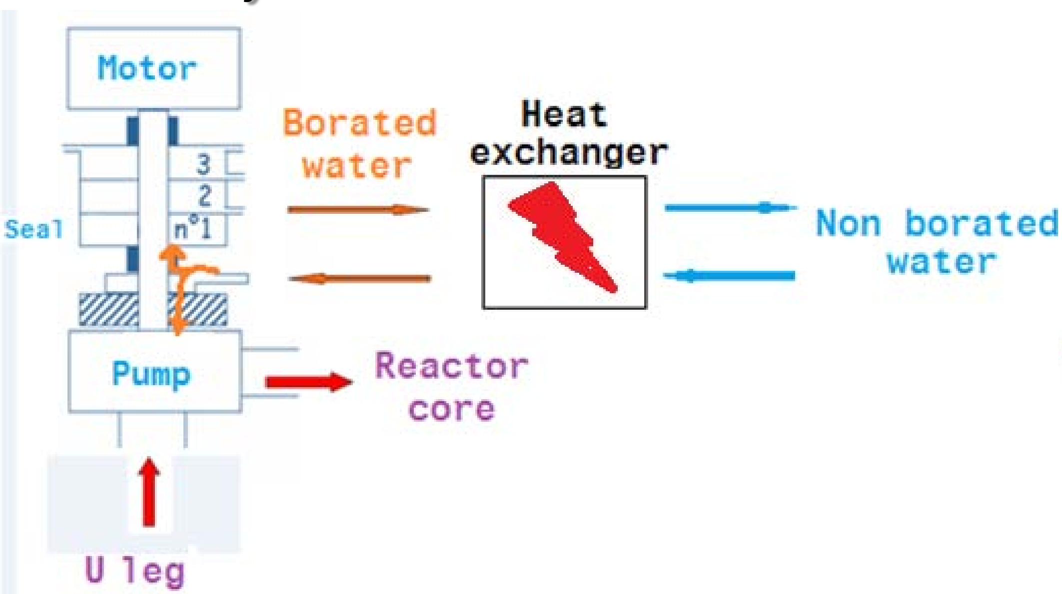
  ➔ ***Injection of non borated water on the primary circuit through the seal of the Reactor Coolant Pump.***
  - A precondition for the slug formation is that a coolant flow stagnates in a loop ➔ ***shutdown conditions***.
  - Diluted water accumulates in the *U* leg ➔ ***slug formation in the U leg***.

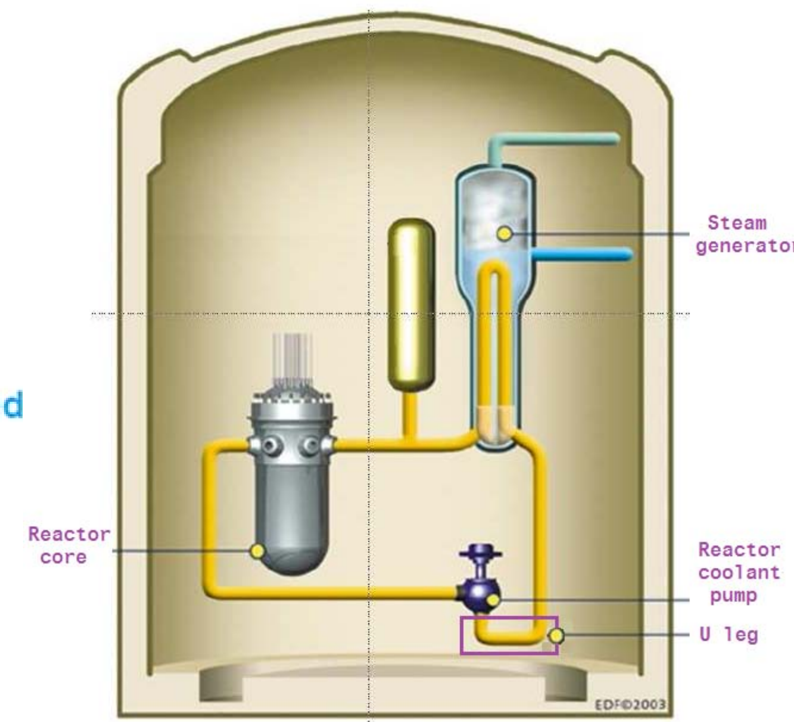
- Slug transport into the reactor core takes place because of restart of one *RCP*.

  ➔ ***non borated or diluted water in the reactor core.***

- Boron is used to control nuclear reaction:

  ➔ ***Reactivity accident***





Industrial context

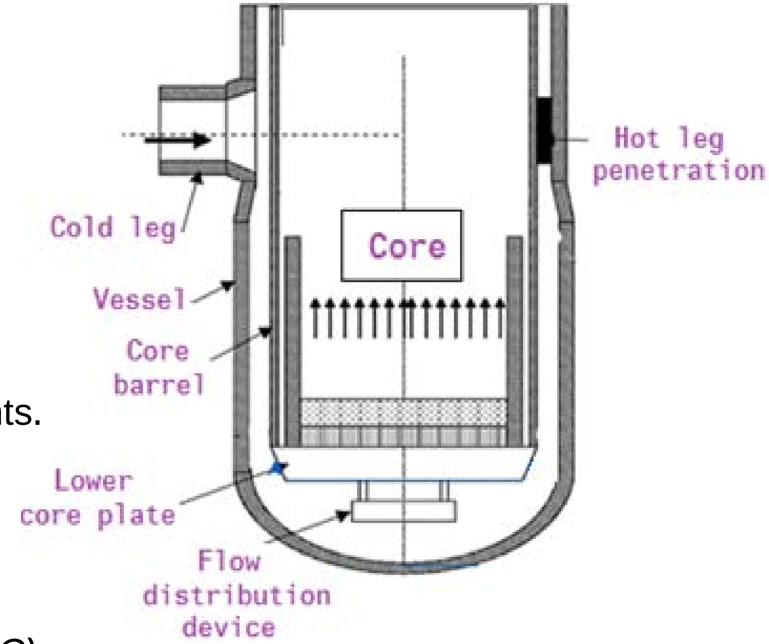
- **Uncoupling approach**
  - Neutronics calculations give the critical concentration Cb_c.
  - No criticality of the reactor core is assured if $Cb_{min} > Cb_c$.
  - Cb_{min} is evaluated with ***CFD calculations.***

- **Coupling approach**
  - Spatial distribution of boron concentration is evaluated with ***CFD calculations.***
  - Cb_{mean} at each fuel assembly are the inlet conditions for neutronics calculations.
  - No criticality of the reactor core is directly checked.

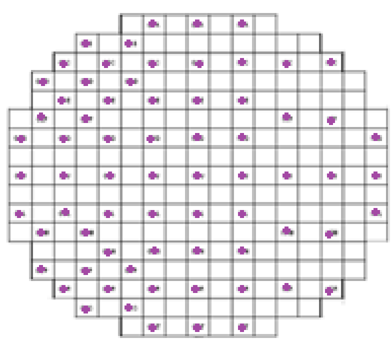
- **Integral validation of *Code_Saturne V3.0* is needed**
  - for external boron dilution transient,
  - regarding the minimum boron concentation at inlet core,
  - and the spatial distribution of the boron concentration at inlet core.

⇨ *JULIETTE* experiments

Experimental mock up

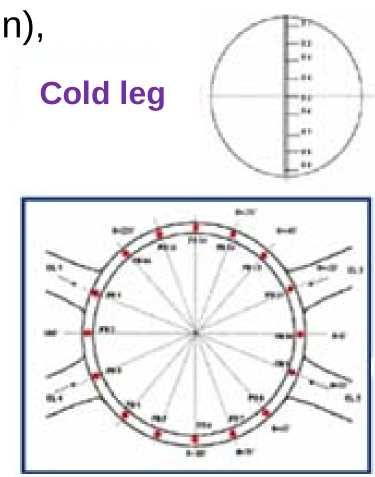


- *EPR* model at *1/5th* scale:
  - *4* cold legs with bends and vessel inlet nozzles.
  - Downcomer and all intruding structures (hot leg penetration).
  - Flow distribution device.
  - Lower core plate with *241* « diaphragm + venturi » equipements.
- Boron concentration change is modelled by a change in temperature:
  - The unborated water slug is simulated by hot water (T_{slug}=50°C).
  - The borated water is simulated by colder water (T_{core}= 20°C).
  - Salt is added to increase the density of hot water to that of core water ➔ ***fix buoyancy effects.***
- About 130 thermocouples measure temperature at:
  - the affected cold leg (concerned by the slug injection),
  - the downcomer,
  - the core inlet.

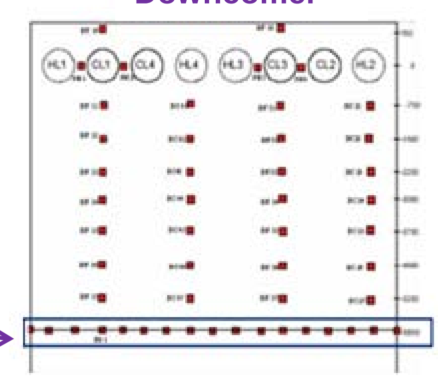


Inlet core

Cold leg

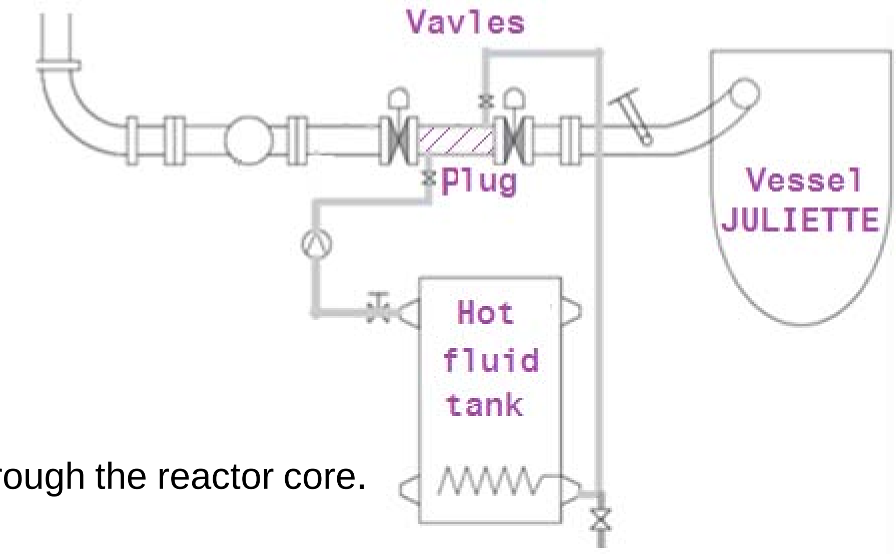


Downcomer



Test procedure

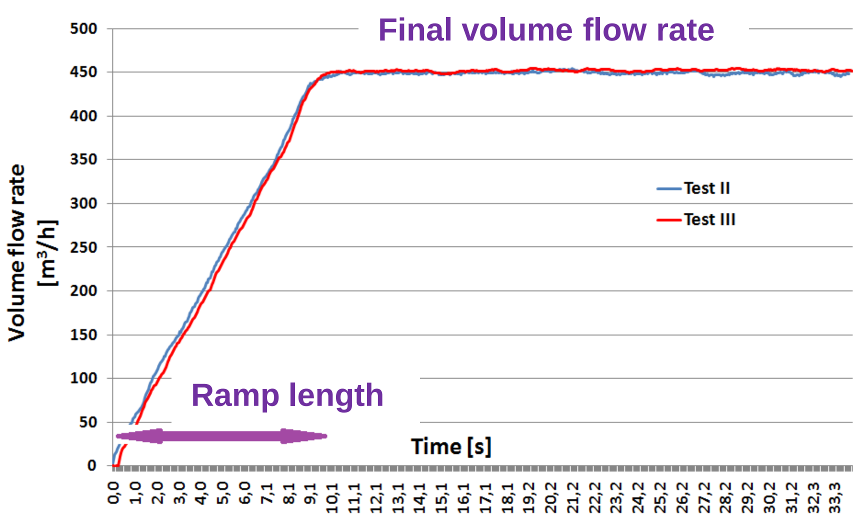
- The test procedure is as follows:
  - The slug is created between two closed valves,
  - The slug water is heated using the hot fluid tank,
  - The density is adjusted with salt addition,
  - The pump is started up with the opening valves,
  - In the same time, data acquisition system begins,
  - Data acquisition is stopped when the slug goes through the reactor core.

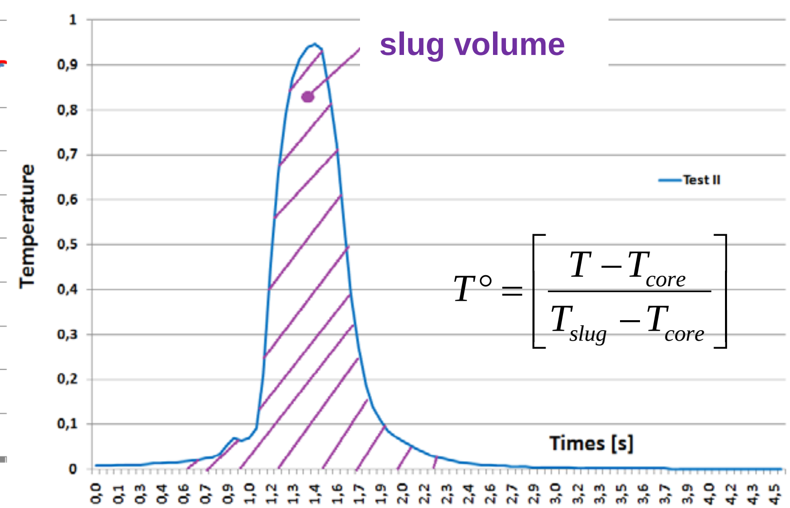


- Test matrix on slug mixing experiments:

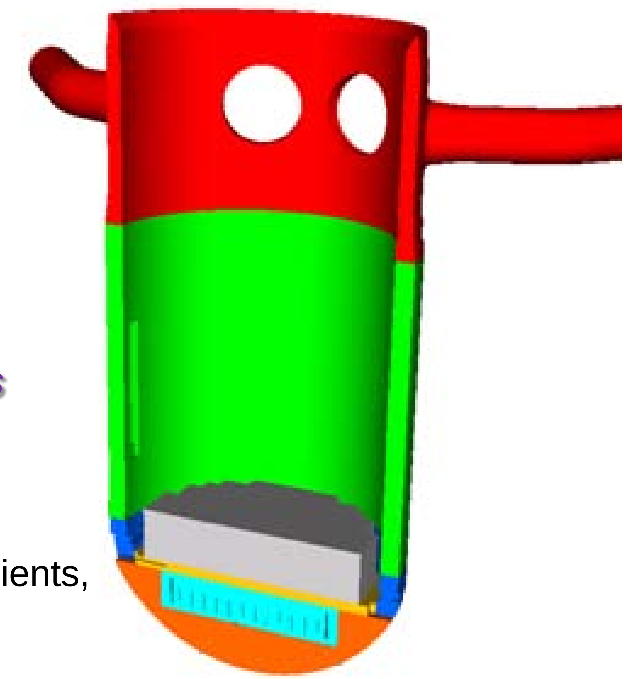
*** Related to the reactor scale**

Test	Ramp length [s]	Final volume flow rate [m³/h]	slug volume* [m³]	Status of unaffected loops
II	10	450	2	Closed
III	10	450	4	Closed





Overview of the *CFD* study



Transient calculation:

- Isothermal with constant physical properties,
- A passive scalar stands for the slug ➔ ***advection equation,***
- Turbulent model : *k-ε PL* with *SGDH* model for scalar.

Sensitivity studies

Mesh properties:

- 1,5 millions of hexahedral cells.
- Mesh is made with seven assembled blocks,
- Non conforming interfaces,
- Lower core plate is modelled as a porous volume with head loss coefficients,
- y^+ values involving the use of high Reynolds number turbulent models.

Boundary conditions:

- *Inlet face* – affected cold leg : Flat velocity and concentration profiles (experimental values). Turbulent values calculated with experimental velocity values.
- *Inlet face* – non affected cold leg : Volume flow rate equals to *0*.
- *Outlet face* – core outlet : free outlet condition.
- *Wall face* : smooth solid wall condition.

Numerical parameters

Indicator	Value	Notes
DTREF	1.5 10^{-3} s	Uniform and constant time step
IPHYDR	1	Take into account of the hydrostatic pressure
ISCHCV	1	Type of second-order convective scheme : centered with slope test for concentration and velocity (*ISSTPC = 0)*
	0	Upwind fo turbulent values

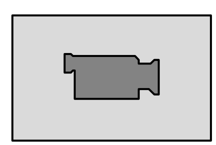
CFD results – Test II

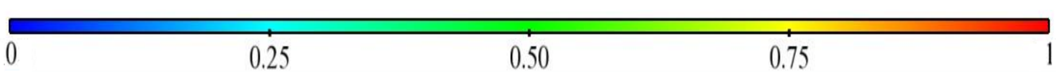
- General behavior of the slug (*1,7m³*)
  - Below plan formed by the cold leg, two principal pockets are formed in two principal directions at *45°* of the affected cold leg.
  - The flow drags the slug away to the bottom of the downcomer.
  - On the top of the cold leg plan, two secondary pockets are also formed and move to the bottom of the downcomer with a temporal shift compared to the two principal pockets.

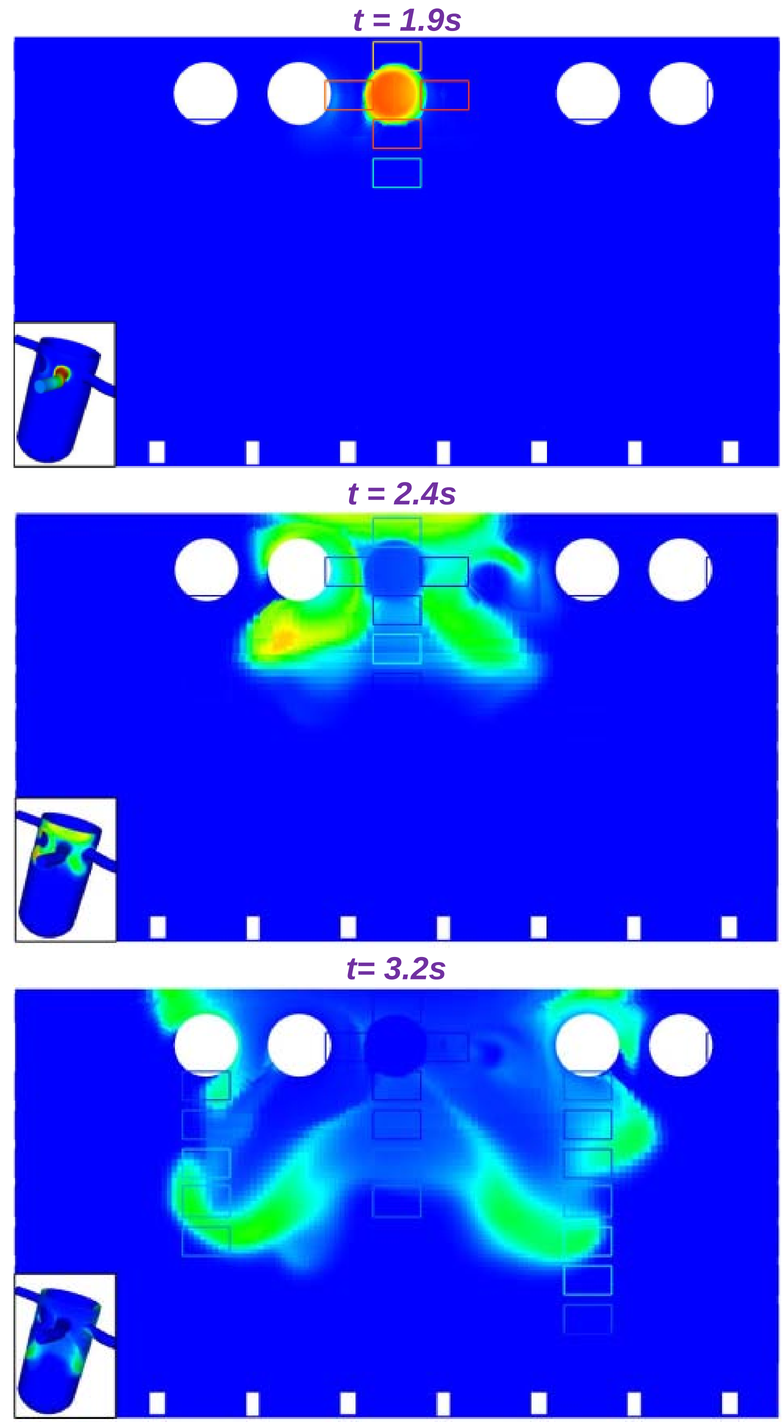
- Comparison calculation/measurement
  - Experimental fields of concentration are also represented on these visualizations.
  - Boxes show up with the values of concentration obtained in their centers.

The behavior of the slug in the downcomer is correctly reproduced by Code_Saturne.

$$[C] = 1 - \left[\frac{T - T_{core}}{T_{slug} - T_{core}} \right]$$





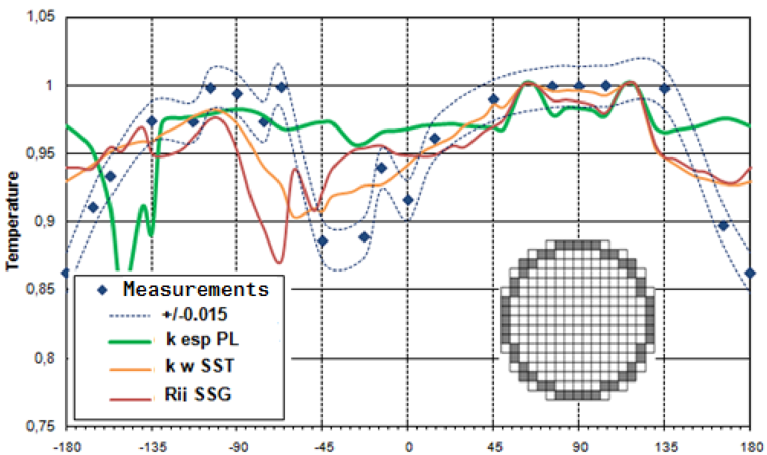


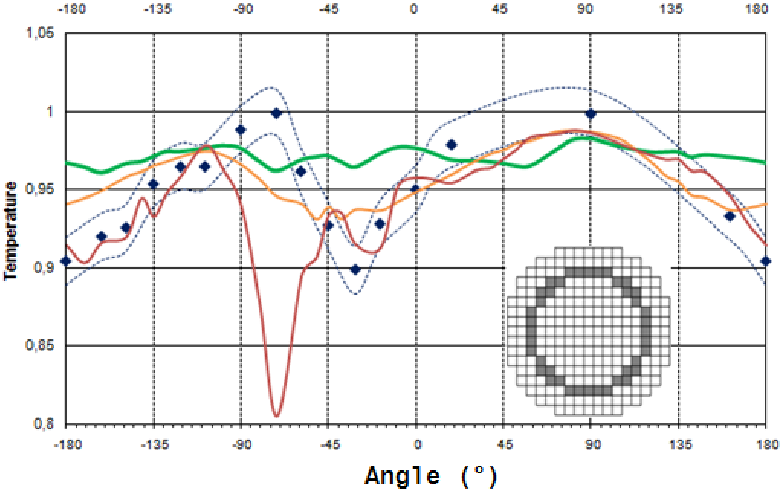
CFD results – Test II

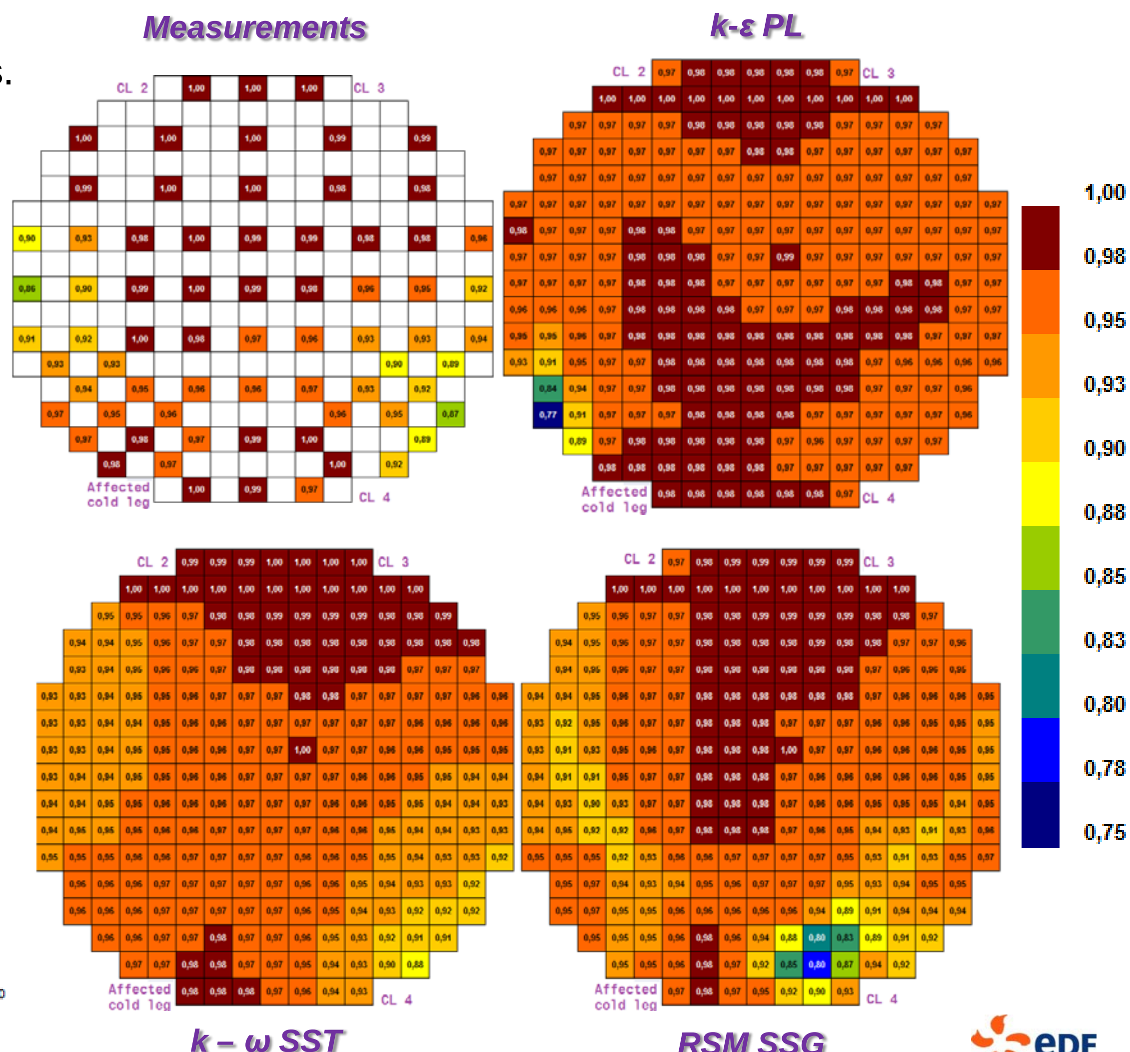
	Minimum of temperature	Times	Error
Experimental	*0.845 < 0.86 < 0.875*	*5.9s*	*/*
k – ε PL	*0.77*	*8.1s*	*9%*
k – ω SST	*0.88*	*7.2s*	*0.5%*
RSM SSG	*0.80*	*7.8s*	*5%*

Comparison at the core inlet

- Two zones of lower temperature:
  - ➔ division of the slug in the downcomer.
- Under estimation of the temperature (*k-ε PL*, *RSM SSG*):
  - ➔ Under estimation of the slug mixing.
- The *k-ω SST* model gives the best results.



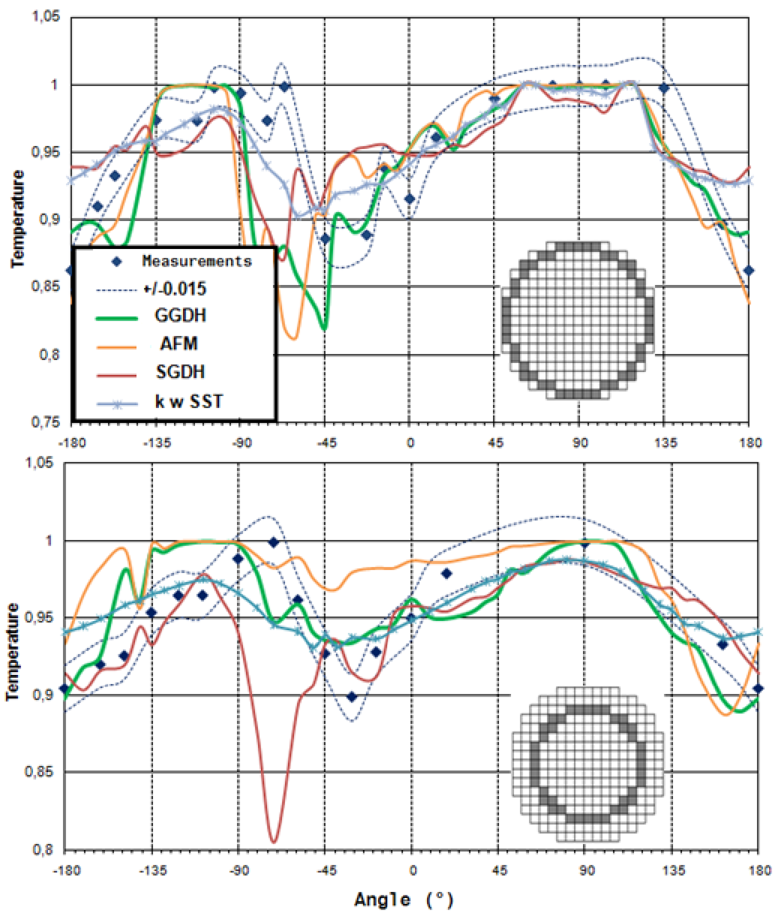


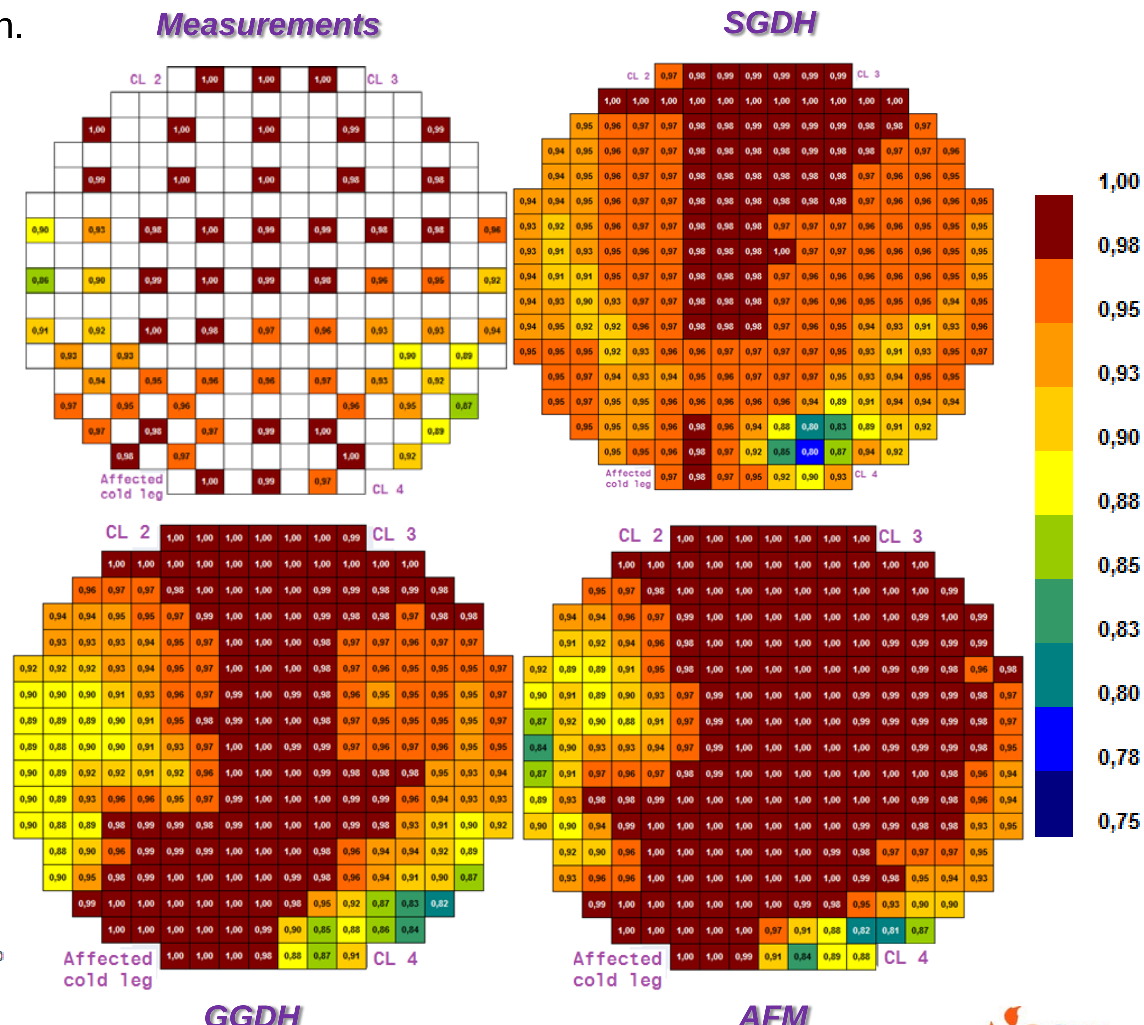


CFD results – Test II

- Comparison at the core inlet
  - *GGDH* and *AFM* models take into account the anisotropy of the turbulent diffusion coefficient of the scalar.
  - Improvement of the slug mixing prediction.

	Minimum of temperature	Times	Error
Experimental	*0.845 < 0.86 < 0.875*	*5.9s*	*/*
RSM SSG - SGDH	*0.80*	*7.8s*	*5%*
RSM SSG – GGDH	*0.82*	*7.1s*	*3%*
RSM SSG - AFM	*0.81*	*6.8s*	*4%*

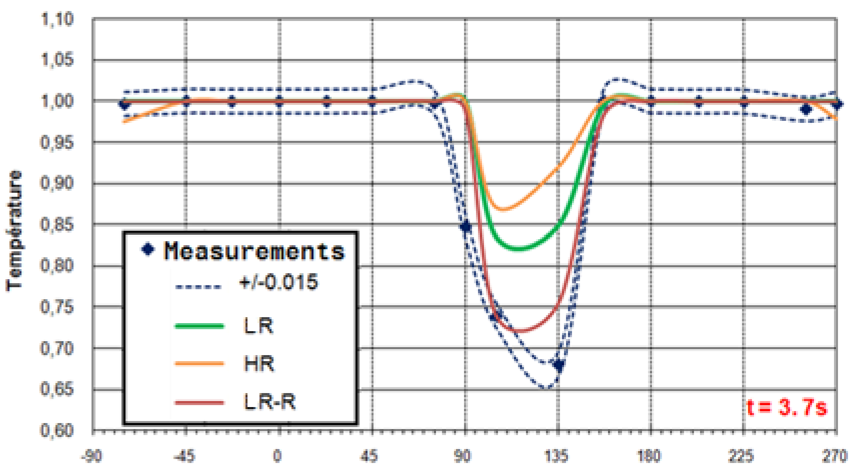




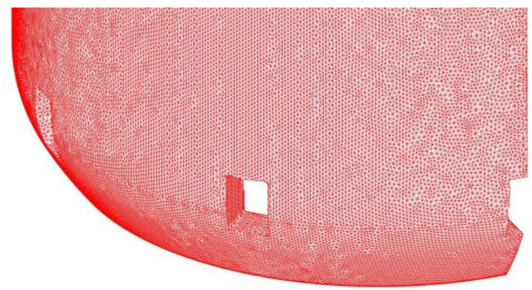
CFD results – Test II

- Sensitivity of meshing
  - Minimum temperature is correctly predicted for all meshes.
  - The temporal shift observed, at the appearance of the minimum temperature, is correlated with the grid used.

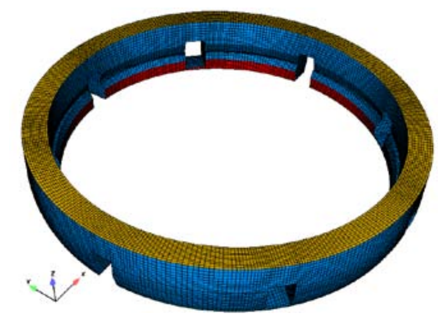
Grid	Cells number	Types	y+
HR	*1.5 M*	*Hexa*	*> 1*
LR	*10M*	*Tetra*	*< 1*
LR-R	*40M*	*Tetra*	*< 1*



LR-R



HR

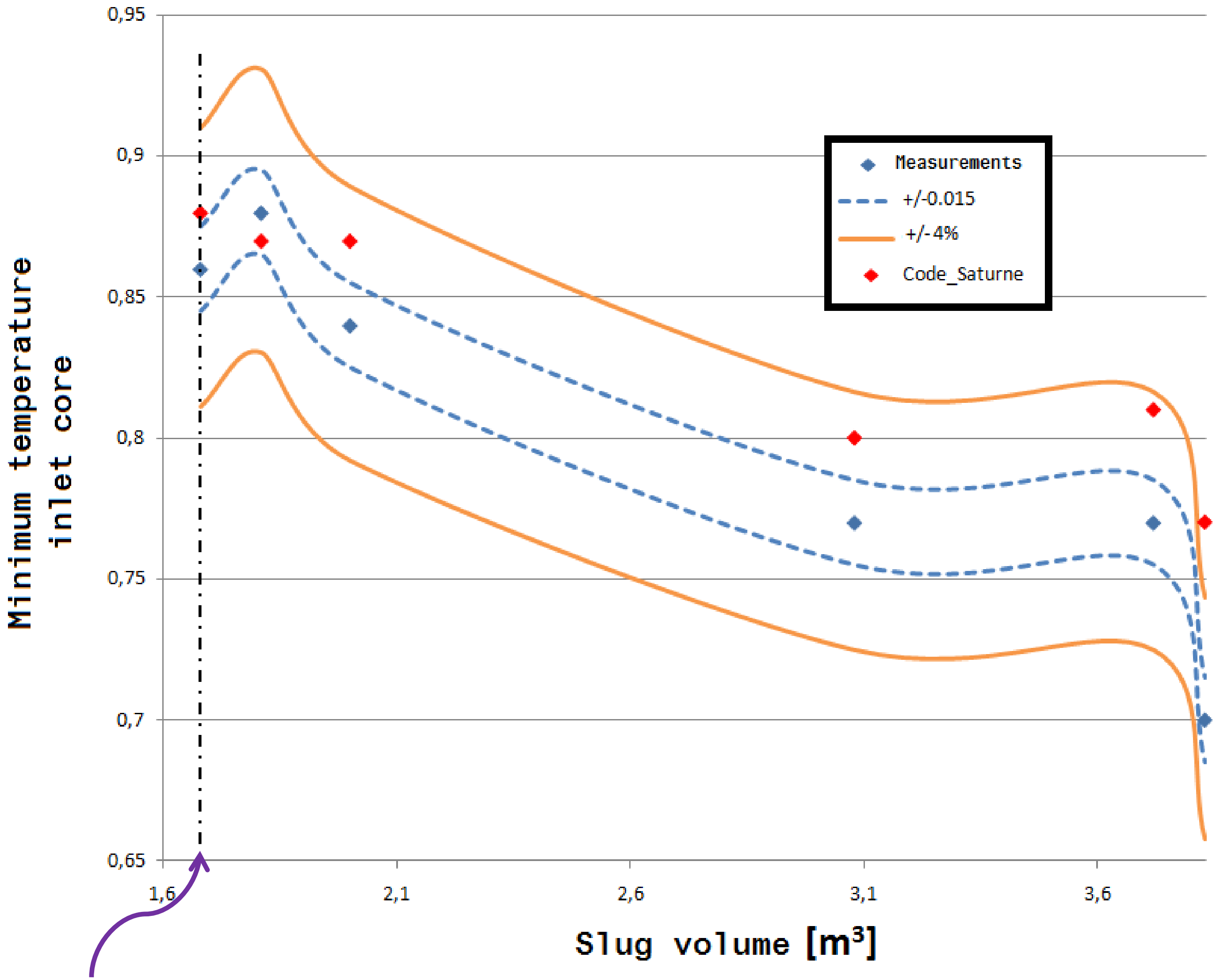


Test II - Inlet core	Minimum of temperature	Times	Error
Experimental	*0.845 < 0.86 < 0.875*	*5.9s*	*/*
HR	*0.88*	*7.2s*	*0.5%*
LR	*0.85*	*6s*	*0%*
LR-R	*0.87*	*5.85s*	*0%*

- Refined meshes give results close to experiments:
  - due to the refinement near the wall,
  - or due to the refinement in the volume domain,
  - or due to the use of tetrahedrics cells instead of hexahedrics cells.

CFD results

- Experimental sensitivity of slug volume ➔ data base for integral validation



Results of the presentation

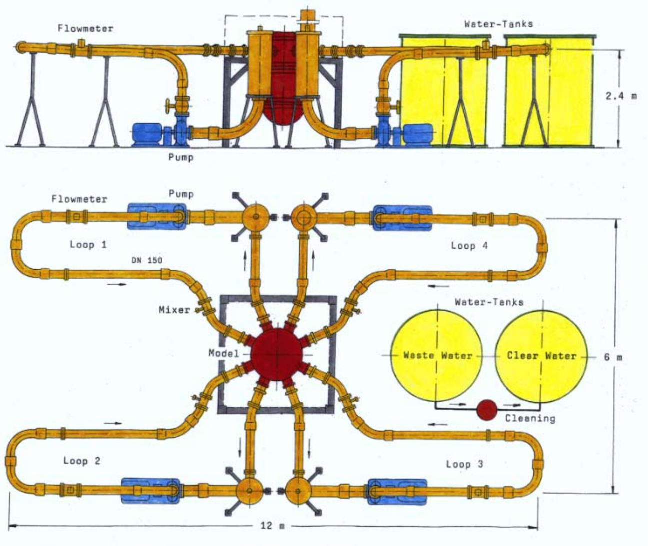
Conclusions and perspectives

Conclusions

- This study focuses on *Code_Saturne* validation on boron dilution transient.
- Comparisons calculations/measurements were made on the two interesting metrics at inlet core:
  → minimum temperature (minimum boron concentration),
  → spatial distribution of temperature.
- *Code_Saturne* gives results close to experiments for all slug volume tested.
- *k-ω SST* has better results compared to *RSM SSG* and *k-ε PL.*
- Advanced turbulent heat flux models improve the slug mixing prediction.
- The temporal shift observed, at the appearance of the minimum of temperature, is correlated with the grids used. However, high Reynolds mesh is sufficient to correctly simulate the minimum of temperature and its distribution in inlet core.

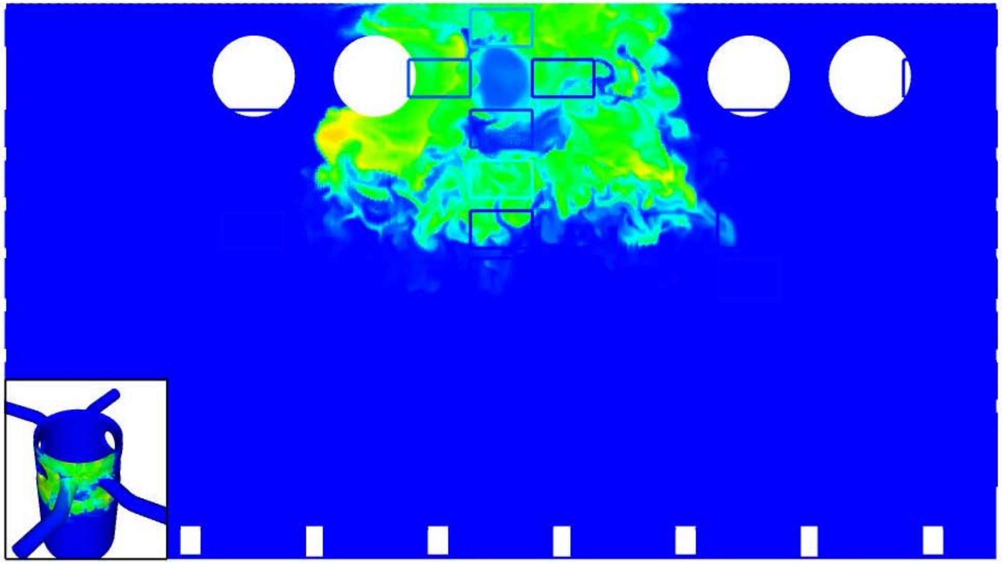
Perspectives

- Validation of *code_saturne* will be also carried out with *ROCOM* experiments (*1/5th* scale *KONVOI* model).
- Conclusions of validation could be applied to full reactor size.



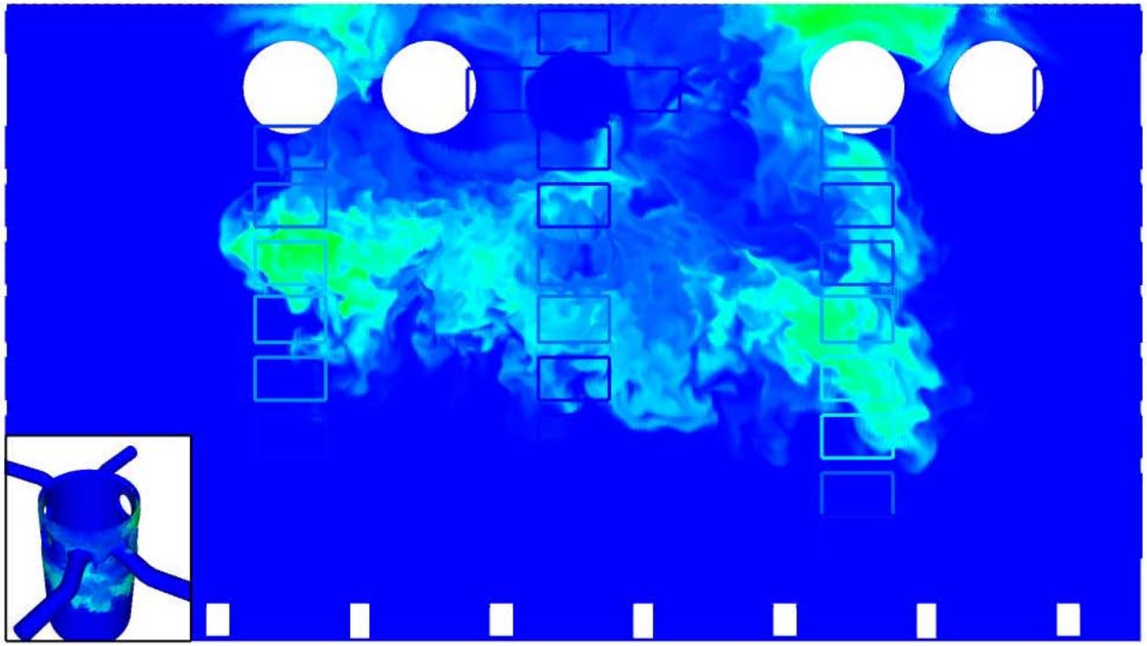
Thank you for your attention !

Temps = 2.4s

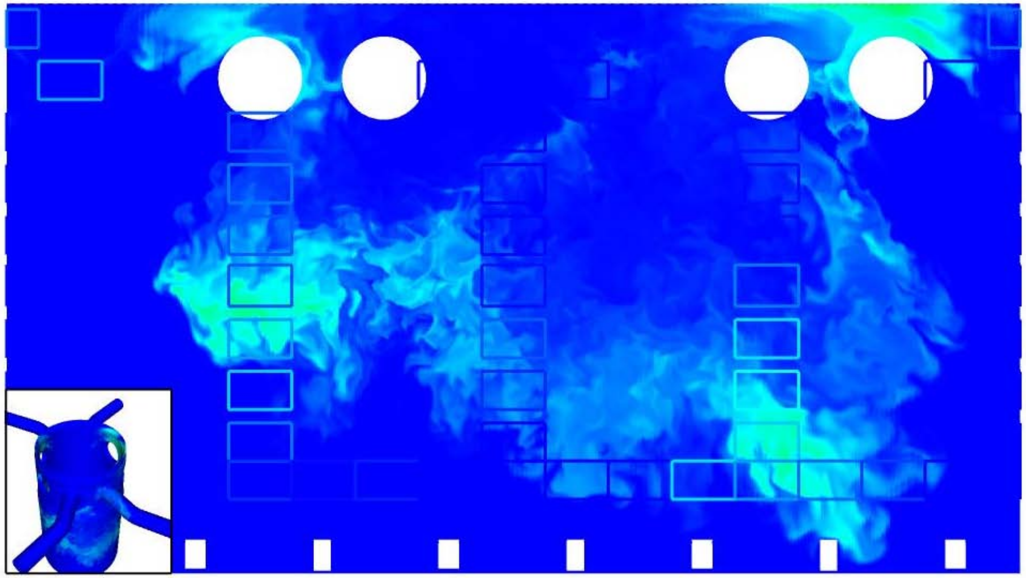


Large Eddy Scale

Temps = 3.2s



Temps = 3.9s



Large Eddy Scale

Temps = 4.5s