CFD of the upper plenum and its hot legs – How to deal with unsteadiness

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Industrial Context

• Uncertainty of the Temperature Measurement:
  - Heterogeneity generates uncertainty in the measurement

• Temperature measurements are useful for several task in the plant operation:
  - Protection systems based on core Inlet/Outlet Temperature differences
  - Control rod guide tubes insertion/extraction
  - Primary Flow measurement by enthalpy balance

• Primary Volume Flow $Q_P$:
  $$Q_P \propto \frac{(W_{th} - W_P)}{H_{HL} - H_{CL}}$$
  - $W_{th}$: Power extracted by the Steam generators
  - $W_P$: Power furnished by the pumps
  - $H_{HL}$: Hot Leg Enthalpy
  - $H_{CL}$: Cold Leg Enthalpy
Overview of the CFD study

Temperature heterogeneities:
• Appear in the reactor core due to the power distribution
• Transported through reactor by secondary structures
• Still present at the end of the hot leg

Objectives of the study:
• Get a better understanding of the physical phenomena leading to heterogeneities
• Reduce the uncertainty on the temperature measurement in the hot leg
• Validate CFD results by comparing with experimental results
Overview - Different cases of the study

• **Elementary case**
  – Try different configurations
  – Scalability tests (mock-up scale to full-scale)

• **Mock-up scale studies**
  – Reynolds $10^6$ in the hot legs
  – Comparison with experimental data
  – Validation of the CFD code

• **Reactor scale studies**
  – Reynolds $10^8$ in the hot legs
  – Reactor measurements available
  – Full scale validation
Overview - Computational cost

- **Mock-up scale calculations:**
  - $Y^+$ up to 1500 in the hot leg for a 35M cells mesh!
  - 2 months calculations

- **Reactor Scale calculations:**
  - First results on a 30M cells mesh yields values of $y^+$ up to 10 000
  - Necessity to refine the mesh to reach optimal values of $y^+$
  - Refined mesh may exceed 200M cells

- **Hardware**
  - Blue Gene Q 65000 Processors Cluster
  - Calculations done on 8000 Processors
CFD Results
Results – Secondary Structures

**Instantaneous** Tangential velocity in a hot leg section

- We could show using CFD that secondary structures can prevent the good mixing of the flow
- We could also show the influence of the control rod guide tubes on the secondary structures

**Average** Tangential velocity in a hot leg section

Average Temperature in a hot leg section
Results - Temperature Heterogeneity in the Hot Leg

- **Unsteady Results**
  Numerically and experimentally, we observe an unsteady behavior.

- **Temperature Heterogeneity**
  We thus consider the *time average* to characterize the heterogeneity.

![Graph showing velocity at 2 different points in the hot leg](chart)

- **Evolution of the Temperature map along the hot leg**

![Images of temperature maps](images)
Results - Time step dependence

• A Time step dependence is observed

• Criteria frequently used in Code_Saturne to choose the time step value:
  \[ \text{Maximum CFL} \approx 1 \]

\[ \text{CFL} = v(\vec{x}, t) \frac{\Delta t}{\Delta(\vec{x})} \]

• Investigation of the representativeness of the criteria to choose the time step
Which CFL criteria have to be used?

- **Distribution of the CFL over the mesh:**
  - Maximum CFL : 2.1
  - Space Averaged CFL : 0.066
  - Ratio Max/Average : 32

- **Disadvantage of the Mean CFL:**
  - Takes into account cells with lower influence on the physics

- **Possible criteria investigated:**
  - Average CFL over a Given part of the mesh
  - Discriminate cells of lower importance using a Criteria (example slower velocities)
Steady-State – Upper plenum case

• One objective of the Steady-State calculation is to reduce calculation time.

Time gain: from several months to a few weeks

• Usage of the Code_Saturne Steady-State Algorithm: (space and time dependent time step)
The results couldn’t be made steady

• Considering the very high number of cells involved in full scale calculations, it seems necessary to have a different Algorithm
Steady-State – New Algorithm

- **Basic Idea of the Algorithm:**
  Force current solution towards a target solution by adding a term in Navier-Stokes

  \[
  \frac{df}{dt} = A(f) \quad \Rightarrow \quad \frac{df}{dt} = A(f) + X(f - f_{\text{Target}})
  \]

- **Target solution** \( f_{\text{target}} \):
  The target solution is the filtered current solution

  \[
  f_{\text{target}} = \int_{0}^{t} T(\tau - t; \Delta) f(\tau) d\tau
  \]

  Exponential filter \( T(\tau - t; \Delta) = \frac{1}{\Delta} \exp\left(\frac{\tau - t}{\Delta}\right) \)

  Differential form of the Filtered solution filter:

  \[
  \dot{f}_{\text{target}} = \frac{1}{\Delta} (f - f_{\text{target}})
  \]
Steady-State – Cylinder in a flow

• Test of a different algorithm on the elementary case “Cylinder in a laminar flow”

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Reynolds Re= 100</td>
<td>Inlet : Uniform velocity</td>
</tr>
<tr>
<td>Free Outlet</td>
<td>No slipping conditions on cylinder wall</td>
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Velocity Vx – **Unsteady Calculation**

Velocity Vx – **Time Averaged**
Steady-State – Results

- **Steady Results:**
  - Saturne basic Steady-State Algo (IDTVAR = 2) (COUMAX = 1)
  - Saturne Steady-State (IDTVAR = -1)
  - New Algorithm

Velocity Vx

# Iterations

Time Averaged Unsteady Result:
Perspectives of the study

• Reactor Scale validation on the go
  - Involves Fine Meshes!

• Very long computation time expected

• Steady Calculation could avoid months of calculation time
Thank you for your attention!

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Results - Turbulence Models dependence
(Tests on elementary case)

- **K-ε** - (Isotropic modelisation of Reynolds Stresses and Turbulent thermal flux)
  - Instantaneous Tangential Velocity
  - Time Averaged Tangential Velocity

- **Rij** - (Anisotropic modelisation of Reynolds Stresses, Isotropic modelisation of Turbulent thermal flux (SGDH))
  - Instantaneous Tangential Velocity
  - Time Averaged Tangential Velocity