CATHARE-TRIO_U Coupled Calculation of the Phénix Reactor Natural Circulation Test

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Outline

- Phenix Reactor
- Natural Convection Test
- Coupling Methodology
- No Mixing Model
- Calculation
- Sensivity Analysis
- Iso Thermal Calculation
- Refined Model
- Conclusions and Perspectives
**Phenix Reactor**

- **PHENIX = French SFR** *(1973-2009)*
- **Prototype + research**
  - 560 MWth then 350 MWth since 1993
- **Suspended reactor block – Pool type**
  - main vessel 11.8 m in diameter
  - ~ 800 tons of primary sodium
  - vessel cooling system
- **Hexagonal fuel assemblies in core**
  - 4.3 m in height - 217 pins each
  - inner-core, outer-core, annular fertile zone, steel reflectors and lateral neutron shielding rods
- **2 pairs of IHX** *(since 1993)*
- **3 primary pumps**
Natural Convection Test

Initial State:
Decrease from 350 to 120 MWth
3 Pumps
2 Secondary Loops
Natural Convection Test

SG feedwater system is switched off
Hot shock at primary IHX
Hot shock at core inlet
Decrease of core power

Time line

t - t₀

Secondary Temperature
Natural Convection Test

SG feedwater system is switched off
Hot shock at primary IHX
Hot shock at core inlet
Decrease of core power

Unprotected Forced Circulation
Natural Convection Test

Time line

\[ t - t_0 = t_0 + 458 \]

Reactor Scram
+ Secondary Pump Trip
+ Primary Pump Trip

Thermal loss
\(~ 1 \text{ MWth}\)

Cold shock followed by hot shock in Hot pool

Natural Circulation
Natural Convection Test

Time line

Opening of SG casing
Thermal loss
> 3 MWth

Decrease of primary average temperature

Protected Natural Circulation

End of test = t2 + 13 560s

Hot Pool

Core

Cold Pool

IHX

\[ t - t_0 = t_1 + 9\,982\,s \]

\[ t_1 = t_0 + 9\,982\,s \]

\[ t_2 = t_1 + 9\,982\,s \]

\[ t_2 + 13\,560\,s \]
Coupling

- **System codes**
  - Represent the whole reactor or facility
  - Low resource consumption
  - Coarse representation
  - Not well suited for big 3D volumes

- **CFD codes**
  - Fine mesh of a local volume
  - Fine phenomena can be represented: mixing, stratification, turbulence,...
  - High resource consumption
  - Not suited for large scale systems

- **System-CFD coupling**
  - Uses CFD fine description where necessary, with feedback to the system.
  - Computes the rest of the loop with system code, giving smart boundary conditions to CFD.
  - Optimizes the use of computer resources by concentrating them where 3D phenomena are important
Computer Architecture

- Computer architecture based on a common API called IcoCo:
  - Flexible solution
  - Algorithm outside the codes: easy to read, modify, reuse
  - Interpolation and data manipulation outside the codes

- ICoCo “Interface for Code Coupling”
  - Defines a C++ mother class with standardized methods
  - For the codes: specifies WHAT the methods should do
  - For the supervisor: specifies WHEN the methods can be called

- Methods define
  - Time-marching (including iterations)
  - Field exchange
  - Save / restore
  - Compatible with parallel computing, and parallel interpolation
Numerical Considerations

Boundary conditions for CFD
- Mass flow-rate imposed at every boundary
- Enthalpies imposed at every boundary

Domain decomposition
- System code does not calculate CFD part

Overlapping
- System code includes CFD part

Same system data deck
- Easy & progressive approach
- Flexible
- Numerical stability
Coupling Methodology

Feedbacks on system code

**Energy Feedback**
System energy equation is replaced at each boundary point by the CFD feedback value.

\[ P_0 - P_{\text{boundary}}^{\text{system}} = P_0 - P_{\text{boundary}}^{\text{CFD}} \]

**Momentum Feedback**
Needed to correct the system head loss (or gain) through the CFD domain

Reconstruction of free levels (density variations)
Non compressible flow with Boussinesq approximation
Coupling Methodology

Validation on simple analytical test cases and on Cathare-Cathare transients (NCT)

One Cathare module plays the CFD role
No Mixing Model

Where should CFD be used?
- Where local phenomena occur
- Where system code's behaviour is highly sensible to the model

No Mixing Model

1D non-compressible thermalhydraulic problem with free surface but no flow mixing

Inlets/Outlets at fixed elevations
- Temperature
- Density
- Mass Flowrate

Maximum layer number can be fixed
No Mixing Model

Example on Astrid Reactor

Core

Hot Collector

IHX

Low Heat removal

Hot stream
Low Flow rate

Core Outlet Temperature

Temperature (°C)

Time (s)

Coupled Model
Regular Transient
Piston Model
Calculation

System part:
- Primary circuit
- Secondary loop = input data

CFD part:
- Upper Core Structure (solid)
  - 50 000 mesh
- Hot collector (fluid)
  - 350 000 mesh
- Cold Collector (fluid)
  - 880 000 mesh

CFD SCALE:
- CFD domain for cold pool (fluid)
- CFD domain for hot pool (fluid)
- CFD domain for the upper core structure (solid)
Calculation Porting

Calculation ported to new versions of codes:
   Cathare v25_3 mod 2.1
   Trio_U v1.6.6

And ported onto new cluster
   ERIS (CEA)

More processors were added:
   Total of 50 procs instead of 20

Good agreement = Robust models and codes

Calculation time reduced
   3 days instead of 8 days
Calculation

THINS February 2013 - Stockholm

See movie

Good agreements between Numerical and Experimental results
Calculation

Na TEMPERATURE - IHX OUTLET WINDOW
bottom of IHX outlet window at -4200; EIM TC-pole near IHXA

Streamline during Phase2 of NCT

Streamline during Phase1 of NCT

EIM-4200: TC for measuring the IHX primary outlet temperature

TIME (s)

4800.0 5000.0 5200.0 5400.0 5600.0 5800.0 6000.0

CFDxSys (EIM-4200)
Exp (EIM-4200)
Sys (IHXA_outlet)
Sys (IHXB_outlet)
Sys (IHXC_outlet)
Calculation

Horizontal top view of the hot collector

Inner and outer core

COLTEMP TC-pole

ML03 TC-pole

Collecteur deau

Thermocouples

UCS

Upper core structure

Core outlet TC

core
Calculation

Na TEMPERATURE - CORE OUTLET
transient starts at t_0 = 5000 s; average value for inner core

CFDxSys (meth1)
CFDxSys (meth2)
Exp
Sys
Sensitivity analysis

Methodology

CFD Collector

System code

Feedbacks

Mass Flowrate
Temperature

CFD Collector
(Variable Hypothesis)

Boundary conditions:
Mass Flowrate
Temperature

Reference Coupled calculation

Sensitivity Analysis

Good agreement with reference
Fast computation
Sensitivity Analysis

Turbulence Model
Smagorinsky sub-grid model
Cs = 0.1 to 2.5

No Impact on results
Low Re number
Diffusive scheme
Sensitivity Analysis

Mesh refinement
Isotropic and uniform x8

350,000 meshes

2,800,000 meshes
4 weeks calculation
Sensivity Analysis

Sodium stream is the same
More mesh = less diffusive
No effect on macroscopic values
Sensitivity Analysis

Upper Core Structure
Solid in model
Fluid with obstructed areas in reality (control rods, grids, instrumentation...)

Internal Flow => Thermal Diffusivity
Modeled with equivalent conductivity
Because of Boyancy effect, conduction may be underestimated
Lambda x10
Iso Thermal Calculation

Full Coupled Calculation
Scram Reactor
Isothermal secondary loop
Primary pump stop

Objective:
Lead to an Iso Thermal state with pump tripped
Control primary flow rate
No parasite momentum source
Iso Thermal Calculation

Cathare:
  Flow rate ~ 0.004 kg/s and tends to 0
Coupled calculation:
  Flow rate ~ 0.017kg/s and stabilizes

Bias effect / Parasite momentum effect?
  Neutronic activation of structure => generate power
  Density differences between CFD and System

Flow rate are much lower than natural convection
  0.017kg/s VS 30kg/s

No parasite momentum effect
Calculation

Object of concern

**IHX MASS FLOW-RATE**
Experimental evolution obtained from a thermal balance method applied on IHX

![Graph showing mass flow-rate vs time](image)
Into Refined Model

Uncertainties:
- Secondary boundary conditions => calculation with shifted time values has been done
- Steel Reflector and Diagrid Leaks

IHX inlet flow rate and core outlet flow rate don't have the same variation scheme
- Re circulation in core?
- We know that our inner wrapper are not fully modeled (1D VS 3D)
Refined Model

Observed discrepancies may be due to heat exchanges between the steel reflector zone and the cold collector.
Refined Model

Add Dead Zone in CFD Hot Collector
Rework Cathare Modelisation
Add heat exchange with Cold Collector
Refined Model

IHX MASS FLOW-RATE
Experimental evolution obtained from a thermal balance method applied on IHX

Without Leaks
No significant improvement
Refined Model

IHX MASS FLOW-RATE
Experimental evolution obtained from a thermal balance method applied on IHX

5kg/s

10kg/s

15kg/s

50kg/s

Leak of Lower Plenum
No experimental data
Refined Model

Calculations are not mature enough to be reliable
The steel reflector has not been modeled
Intermediate simulation
Leak sensitivity analysis show us some clues

Still work and reflection to do
  How to model the steel reflector?
  How to model inner wrapper flow?
Conclusion

• Phénix NCT:
  • Very rich test from the Thermal-hydraulic point of view
  • Forced $\leftrightarrow$ natural circulation transitions in both collectors
  • Mixing $\leftrightarrow$ thermally stratified transitions in both collectors
  • Complexity due to the reactor environment: uncertainties on boundary conditions, lack of sensors …

• Coupled Calculations:
  • Coupling methodology has been verified
  • The results of the coupled calculation have been extensively post-processed and verified
  • The validation of the coupled model against available experimental data shows a reasonable agreement $\rightarrow$ the model has reached a good level of maturity.
  • Developments are foreseen to further improve the model (will be continued beyond THINS project)
  • Use the results to help the validation of the system alone calculation

Still work to do for prediction calculations
Perspective

- Comparaison with KIT coupled calculations
- **Steel reflector** + **Core** : reflexion on new 3D model
  - TRIO MC2 model ?
- Best Practice Guideline
- For methodology validation :
  - Phenix Dissymmetric Test

THANK YOU FOR YOUR ATTENTION