KIT Neutronic Computational Tools for SMR-Core Analysis

Content

- Background

- Challenges
  - Neutronics
  - Thermal hydraulics

- KIT approach

- Outlook
Background [1]

- Increase interest on SMR
  - Water cooled
  - Gas-cooled
  - Liquid-metal cooled
  - Etc.

- Multiple-use
  - Electricity, heat
  - Water desalination
  - Hydrogen production

- Attractiveness:
  - Module factory fabrication
  - Pursuing economies of series production and
  - Short construction times

SMR will be built only if economically competitive and safe.
Water Cooled SMR-Cores: Different designs \[1,2\]
Common Features of Water-cooled SMRs [1]

- Compactness
- Small size (H and D)
- Heterogeneity (radial, axial)
- High leakage
- Harder spectrum
- Complex control rod designs
  - Different types
  - Axial heterogeneity
- Increased role of reflector

- Boron free cores:
  - Need innovative control rod design
  - Optimized shutdown reactivity
  - Reduced reactivity swing over the cycle
  - Etc.

➔ Innovations needed to improve economics and keep high safety
KSMR Design: Example [3,4,5]
Highly heterogeneous /complex control rods

Core Configuration

With 20 BPRs (1,2,3)
With 24 BPRs (4,5,6)
Challenges
Neutronics: Core Design Challenges [30]

- Typical SMR core size is 37 – 89 FAs
  - NuScale: 37 FAs, SMART: 57 FAs,
  - CAREM-25: 61 FAs
  - mPower: 69 FAs
- Core height is almost half of large LWR

- Increased neutron leakage
- Less degree of freedom
  - Lower fuel utilization

Ref [30]
Safety-related Thermal Hydraulics [1] :

- Experimental data exist but proprietary (SMR developers)

- Public SMR-specific data for research community needed e.g.
  - Cross flow in the core
  - Helical HX
  - Transition from
    - Forced to natural convection
    - Natural to forced convection
  - Safety parameters like
    - CHF
  - 3D flow inside the RPV
  - Effectiveness of PRHRS
  - Stability of natural convection flow

- Data need for code validation

McSAFER Solution Approach:

- COSMOS-H experimental program:
  - Fundamental HT, boiling, CHF

- HWAT experimental program:
  - System behavior under natural circulation
  - Transition to forced convection
  - Transition to natural convection

- MOTEL experimental program:
  - Helical HX heat transfer, pressure drop
  - Cross flow in the core
KIT Approach for SMR Core Analysis: Multiphysics
KIT Approach: Multiphysics

- **Industry-like approach: Nodal diffusion / 1D system TH**
  - PARCS / TRACE or PARCS / RELAP5 [6]

- **Improved core thermal hydraulics:**
  - Subchannel codes: Subchanflow (in-house) [7,8]
  - Porous-media 3D TH: Twoporflow (in-house) [9]

- **Improved neutronics:**
  - Simplified transport solvers at pin level:
    - PARCS-SP3
  - Monte Carlo codes:
    - Static simulations: Serpent2 [10]/Subchanflow/ICoCo [11]
    - Dynamic simulations: internal coupled Serpent2/Subchanflow [13,14,15]
  - Deterministic transport solvers e.g. PARAFISH (in-house) [12]
KIT Core Analysis Tools: Internal Coupling

- **Reactor Physics**
  - Serpent XS
  - GenPMAKS [17,18]

- **Thermal-Hydraulics**
  - TRACE
  - PARCS nodal diffusion
  - RELAP5

No direct prediction of **local** safety parameters

- Core design and core optimization tools:
  - Reactor Physics
    - Lattice Physics
    - Core Simulator
    - SERPENT
    - PARCS
    - GenPMAKS
  - Thermal-Hydraulics
    - Core TH Subchannel Analysis
    - SUBCHANFLOW

- 3D core reference solutions:
  - Core Analysis
    - SERPENT
  - Core TH Subchannel Analysis
    - SUBCHANFLOW
  - Visualization Tool

[Image of a diagram showing the internal coupling between PARCS/SCF and SERPENT2/SCF, including the tools and their interactions.]
KSMR:
rel. radial pin Power Distribution at HFP [3,4,5]

- Hottest pin in the core
- Control Rods Critical Configuration at HFP Condition

CSDM with single failure = -3,000 pcm
FTC = -2.0 pcm/K
MTC = -76.0 pcm/K

REA: MDNBR

Min. MDNBR = 1.34
At t = 0.25 sec.

W-3 Safety Limit = 1.3
ICoCo-based Coupling of PARCS/ Subchanflow (2021) [18]

Ref. [18]
KSMR REA: ICoCo PARCS/SCF Analysis [20]

KSMR Rod Ejection Accident with Pin Power Reconstruction at power peak

Ref. [20]
PARCS/SCF/ICoCo: Analysis of CAREM: Overcooling Transient [20]

- Coolant temperature decrease
- Mass flow rate change
- Outlet pressure evolution
- Normalized Power [a.u.]
- CAREM Overcooling transient: Key-parameters
ICoCo-based coupling of PARCS/Twoporflow (2022)

- External coupling.
- Serial execution.
- Domain overlapping.
- Fields mapping via MEDCoupling library.
- Explicit iterative scheme.
- Node-wise feedback.

Ref. [9]
KSMR: REA Analysis at HZP

- Half highest CR worth extraction (0.725 $) at the hot zero power (HZP) condition.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial core power</td>
<td>1.0E-4 %</td>
</tr>
<tr>
<td>Highest CR worth</td>
<td>1.45 $</td>
</tr>
<tr>
<td>Ejection duration</td>
<td>0.05 s</td>
</tr>
<tr>
<td>End of transient simulation</td>
<td>1.0 s</td>
</tr>
</tbody>
</table>

Ref. [9]
SMART REA Analysis: PARCS/SCF vs. PARCS/TFP

PARCS Total Core Power

Parcs Total Reactivity

Ref. [9]
High Fidelity MC-based Multiphysics: SSS2-SCF

Internal coupling of SSS2-SCF:
- MCSAFE [16] pin-by-pin TH coupling
- Inherits all SSS2 and SCF capabilities
  - Including transients (dynamic)
- Multiphysics with IFCs superimposed TH fields
- Internal mapping
- Same preprocessor as PARCS-SCF

Ref. [20, 13,14,23,24]
KSMR: Comparison of PARCS/SCF and SSS2/SCF Solutions [22]

SSS2: axially integrated FA normalized radial power for HFP ARO

PARCS-SSS2: axially integrated FA normalized radial power relative difference for HFP ARO

SSS2: axially integrated pin normalized radial power for HFP ARO

PARCS-SSS2: axially integrated pin normalized radial power relative difference for HFP ARO. Values are truncated in the interval [-10; 10] %

Ref. [20]
Outlook
Next steps:
Simplified transport solver PARCS-SP3 pin-by-pin (1/2)

Motivation: Pin-wise Simulation, XS Optimization, TH Feedback

PARCS V331 has two methods for pin-wise results:

- Nodal + Pin power reconstruction
- FMFD (Fine Mesh Finite Difference)

<table>
<thead>
<tr>
<th>Advantage:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast running.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Limitation:</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Pin-wise TH coupling.</td>
</tr>
<tr>
<td>No Pin-wise XS optimization.</td>
</tr>
</tbody>
</table>

In KIT, we would like to do:
- Pin-by-pin simulation in core-scale with "ASSY_TYPE".
- Enable pin-wise XS optimization and TH feedback.

PARCS V331 can not do this
Function extension is required

Referenced: [22]
Next steps:
Simplified transport solver PARCS-SP3 pin-by-pin (2/2)
- First Results: KSMR core steady state

Axial power distribution

Radial power distribution

Spatial power distribution

Ref. [22]
Next steps:
Simplified transport solver PARCS-SP3 pin-by-pin (2/2)

Pin /subchannel coupling based on same ICoCo-Interface FA-based Coupling
Next steps: High fidelity Transport Solver

- PARAFISH code development
  - Finite element spherical harmonic neutron transport solver
  - Written in C++
  - Domain decomposition

- At present: steady state solver

- Next steps:
  - Time-dependent solver
  - Coupling with TH e.g. SCF
  - Pin-by-pin analysis of SMR-core transients
  - Code-to-code comparisons
    - E.g. SSS2/SCF

Ref. [12]

Small PWR: LWR based on the Kyoto University Critical Assembly (KUCA)
References

11. The ICoCo API, https://docs.salome-platform.org/7/dev/MEDCoupling/icoco.html
22. K. Zhang, L. Mercatali, J. Blanco, V. Sanchez-Espinoza; Optimized Cross-Section (XS) Group Generation for PARCS from SERPENT Statics based on the SuPer-Homogenisation (SHP) Technique. D3.5 McSAFER H2020 Project. 2021