Multi-Scale Coupling of TRACE and SUBCHANFLOW based on ECI for the Analysis of 3D Phenomena inside the PWR RPV

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Presentation Outline

• Backgrounds
• Objective of the Coupling
• Introduction of ECI
• Implementation of the Coupling
• Code Verification
• Summary
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**Backgrounds**

*Note:* Simulation tools play essential roles in Nuclear Insucrty and Research on improving the system economy and safety and consistent efforts have been made on development and validation of these tools.

We want to simulate the dynamic of the whole system in order to study the whole system's behaviour under normal, accident and some special conditions.

- Could better simulate the lateral flow between assemblies and fuel rods.
- Fine description of phenomenon occuring in the core.

**Modeling of the Nuclear Power Plant by a System Code**

- The basic requirement of the system codes is speed so that it could simulate the whole system dynamic on a large time scale.
- In order to achieve high speed, system codes usually apply coarse mesh.

- Resolution of the physical field distribution is poor.
- e.g: Important 3D phenomenons in the core: lateral flow between assemblies and fuel rods are missing.

For some cases, we want to study specially on the reactor core and study the physical phenomenon in detail.
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Objective of the Coupling

**Goal:** Coupling of **TRACE** and **Subchanflow (SCF)** based on **Exterior Communication Interface (ECI)**

- **What is TRACE?** – System codes/System scale
  - Full name: TRAC/RELAP Advanced Computational Engine which is formerly called TRAC-M.
  - Developed by US NRC for simulating the whole system of light water reactors.
  - Combines the capabilities of NRC four main system codes: TRAC-P, TRAC-B, RELAP5 and RAMONA.

- **What is Subchanflow (SCF)?** – Subchannel codes/Component scale
  - SCF is a thermal hydraulic sub-channel code developed for the simulation of fuel rod bundles.
  - Developed by KIT-INR for light water and innovative reactor systems.
  - Based on the COBRA-family.

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**TRACE**

- 1D or 3D coarse mesh TH.
- Could **catch** the **dynamics** of the whole system.
- Simulation of the **3D phenomenon** in the **vessel** and **core** is **poor**.

**Motivation**

We want to enhance the 3D phenomenon simulation capability of system code.

**SUBCHANFLOW**

- Mesh on component scale.
- **Isolated** from the system **dynamics**.
- Simulation of the **3D phenomenon** in the core area is **good**.

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The tool implementing the coupling

- Key concepts need further illustration
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Introduction of ECI

Exterior Communications Interface (ECI)
Developed by US NRC, inherently for TRACE

- Designed for Codes Coupling by generating a multi-task system.
- Could run on distributed computer systems and run in parallel way.
- Closely related to the coupled codes' data structures and each coupled code should has its own specially designed ECI.

TRACE 1
**task 1**

TRACE 2
**task 2**

**task 3**
Other code1

**task 4**
Other code2

Severless, all the tasks can communicate directly with each other.

Process #1
ECI
socket

Process #2
ECI
socket

ECI use socket for data transfer.

Open MPI
socket

MPICH
socket

The low level of OpenMPI, MPICH is also the socket.

ECI doesn't use MPI tools, it directly handle the socket.

Code subroutines

ECI subroutines

ECI is not an uniform module for all codes.
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Implementation of the Coupling

**Question 1:** Since SCF is in charge of the core area, whether TRACE will still simulate the core or just ignore it?

**Two options:**
- TRACE simulates the core area – **Overlapping** coupling – feedback from SCF is treated as additional source to TRACE.
- TRACE doesn’t simulate the core area – **Non-Overlapping** coupling – feedback from SCF is treated as direct boundary conditions to TRACE.

For most cases, the Non-Overlapping shows good robust and the feedback can be introduced to the domains directly through boundary conditions without any further calculation. So the Non-Overlapping coupling was selected.

**Question 2:** Since the two codes’ mesh differs from each other at the interface, how to manage the data transfer?

A subroutine was developed to manage the data mapping (overlapping area weighted).
Implementation of the Coupling

**Spatial Coupling** – Non-overlapping domains and Area factor weighted

Suppose there is a case:
- The VESSEL in TRACE has *four azimuthal sections, two radial sections*. The system has four hot legs and four cold legs.
- The SCF model has *nine centrosymmetric channels*.

The new FILL and BREAK can be arranged flexibly and the system will recognize them as interfaces automatically.
Implementation of the Coupling

**Numerical Coupling** – Inter-timestep coupling and Parallel computing

Process 1: TRACE
Process 2: SCF

Steady State(SS) and Transient

<table>
<thead>
<tr>
<th>Curve 1</th>
<th>Curve 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>Value</td>
</tr>
<tr>
<td>①</td>
<td>①</td>
</tr>
<tr>
<td>②</td>
<td>②</td>
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<td>③</td>
<td>③</td>
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<tr>
<td>④</td>
<td>④</td>
</tr>
<tr>
<td>⑤</td>
<td>⑤</td>
</tr>
</tbody>
</table>

**Problem time**

- **Data transfer between two processes, at the beginning and end of a timestep**

**Data transfer, including massflow, temperature, pressure, timestep and other calculation control data**

**Curve 1** – variables at the **bottom and top of the core**, data from TRACE to SCF.

**Curve 2** – the **global convergence curve** of TRACE.

1 – TRACE run standalone and **converge the first time**. SCF is **activated**.
2 – Data from TRACE to SCF become **stable**. SCF is **deactivated**, TRACE keeps running.
3 – Data from TRACE to SCF has an over-criterion **perturbation**, SCF is **re-activated**.
4 – Data from TRACE to SCF become **stable again**. SCF is **deactivated again**, TRACE keeps running.
5 – TRACE **converge again**. This is the end of the whole calculation.
Implementation of the Coupling

Steady State(SS) and Transient

**Two modes:**

- **Step to Step coupling**

  - Data transfer perform at each timestep. Timestep of SCF will be transferred to TRACE who will compare and select the smaller one as the **global timestep**, then transfer back to SCF.

- **SCF timestep skipped coupling**

  - Under this mode, TRACE is enabled to skip several SCF timesteps.
  - The skipped steps number depends on both TRACE and SCF timestep size.

**The first skip:**

- **SCF** _0.04s_ = **TRACE** _0.01s + 0.02s + 0.01s_
- The skipped SCF step number is 2

**The second skip:**

- **SCF** _0.11s_ = **TRACE** _0.03s + 0.02s + 0.04s + 0.01s_
- The skipped SCF step number is 3

- The final SCF step will be always be equal or larger than its originally determined size. 0.04 = 0.04, 0.11 > 0.1
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Code Verification: Specifications of the benchmark


**Phase 1, V1000CT-1:** Led by Pennsylvania State University (PSU).
A main coolant pump (MCP) start-up while three other MCP are in operation.

**Phase 2, V1000CT-2:** Led by CEA.

- **Exercise 1:** Computation of Flow Mixing Experiments. – Step1: Experiment; Step 2: Numerical calculation.
- **Exercise 2:** Coupled 3D neutronics/vessel thermal hydraulics response.
- **Exercise 3:** Best-estimate coupled code plant transient modeling.

Description of the VVER-1000 RPV:

The plant consists of four loops, each one with a horizontal steam generator (SG) and a main coolant pump (MCP).

The loops are not symmetrically arranged. There are 163 hexagonal fuel assemblies (FA) and 48 reflector assemblies (RA) in the core.

An elliptical cone with many perforations and 163 support columns exist in the lower plenum.
**Code Verification:** Specifications of the benchmark

**Before the test:**
- The power was **281 MW** with all main coolant pumps running.
- On the secondary side all steam generators were available.
- The core was at beginning of cycle conditions (BOC).
- **Control rod groups:** group #9 and #10: fully inserted; groups #1-#7: fully withdrawn and the regulating rod group #8 was about 84% withdrawn from the bottom of the core.
- The main steam header pressure amounts **5.07 MPa**.
- The main operational parameters are summarized in Table 1.

**The test phase:**
- Isolation of the steam generator of **loop-1** and isolation of the steam generator from feed water.
- Primary coolant **temperature** of loop-1 increase up to about 14 °C.
- **Coolant mixing** occurred first of all in the downcomer region.
- Coolant mixing occurred in the **lower plenum, core** and **upper plenum**.
- Temperature of the unaffected loops increased.
- The test lasted for **1800s**. At that time the power increased up to 286 MW.
- The coolant temperature at the **cold/hot legs** was measured.
- Coolant temperature at some **fuel assembly outlet** was measured.

**Table 1 Main parameters of the loops before test**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial State</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power, MW</td>
<td>281</td>
<td>± 60</td>
</tr>
<tr>
<td>Pressure above core, MPa</td>
<td>15.593</td>
<td>± 0.3</td>
</tr>
<tr>
<td>Pressure drop over RPV, MPa</td>
<td>0.418</td>
<td>± 0.043</td>
</tr>
<tr>
<td>Coolant temperature at core inlet #1, K</td>
<td>541.70</td>
<td>± 1.5</td>
</tr>
<tr>
<td>Coolant temperature at core inlet #2, K</td>
<td>541.85</td>
<td>± 1.5</td>
</tr>
<tr>
<td>Coolant temperature at core inlet #3, K</td>
<td>541.75</td>
<td>± 1.5</td>
</tr>
<tr>
<td>Coolant temperature at core inlet #4, K</td>
<td>541.75</td>
<td>± 1.5</td>
</tr>
<tr>
<td>Coolant temperature at core outlet #1, K</td>
<td>545</td>
<td>± 2.0</td>
</tr>
<tr>
<td>Coolant temperature at core outlet #2, K</td>
<td>545</td>
<td>± 2.0</td>
</tr>
<tr>
<td>Coolant temperature at core outlet #3, K</td>
<td>554.9</td>
<td>± 2.0</td>
</tr>
<tr>
<td>Coolant temperature at core outlet #4, K</td>
<td>545</td>
<td>± 2.0</td>
</tr>
<tr>
<td>Mass flow rate of loop #1, kg/s</td>
<td>4737</td>
<td>± 110</td>
</tr>
<tr>
<td>Mass flow rate of loop #2, kg/s</td>
<td>4718</td>
<td>± 110</td>
</tr>
<tr>
<td>Mass flow rate of loop #3, kg/s</td>
<td>4682</td>
<td>± 110</td>
</tr>
<tr>
<td>Mass flow rate of loop #1, kg/s</td>
<td>4834</td>
<td>± 110</td>
</tr>
</tbody>
</table>

Control rod groups of the core
Code Verification: Specifications of the benchmark
Code Verification: TRACE/SCF-ECI model

TRACE model – TRACE V5.1051

SCF model – Subchanflow3.3

F–FILL
Core outlet

B–BREAK
Core inlet

Loop 4
PIPE 204

Loop 3
PIPE 203

Loop 2
PIPE 201

Loop 1
PIPE 205

October 14th – October 18th, 2018
Code Verification: Results (1/4)

Temperature of cold leg

Loop 1

Temperature of cold leg

Loop 2

Loop 3

Loop 4
Code Verification: Results (2/4)

Temperature of hot leg

Loop 1

Loop 2

Temperature of hot leg

Loop 3

Loop 4

Pipe 201

Pipe 202

Pipe 203

Pipe 204

Pipe 205

Pipe 206

Pipe 207

Pipe 208

546 - 547 Temperature (K)

0 500 1000 1500 2000 Time (s)

544 - 556 Temperature (K)

0 500 1000 1500 2000 Time (s)
The result under timestep skipped mode with a SCF timestep of 0.5s is the same with the result of a typical step to step coupling.

The result under timestep skipped mode with a SCF timestep of 1.0s is also the same with the result of a typical step to step coupling.

The timestep skipped mode of the coupling codes behaves just as good as the step to step mode.

The SCF timestep seems has no significant effect on the final results.

- Or to be more precise, the cases which were tested just share the same results.
- However, there could be difference between the two modes when the SCF timestep is set too big, which could lead to the lost of real transient details.
Analyze of the Computing time.

Data from three sources are compared: TRACE-Standalone, TRACE/SCF-ECI

Operating System and version: Debian GNU/Linux 8
Software title and version: TRACE V5.1051 and Subchanflow 3.3
Hardware information: Processor – 48 Intel(R) Xeon(R) CPU E5-2697 v2 @ 2.70GHz,
Installed memory (RAM) – 378 GB, System type – 64 bit

- the OpenMP capability of SCF could reduce the elapsed time.
- The time-step skipped trick could significantly save CPU time.
- The larger the skipped timestep is, the less elapsed time will the computation take.
- The test by Valgrind-Callgrind tool and manually CPU time analyze show that the there are no bottleneck in the new added codes.

Steady State
- TRACE-Sandalone - 1 core: 14min
- TRACE/SCF-ECI - 2 cores: 42min

Transient
- TRACE-Standalone - 1 core: 1h 15min

TRACE/SCF-ECI
- Step to Step: 2 cores
- Step to Step: 9 cores
- Skipped 0.5s: 2 cores
- Skipped 1.0s: 2 cores

Step to Step: TRACE and SCF run one by one, step by step.
Skipped 0.5s: SCF steps could be skipped, the minimum SCF timestep is 0.5s.
Skipped 1.0s: SCF steps could be skipped, the minimum SCF timestep is 1.0s.
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**Goal:**
- **Coupling** of **TRACE** and **SCF** based on **ECI**
  - Spatial coupling
  - Numerical coupling
  - Computational domain: Non-overlapping
    - Geometrical: Area factor weighted
  - Inter-timestep: Parallel
  - Steady State (SS):
    - Only the SCF SS function is called. TRACE controls SCF’s running.
  - Transient:
    - Two modes: step to step and SCF timestep skipped coupling.

**System code**
- Simulate on system scale
  - Developed by US NRC
  - The tool implementing the coupling.
  - Generate multi-task system.
  - Use socket and run in parallel way.
  - Closely related to code’s structure.
  - Specific for specific code.

**Subchannel code**
- Simulate on component scale
  - Developed by KIT INR

**TEST:** with a **Coolant Mixing Experiment** performed on **VVER-1000**

- Comparison of Temperature distribution at coldlegs and hotlegs: **Experiment**, **TRACE-Standalone** and **TRACE/SCF-ECI**
  - Notable improvement was observed in the TRACE/SCF-ECI result compared with TRACE standalone.

- Comparison of the Temperature distribution at hotlegs: **Couple-Step_to_Step**, **Couple-Skip_0.5**, **Couple-Skip_1.0**
  - The results are almost the same, which indicates that the timestep skipped mode work well just as a typical coupling.

- Comparison of the computing time: **Couple-ECI- (Step_to_Step, OpenMP_SCF, Skip_0.5, Skip_1.0)**
  - OpenMP capability of SCF could reduce the computing time.
  - The timestep skipped mode could significantly reduce the computing time.
Thanks for your attention.
Summary

**Goal:** Coupling of TRACE and SCF based on ECI

- **Spatial coupling**
  - Computational domain: Non-overlapping
  - Geometrical: Area factor weighted

- **Numerical coupling**
  - Inter-timestep: Parallel

**Steady State (SS):**
- Only the SCF SS function is called.
- TRACE controls SCF's running.

**Transient:**
- Two modes: step to step and SCF timestep skipped coupling.

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