Development of TALL-3D Facility Design for Coupled STH and CFD Code Validation

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Outline

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Motivation and main messages

• Generation IV designs lean towards compact pool type reactors which are complex systems where interactions between different physical phenomena of different time and spatial scales are present.
• The compactness of the pool designs has also a byproduct in thermal-hydraulic coupling between 1D and 3D phenomena in the primary coolant system.
• One dimensional System Thermal Hydraulics (STH) codes are generally inadequate for resolving complex transients with mixing and stratification.
• Computational Fluid Dynamics (CFD) codes are computationally too expensive for resolving the whole primary coolant system.
• Code coupling is done to achieve necessary accuracy with affordable computational efficiency.
• Validation of coupled codes is an important pre-requisite for the reliable safety analysis yet data for such complex systems is rarely available.

• The goal is to design TALL-3D facility in order to provide experimental data for validation of coupled STH and CFD codes.
- **TALL-3D facility** is designed to provide high grade validation data for thermal-hydraulics models.

- The facility is comprised of 3 vertical legs (~6m):
  - main heater leg,
  - 3D test section leg
  - heat exchanger leg

- The differential pressure measurement system combines
  - 5 DP groups of pressure transducers,
  - 11 measurement points
  - total 15 differential pressures around the loop can be measured.

- LBE flow rates are measured by two Coriolis flow meters installed after the heat exchanger on the heat exchanger and 3D test section legs.
TALL-3D instrumentation

- Proper choice and positioning of the instrumentation in the loop is a key to provide necessary data for code validation.

- Instrumentation is positioned such that the loop can be virtually divided into several sections.

- For each sub-section boundary inlet and outlet conditions can be provided for separate validation of the codes.
STH pre-test analysis

• A modified RELAP5-LBE code (developed at ENEA) is used for STH pre-test analysis.

• The main objective of STH pre-test analysis was to propose the dimensions of the loop characteristics
  – 3D test section inlet diameter.
  – 3D test section heater power.
  – Main heater section flow area.
  – Main heater power.

• The goal of the design is to provide:
  – Mixing in 3D test section in forced circulation condition.
  – Stratification development in natural circulation conditions.

1. Main heater section; 2. Heat exchanger; 3. 3D test section; 4. EM pump; 5. Coriolis flow meters; 6. Expansion tank
Forced to natural transient was chosen as one of the most interesting case because of:
- Instable flow conditions
- Possible reverse flow in the 3D test section
- Relatively fast transient

Initial steady state:
- Mass flow in EM pump: 4.77 kg/s
- Mass flow in main heater leg: 2.84 kg/s
- Mass flow in 3D test section leg: 1.93 kg/s
- Main heater power: 5 kW
- 3D heater power: 5 kW

Transient:
- At 10000 seconds, EM pump is stopped
• Using different heater powers (7 kW in main heater and 8 kW in 3D test section heater) reverse flow can be eliminated.

• Finding cases with high amplitude oscillations is needed to provide both mixing and stratification condition in the 3D test section pool.

• Mixing and stratification conditions are discussed in the next section.

• It must be noted that STH results fail to capture 3D effects and therefore the results of single code calculation will not match the experiment.
CFD pre-test analysis

- 3D test section is designed to introduce a 3D pool in the system which flow conditions will not be captured by 1D STH code during transients.

- The test section inlet diameter is selected to provide ample jet into the pool to mix the fluid while flow is rapid.

- The function of the plate inside the pool is to break the jet and distribute the momentum inside the pool.

- In low flow conditions the stratified layer will prevent the jet to reach the plate.
TALL-3D instrumentation (cont.)

- The TALL-3D test section is an axisymmetric cylindrical stainless steel vessel (diameter 30 cm and height 20 cm).

- Temperature distribution is measured by thermocouples
  - along internal and external surfaces of the test section walls
  - in radial direction close to the flow reflecting plate.
  - in the flow

- Measurements provide boundary conditions for STH and CFD codes
  - differential pressure over the test section,
  - temperatures in the inlet and outlet and
  - mass flow rate of LBE.
The dimensions and heater parameters of the pool have been selected using the scaling analysis developed for buoyant jets in pool-like geometries (Peterson 1994)

\[
\left( \frac{H_{\text{tank}}}{d_{\text{inlet}}} \right)^{1/3} \left( 1 + \frac{d_{\text{inlet}}}{4\sqrt{2} \alpha_TH_{\text{tank}}} \right)^{2/3} > C
\]

\[
Ri_{d_{\text{inlet}}} = \frac{(\rho_{\text{inlet}} - \rho_{\text{outlet}})g d_{\text{inlet}}}{\rho_{\text{inlet}} v_{\text{inlet}}^2}
\]

Peterson's analysis is developed for large stratified enclosures, but flow inside the 3D test section is bounded and the volume is relatively small.

Value \(C = 3.0\) shows good agreement with results obtained in pre-test CFD simulations.
In case of forced inlet jet, the fluid in the bulk volume is stratified if the left-hand-side (LHS) value of the Peterson equation is greater than the modified criterion (blue dashed line).

Figure a) shows that fluid in the 3D test section is well stratified at 0.3 kg/s inlet mass flow rate and mixed at 0.7 kg/s for inlet diameter of 17 mm.

Figure b) is an alternative representation of the analysis for 17 mm inlet with respect to mass flow rate. It can be seen that, in case of 17 mm inlet, if the mass flow is below ~0.65 kg/s then the pool becomes stratified.
Single CFD

\[ \dot{m}_{in} = 0.3 \, \text{kg/s} \]

\[ \dot{m}_{in} = 0.7 \, \text{kg/s} \]

~90k polyhedral cells with local refinements
General idea of coupling

- Codes coupled: Star-CCM+ and RELAP5-LBE

- Data exchange is driven by java macro nested in Star-CCM+ since the source code is unavailable

- Incentive: to achieve higher accuracy while keeping the computational effort at a reasonable level
Coupling algorithm

Star-CCM+

1 coupling time step
TALL-3D model in Star-CCM+

1 coupling time step
TALL-3D model in RELAP5

Convergence?

Calculation end?

End coupled calculation

Java macro

YES

NO

YES

NO
Explicit domain overlapping

- Coupling simulation is started inside Star-CCM+ using Java macro
- Java macro is responsible for:
  - extracting information from RELAP5 results
  - extrapolating next timestep inlet boundary values for Star-CCM+
  - Running Star-CCM+ for one coupling time-step
  - Extrapolating the Q needed to match CFD and STH
  - T<sub>out</sub>
  - Running RELAP5 for one time-step
  - Check convergence
  - Calculate new Q if not converged

\[
\begin{align*}
\text{massflow}_{\text{in}} & \quad \text{massflow}_{\text{in}} \\
\text{STH} & \quad \text{CFD}
\end{align*}
\]
Results
Results

• Forced to natural transient
  – 5 kW main heater
  – 5 kW 3D test section heater
• Mass flows in the three legs:
Results

- Temperatures in inlets and outlets of:
  - 3D test section
  - Main heater section
  - Heat exchanger section
• TALL-3D facility is designed to provide high grade validation data for thermal-hydraulics models.
• The strategy for validation of a coupled code can be divided into five steps:
  1. **Definition of validation metrics.** The output values that are used in validation step must be selected with respect to the physical phenomena that a code (or its constituent models) is designed to represent.
  2. **Definition of uncertain input variables.** A model requires a specific set of input data to produce the output. Selection of the input variables is determined by the output variables one wants to use in metrics.
  3. **Quantification of uncertain input parameters and the uncertainty.** This step is to build confidence in the output of a model being a prerequisite for a model performance to have correct input values. Aleatory and epistemic sources of uncertainties are addressed.
  4. **Evaluation of uncertainty in experimental measurements** used in validation process. Information about accuracies of the instruments is crucial here.
  5. **Data comparison.** The calculated output quantities are compared with experimentally measured quantities. Uncertainties in both are taken into account.
Validation approach (cont.)

• STH modeling and simulation will be validated section-wise.
• Influence of numerical diffusion can be assessed by measuring the stream-wise temperature profile.

• CFD modeling and simulation will be validated:
  – Integrally, using the section-wise validation as for STH.
  – Internally, using local thermocouples in the 3D test section pool (temperature field).

• Uncertainties in measured input and output parameters are estimated by the accuracy specification for measurement instrumentation.
Validation approach (cont.)

- The result of coupled STH/CFD codes calculation depends on
  - **What** information is exchanged
    - Inlet temperature
    - Inlet mass flow
    - Pressure drop
    - Outlet temperature
    - ...
  - **Where** the information is exchanged
    - At the boundaries of the calculation domains at which point transition of data from 1D to 3D (or vice versa) is lossless (e.g. flow is fully developed).
  - **When** the information is exchanged
    - The time-step of coupled calculation is chosen in a way to capture the rate of change in parameters

- The goal of coupled code validation is to prove that the method is accurate within the limits of experimental measurement errors.
Conclusions

• Development of the TALL-3D HLM thermal-hydraulic facility, designed for validation of coupled STH and CFD codes, is described.

• The design of the facility comprises specific features such as mutual feedbacks between a component and the whole system in order to provide challenge for single and coupled thermal-hydraulic codes.

• Pre-experiment STH and CFD simulations are carried out to select main loop and 3D test section parameters, respectively.

• Simulations confirm the desired behavior of the system – stratification in the pool-type component is achieved at low flow rates and the flow in the pool is mixed at high flow rates.
Conclusions

- Selection and positioning of the instrumentation that provides comprehensive experimental data from TALL-3D steady state and transient experiments for code validation has been described.

- Coupling methodology with explicit domain overlapping between STH and CFD codes has been proposed.

- First coupled simulations indicate the influence of 3D flow effects on the system behavior.

- The validity of the results will be compared against experimental data from the future TALL-3D tests.