Validation of Traditional and Novel Core Thermal-Hydraulic Modeling and Simulation Tools

*Issues in Validation Benchmarks: NEA OECD/US NRC NUPEC*

*BWR Full-size Fine-mesh Bundle Test (BFBT) Benchmark*

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NEKVaC/NUC Workshop
“Multi-Physics Model Validation”
Session: Verification and Validation of Advanced Simulation Codes

June 28, 2017
Needs

- The need for model refinements for best-estimate calculations on high-fidelity data bases was identified during the 4th OECD/NRC BWR Turbine Trip Benchmark Workshop in 2002.

- It was explicitly expressed that such investigations should not be limited to macroscopic approaches but should also include next generation analysis tools (i.e. CFD codes).

- A sound experimental data base was supplied by NUPEC (Nuclear Power Engineering Cooperation), which performed a large series of full-size BWR and PWR assembly void and critical flux measurements between 1987 and 1995.

- Measurements comprised of State-of-the-Art CT technology for visualization of void distribution on small scales, as well as steady-state and transient critical power test series.
BF BT Benchmark

**Phase I – Void Distribution Benchmark**
- Exercise 1 – Steady-state sub-channel grade benchmark
- Exercise 2 – Steady-state microscopic grade benchmark
- Exercise 3 – Transient macroscopic grade benchmark
- Exercise 4 – Uncertainty analysis of void distribution benchmark

**Phase II – Critical Power Benchmark**
- Exercise 0 – Steady-state pressure drop benchmark
- Exercise 1 – Steady-state critical power benchmark
- Exercise 2 – Transient critical power benchmark
- Exercise 3 – Uncertainty analysis of critical power benchmark

*Very good database for applying uncertainty and sensitivity analysis techniques → The benchmark is utilized in Phase II of the OECD LWR UAM benchmark*
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BFBT Void Fraction Measurements
**BFBT Void Fraction Measurements**

Spatial resolution = 0.3 mm  
Scanning time = 15 s  
Accuracy of void fraction:  
Pixel = 8 %  
Sub-channel = 3 %  
Cross-sectional = 2 %

\[ 512 \times 512 = 0.26 \text{ M pixels} \]

Photo Image

Digital Data
BFBT Void Fraction Measurements

Data Reduction of Void Distribution Measurements

Diagram showing the process of data reduction for void fraction measurements.
Issue with Symmetry Void Measurements

All tests; Side channel type

Mean error = 6.05%
Standard deviation = 9.07%

Side channel void predictions
Issue with Symmetry Void Measurements

All tests; Corner channel type

Mean error = 3.21 %
Standard deviation = 7.61 %

Corner channel void predictions
Issue with Symmetry Void Measurements

All tests; Channels touching unheated type

Mean error = 9.51%
Standard deviation = 11.70%

Void predictions near unheated channels
Issue with Symmetry Void Measurements

All tests; Normal inner channel type

Mean error = 4.01 %

Standard deviation = 5.53 %

Inner channel void predictions
**Issue with Symmetry Void Measurements**


**BFBT Benchmark - Effects of rod displacements on subchannel void distributions**  
(Analysis of experimental data for duplicated tests)

Experimental subchannel void distributions were showing non-symmetrical results for symmetrical test conditions (discrepancies higher than the given measurement error of 3%)
Issue with Symmetry Void Measurements

Issue with Symmetry Void Measurements


Duplicated tests with a weak displacement of few rods

- Radial location of the rods: comparison of “rod prints” deduced from 512x512 void map
- For duplicated tests, the superposition of structures can be checked
- The bounding box is positioned similarly in twin tests (no “box prints” can be found)
- Displacement by 1-2 pixels for few rods regularly scattered within the bundle (no overall deviation)
1. **Displacements of rods**

2. **Differences in subchannel void fraction**

**Issue with Symmetry Void Measurements**

**Source:** M. MARTIN, “BFBT Benchmark - Analysis of experimental data for duplicated tests: Effects of rod displacements on subchannel void distributions”, BFBT-5, Garching, Germany, April 2008

- Example of duplicated tests: 0011-85 vs 0011-86
  - comparison of “rod prints” deduced from 512 x 512 void map
  - comparison of “subchannel maps” of measured void fraction

Differences in subchannel void maps are exactly located where rod displacements can be found (under the following assumption: the x-y axis must be permuted for subchannel void map)

A rod displacement by 1 pixel results in a subchannel void difference by 1-2%
Duplicated tests with a significant rotation of the whole bundle

- Radial location of the rods: comparison of “rod prints” deduced from 512 x 512 void map
- For duplicated tests, the superposition of structures can be checked
- The bounding box is positioned similarly in twin tests (no “box prints” can be found)
- Overall rotation of the bundle resulting in displacements by 5 pixels of peripheral rods
Issue with Symmetry Void Measurements


Example of duplicated tests: 0011-56 vs 0011-57
1. comparison of “rod prints” deduced from 512 x 512 void map
2. comparison of “subchannel maps” of measured void fraction

Distortions in subchannel void maps are consistent with the bundle rotation observed (under the following assumption: the x-y axis must be permuted for subchannel void map)

Rod displacements by 5 pixels result in a subchannel void difference by 5-10%

1. Overall rotation of the whole bundle
2. Differences in subchannel void map
Issue with Symmetry Void Measurements


From fine-scale void maps, angular distortions can be observed both for the rod bundle and the channel box.

- Source of distortions: a physical misplacement of the bundle due to a rotation of grids OR an angular bias artificially introduced by the CT-scanner?

From analysis of duplicated tests:

1. Weak displacements of few rods → small discrepancies in SC void maps
2. Large rotation of the whole bundle → high angular distortion in SC void maps

From the fine-scale void map to the subchannel void map, the x-y axis should be permuted to ensure consistency between rod displacements and void map distortions

Considering the observed distortions, the following must clarify:

1. The x-y axis for subchannel void map in respect to x-y axis for fine-scale void map
2. The definition and position of the “subchannel filter”
3. The geometrical uncertainties to propagate through the code
Uncertainties of alley void measurements (by DENSITOMETER)

BFBT Benchmark – CT-scan vs. X-ray densitometer measurements of void fraction

Turbine Trip

Cross-sectional averaged void fraction, %

Transient time, sec

DEN # 3 - measured
DEN # 2 - measured
DEN # 1 - measured
DEN # 3 - predicted
DEN # 2 - predicted
DEN # 1 - predicted
CT Scanner - measured
CT Scanner - predicted
Uncertainties of alley void measurements (by DENSITOMETER)

Bubbly flow
- void concentrated near walls
- void under predicted in alley measurement

Slug flow
- void concentrated in center of sub-channel
- void over predicted in alley measurement

Calc. bundle aver. void fraction [-]

Measured bundle average void fraction [-]

DEN#3 (z = 682 mm), DEN#2 (z = 1706 mm), DEN#1 (z = 2730 mm), and CT (z = 3758 mm) measurement positions

\[ \alpha_{\text{corrected}} \] = \frac{\hat{\alpha}_{\text{measured DEN}}}{-0.001 \hat{\alpha}_{\text{measured DEN}} + 1.231} 

(Assembly 0-1)

\[ \alpha_{\text{corrected}} \] = \frac{\hat{\alpha}_{\text{measured DEN}}}{-0.001 \hat{\alpha}_{\text{measured DEN}} + 1.167} 

(Assembly 4)

Bundle aver. void fraction [-]

Axial height [m]

DENSITOMETER values corrected
What should we do ...?

Measured data are “signals from the real world”!

- Use raw data or “filtered” data for model validation?
  - or maybe raw data with “true” uncertainties?
- Can experimentalists provide “true” uncertainties?

*More questions can be asked, but let’s stop here ...*