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PREDICTION OF VOID FRACTION IN A SUBCHANNEL AND BUNDLE GEOMETRY WITH FLICA4 AND TRACE

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Abstract

In order to encourage advancement in subchannel analyses of fluid flow in rod bundles, an international benchmark program, namely the OECD/NRC PWR Subchannel and Bundle Test (PSBT) benchmark, has been organized. The PSBT benchmark aims at assessing the capabilities of subchannel analysis codes, system codes, and computational fluid dynamics (CFD) codes for the prediction of detailed void distributions in subchannels, including departure from nucleate boiling, on the basis of experimental data measured at a full scale prototypical PWR rod bundle. Within the framework of the PSBT benchmark, analyses of the void distribution in a subchannel and bundle geometry have been performed at the Paul Scherrer Institut by means of the subchannel analysis code FLICA4, and the thermal-hydraulic system code TRACE. Steady-state scenarios are analyzed by using both FLICA4 and TRACE and transient analyses are performed with FLICA4. In particular, the TRACE calculations for bundle geometry have been carried out employing a three-dimensional vessel component to model cross flows between subchannels. The analysis aims at evaluating the applicability of a three-dimensional vessel component of TRACE for subchannel analyses, as well as validating the subchannel code FLICA4. The calculated void fractions are compared to the experimental data, and the accuracies of the predictions by both codes are appraised by means of a statistical analysis.

Introduction

In order to encourage advancement in subchannel analyses, the international benchmark program OECD/NRC NUPEC BWR Full-size Fine-mesh Bundle Test (BFBT) Benchmark [1] was organized. The BFBT benchmark finished successfully with about 30 organizations from 15 countries was used for the validation of computational fluid dynamics, subchannel, and system thermal-hydraulic codes. The void fraction analysis for the benchmark indicated that most scatter in code predictions was observed for low void fraction less than 40 % [2].

Based on the success of the BFBT benchmark, the international benchmark program OECD/NRC NUPEC PWR Subchannel and Bundle Tests (PSBT) Benchmark has been launched [3]. The benchmark is aimed at assessing the capabilities of system codes, subchannel codes and computational fluid dynamics (CFD) codes for the prediction of detailed void distributions in subchannels, including departure from nucleate boiling (DNB), on the basis of experimental data measured at a full scale prototypical PWR rod bundle. This paper describes the analyses on the void fraction distribution conducted at Paul Scherrer Institut within the framework of PSBT.

1. Description of Benchmark

1.1 Experimental Apparatus

Figure 1 depicts the NUPEC test facility, where the experiments selected for the PSBT benchmark were carried out. This consists of a high pressure and high temperature recirculation loop, a cooling loop instrumentation and data recording systems. The recirculation loop consists of a test section, a circulation pump, a preheater, a steam drum (acting as a pressurizer), and a water mixer. Different test sections (see section 1.2 and 1.3 for more details) were constructed to represent a single subchannel, and a complete rod bundle respectively. The design pressure and temperature are 19.2 MPa and 362 °C, respectively.

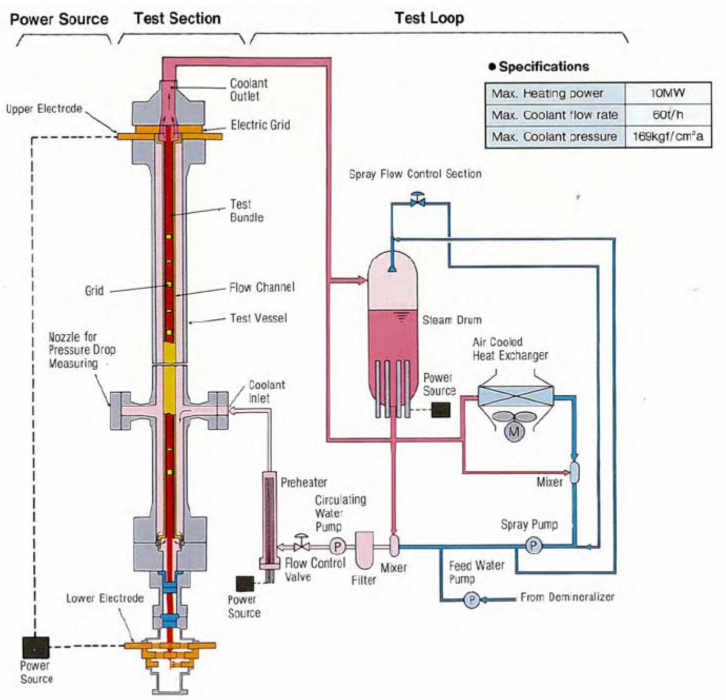
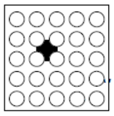
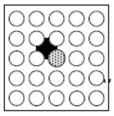
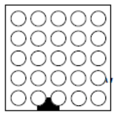
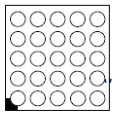


Figure 1 System diagram of NUPEC PWR test facility

1.2 Single Channel Experiments

Four different subchannels, as shown in Table 1 and Figure 2, were employed for the single channel experiment. Each test cross-section represented a subchannel type in a bundle geometry (center, side, and corner subchannel types), and were mounted in the test section depicted in Figure 2. The effective heated length is 1555 mm, and the cross-section where the void measurements were carried out is at 1400 mm from the bottom of the heated section. The chordal averaged void fraction was calculated from the mixture density measured by a gamma-ray transmission method. The uncertainty on the void measurements is of 4 % absolute void.

Item	Data			
Assembly (Subjected subchannel)	 **S1**	 **S2**	 **S3**	 **S4**
Subchannel type	Center (Typical)	Center (Thimble)	Side	Corner
Number of heaters	4×1/4	3×1/4	2×1/4	1×1/4
Axial heated length (mm)	1555	1555	1555	1555
Axial power shape	Uniform	Uniform	Uniform	Uniform

■: Subjected subchannel ○ : Heated rod ◍: Thimble rod

Table 1 Geometry and power shape for single channel tests

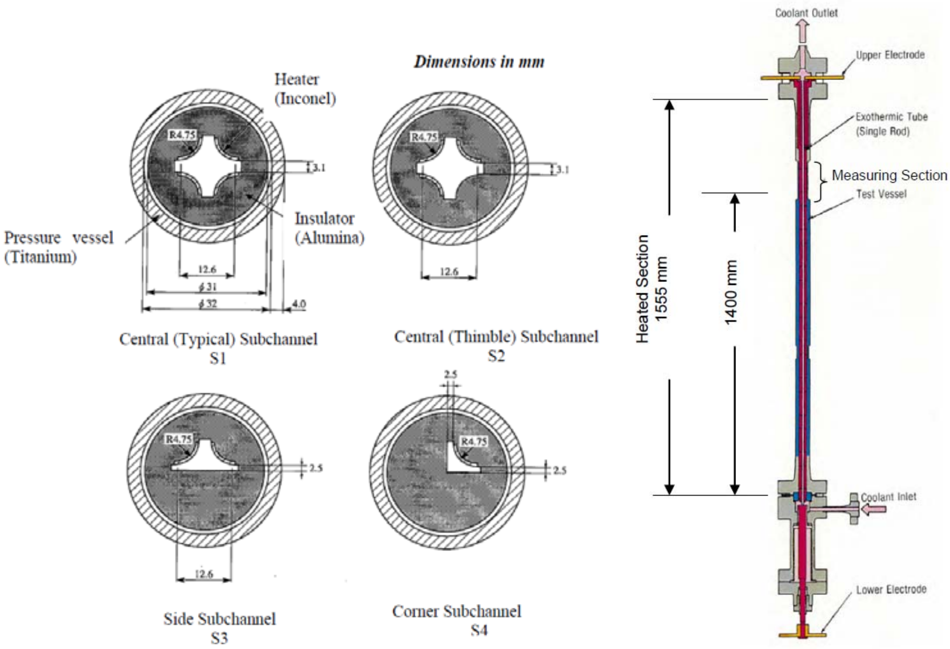
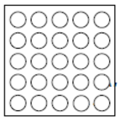
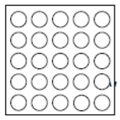
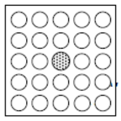


Figure 2 Test sections for single channel tests

Item	Data		
Assembly	 B5	 B6	 B7
Rods array	5×5	5×5	5×5
Number of heated rods	25	25	24
Number of thimble rods	0	0	1
Heated rod outer diameter (mm)	9.50	9.50	9.50
Thimble rod outer diameter (mm)	-	-	12.24
Heated rods pitch (mm)	12.60	12.60	12.60
Axial heated length (mm)	3658	3658	3658
Flow channel inner width (mm)	64.9	64.9	64.9
Radial power shape	A	A	B
Axial power shape	Uniform	Cosine	Cosine
Number of MV spacers	7	7	7
Number of NMV spacers	2	2	2
Number of simple spacers	8	8	8
MV spacer location (mm)	471, 925, 1378, 1832, 2285, 2739, 3247		
NMV spacer location (mm)	2.5, 3755		
Simple spacer location (mm)	237, 698, 1151, 1605, 2059, 2512, 2993, 3501		

○: Heated rod ◍: Thimble rod
MV: Mixing vane, NMV: No mixing vane
Spacer location is distance from bottom of heated length to spacer bottom face.

Table 2 Geometry and power shape for bundle tests

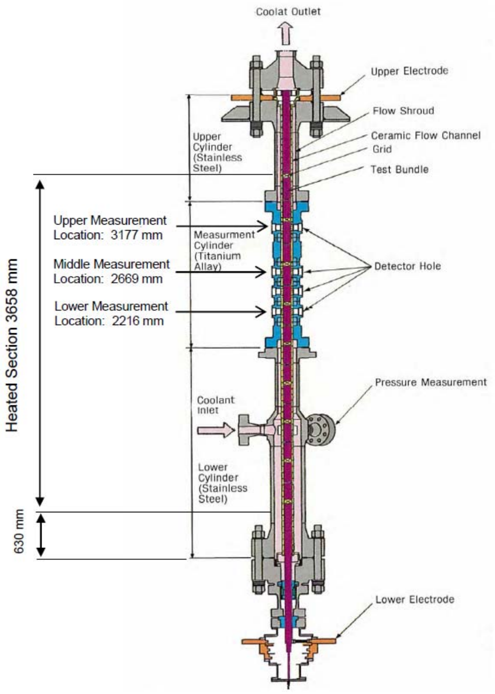


Figure 3 Test section for bundle tests

1.3 Test Section for Bundle tests

The bundle experiments were performed with three test sections, as described in Table 2 and Figure 3. The difference between assemblies B5 and B6 is the axial power profile. The uniform and cosine axial power profiles were employed for assemblies B5 and B6, respectively. In case of assembly B7, all specifications are exactly the same as those of assembly B6, except for a guide thimble at the center instead of a heater rod. Electrically heated rod bundle was used to simulate the partial cross-section (5x5 fuel rods) of a full length PWR fuel assembly. The effective heated length is 3658 mm, and the void fraction was measured at three different elevations: 3177 mm (upper), 2669 mm (middle), and 2216 mm (lower) respectively. A multi-beam gamma tomography system was used to measure the void fraction of each subchannel in the rod bundle. An iterative method was employed to reconstruct the void fraction of the 36 subchannels. The average void fraction of the four central subchannels is given in the benchmark database and the uncertainties of the measurement were indicated as 4 % and 5 % absolute void fraction for steady-state and transient experiments, respectively.

2. Numerical Analysis

2.1 Thermal Hydraulic Codes

The void distribution tests were analyzed by means of the subchannel analysis code FLICA4 V1.10.8 [4] and the best-estimated thermal hydraulic system code TRACE (TRAC/RELAP Advanced Computational Engine) V5.0 Patch 2 [5].

FLICA4 is a three-dimensional (3D) two-phase flow analysis code developed for subchannel analysis by CEA (Commissariat à l'Energie Atomique et aux Energies Alternatives). The two-phase flow model in FLICA4 is based on a 4-equation model, combined with a drift flux model to describe the relative velocity between phases.

TRACE is the latest best-estimate system code developed by USNRC for analyzing steady-state and transient neutronic/thermal-hydraulic behavior of light water reactors (LWRs). It is a product of a consolidation of the capabilities of the main system codes of USNRC such as TRAC-PF1, TRAC-BF1, RELAP5, and RAMONA. As state-of-the-art thermal-hydraulic codes, TRACE employs a 6-equation model for the description of two-phase flows.

2.2 Thermal Hydraulic Model

2.2.1 Single channel analysis

Identical nodalizations were used for the single channel analyses carried out with FLICA4 and TRACE. The single channel test-section was nodalized with 32 axial nodes. Four different geometries were prepared, to take into account the difference in cross section of each case. The Chexal-Lellouche model was employed as a drift-flux model for the FLICA4 calculations. The turbulent conductivity and viscosity, K_t and M_t, were set to 0.01 based on a sensitivity analysis. A value of 1.0E-4 was employed for the recondensation coefficient, KV0. In case of TRACE, the single channel was modeled by using a PIPE (one-dimensional) component. Inlet mass flux and temperature, and outlet pressure were imposed as boundary conditions.

2.2.2 Bundle analysis

The test assemblies B5 and B6 for the bundle exercise consists of 25 heater rods and 36 subchannels. The heater rods were classified into two groups based on the radial power distribution: 9 rods for central region and 16 rods for peripheral region. Relative powers for central and peripheral regions are 1.0 and 0.85, respectively. In case of assembly B7, the central region consists of 8 heated rods due to a guide thimble at the center. The geometry and the power distribution are symmetrical in all test assemblies.

Since it is possible to employ the symmetric boundary condition in FLICA4, each test assembly was described by using 1/8 symmetrical model, as shown in Figure 4. The Chexal-Lellouche model was employed for the bundle analysis as well. For all bundle cases, except for assembly B7, a value of 0.01 was used for K_t and M_t. For assembly B7 that has a guide thimble at the center, K_t and M_t were set to 0.05. A value of 7.5E-4 was imposed for KV0 for all bundle calculations. For the TRACE calculations, the full geometry was modeled instead by using a 3D VESSEL component in Cartesian coordinates.

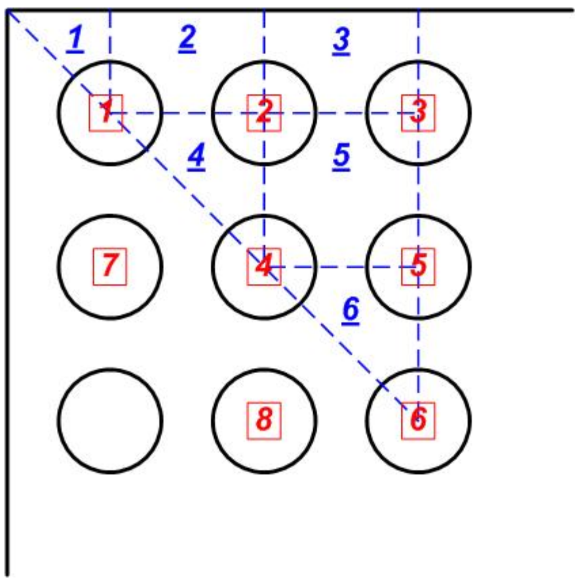


Figure 4 1/8 symmetrical model for FLICA4

3. Result and Discussion

3.1 Single channel analysis

All cases in the PSBT benchmark single channel exercise were analyzed by means of FLICA4 and TRACE. The single channel exercise consists of steady-state experiments and the ranges of the boundary conditions were as follows:

- Pressure : 4.90 – 16.6 (MPa)
- Mass Flux : 4.94E+02 – 4.14E+03 (kg/m^2-sec)

- Power : 12.5 – 90.0 (kW)
- Inlet Temperature : 164.1 – 345.0 (°C)

The results of the void fraction for series 1 to 4 are depicted in Figures 5. Generally, both FLICA4 and TRACE could predict the experimental results well. However, both codes underpredicted the void fraction, taking into account a measurement accuracy of 4.0 % (absolute void fraction), especially for the corner subchannel type (series 4).

The bias of the calculation results from FLICA4 and TRACE has been assessed by using the linear regression method. Figure 6 shows the results from the linear regression for the void fraction calculated by FLICA4 and TRACE. Each result is fitted by a linear function with a high correlation coefficient (adjusted R^2) of 0.95. The linear regression analyses indicate that the void fraction results from FLICA4 and TRACE are biased from the experiments by 2.89 % and 3.85 % in average, respectively. The mean absolute errors of the FLICA4 and TRACE calculations are 4.46 % and 4.95 %, respectively. Considering a measurement error of 4.0 % absolute void fraction, both codes reproduce the experimental data with slightly higher error.

3.2 Bundle analysis

The PSBT benchmark bundle test cases were analyzed by using both FLICA4 and TRACE. The void fractions of four central subchannels were averaged and compared with the experimental data. The results of both codes presented in Figure 7 indicate that, in general, both codes overpredicted the void fractions from the experiments. Especially, TRACE overpredicted the void fraction in lower and middle regions evidently. The linear regression method was applied to estimate the bias of each calculation quantitatively. As shown in Figure 8, the results from FLICA4 and TRACE are biased by 2.10 % and 6.78 % in average, respectively. The accuracies of the calculation represented by the mean absolute error are 4.09 % and 8.71 % for FLICA4 and TRACE, respectively. Considering the measurement error of 4.0 % void fraction, the difference between the experiments and the TRACE results are relatively high. As confirmed by the mean absolute error of each region listed in Table 3, this difference mainly came from the lower and middle regions, where smaller void fraction is expected. TRACE tends to overpredict the void fraction especially for values below 30%. In Figure 9 the axial void fraction profile of a case from test series B5 is presented together with experimental data. The void fraction predicted by TRACE starts increasing rapidly at an elevation of about 1.8 m. This points out the necessity of additional investigations and validation of the subcooled boiling model in TRACE. FLICA instead reproduces the experimental data reasonably well.

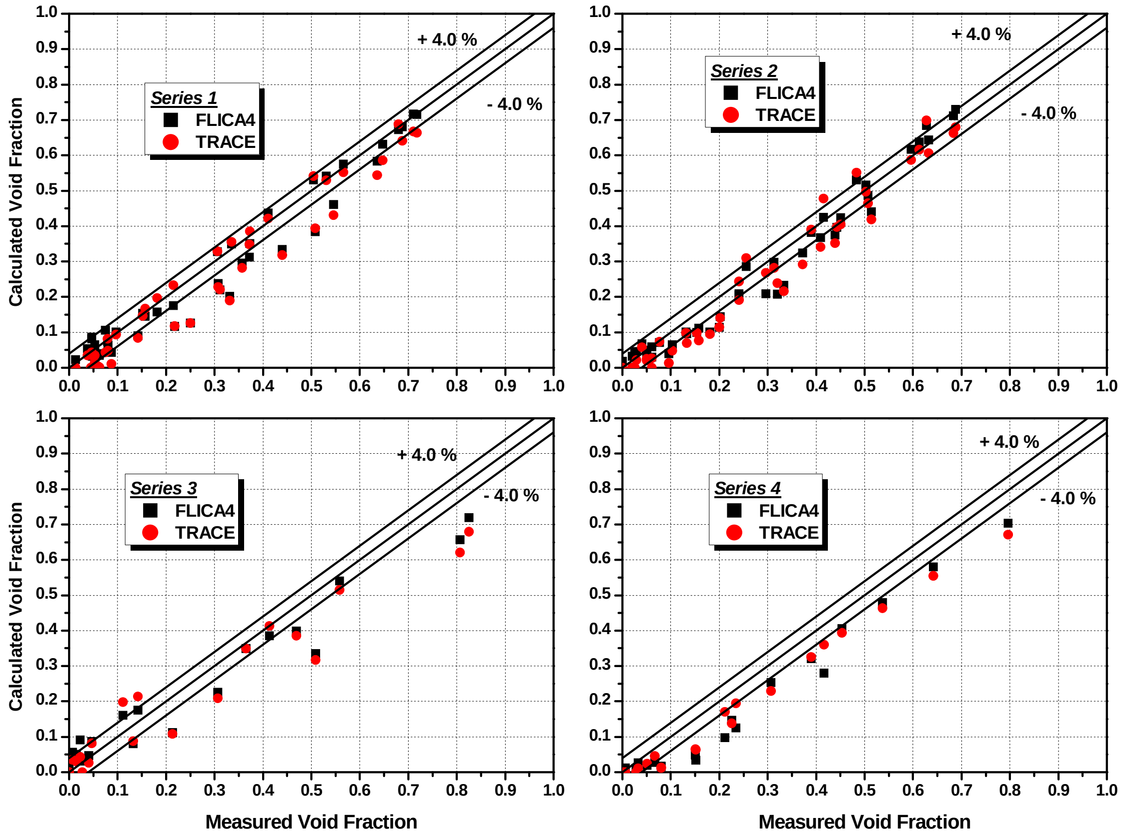


Figure 5 Void fraction predictions for single channel exercise

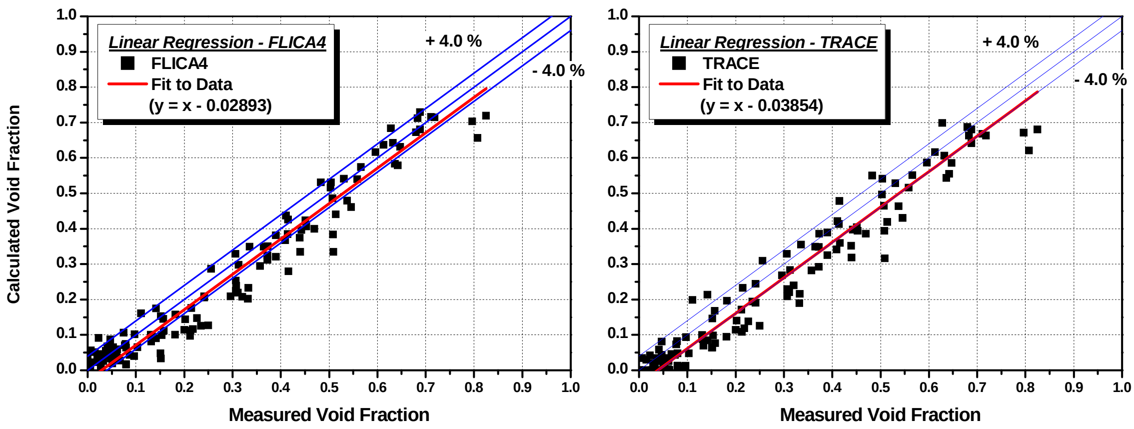


Figure 6 Results from linear regression analysis

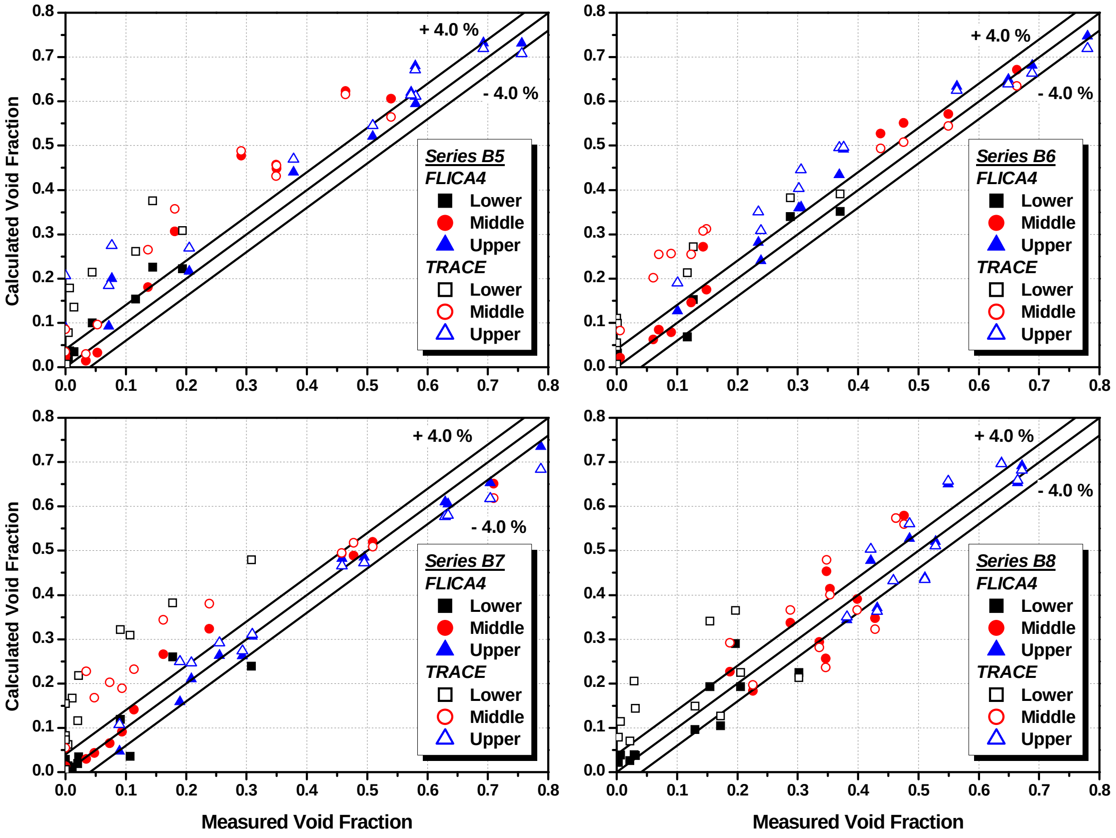


Figure 7 Void fraction of bundle exercise

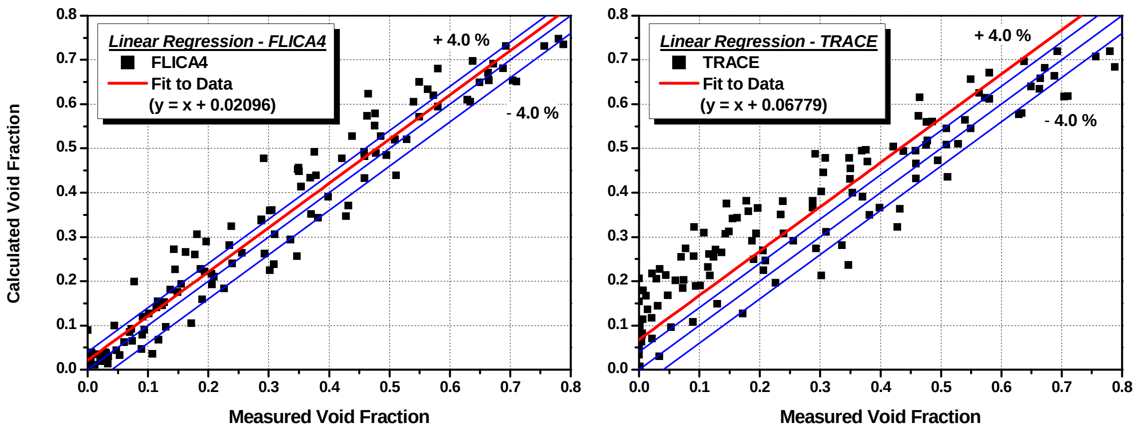


Figure 8 Results from linear regression analysis

Code	Lower	Middle	Upper	Overall
FLICA4				
Averaged Error (%)	1.18	3.54	1.59	**2.10**
Mean Absolute Error (%)	2.95	5.29	4.04	**4.09**
TRACE				
Averaged Error (%)	9.54	7.45	3.35	**6.78**
Mean Absolute Error (%)	10.1	9.49	6.49	**8.71**

Table 3 Mean absolute error of void fraction

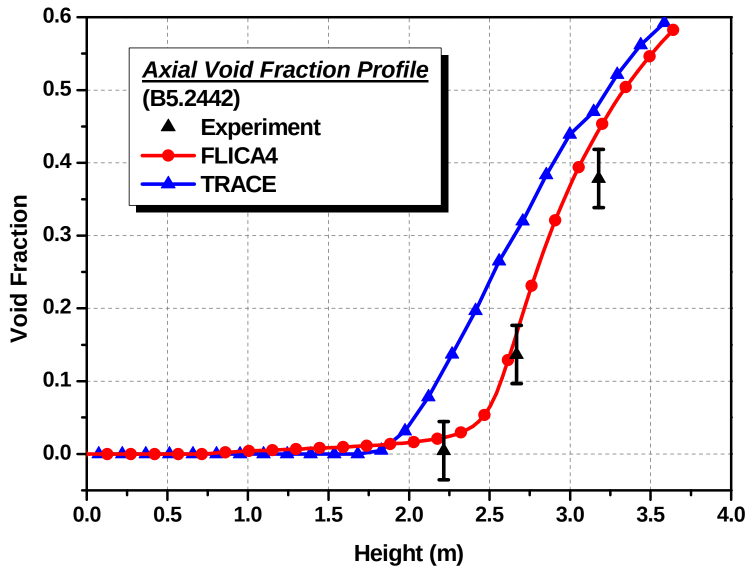


Figure 9 Axial void fraction profile of case B5.2442

3.3 Transient Analysis

The transient experiments conducted with the assemblies of B5, B6, and B7 were analyzed by using FLICA4. The exercise consists of four different transients: a power increase, a flow reduction, a depressurization, and a temperature increase respectively. As an example, the transient results obtained for the B5 assembly are reported in Figure 10 together with the experimental data. It was found that FLICA4 could reproduce the experimental data reasonably well even in fast transients such as the power increase and the flow reduction. However, a large discrepancy was observed in case of the temperature increase case. It is presumed that the discrepancy is originated from a delay in the experimental inlet temperature variation. Since the location of the inlet temperature measurement was between the preheater and the inlet nozzle of the test vessel, the actual temperature increase at the inlet of the test section would happen with some delays from the temperature variation at the measuring point. As a matter of fact, when shifting the FLICA4 results by 7.0 sec with respect to the original simulation time (see Figure 11), very good agreement with the experimental data is obtained. Therefore, it can be concluded that the transient exercise was well predicted by FLICA4.

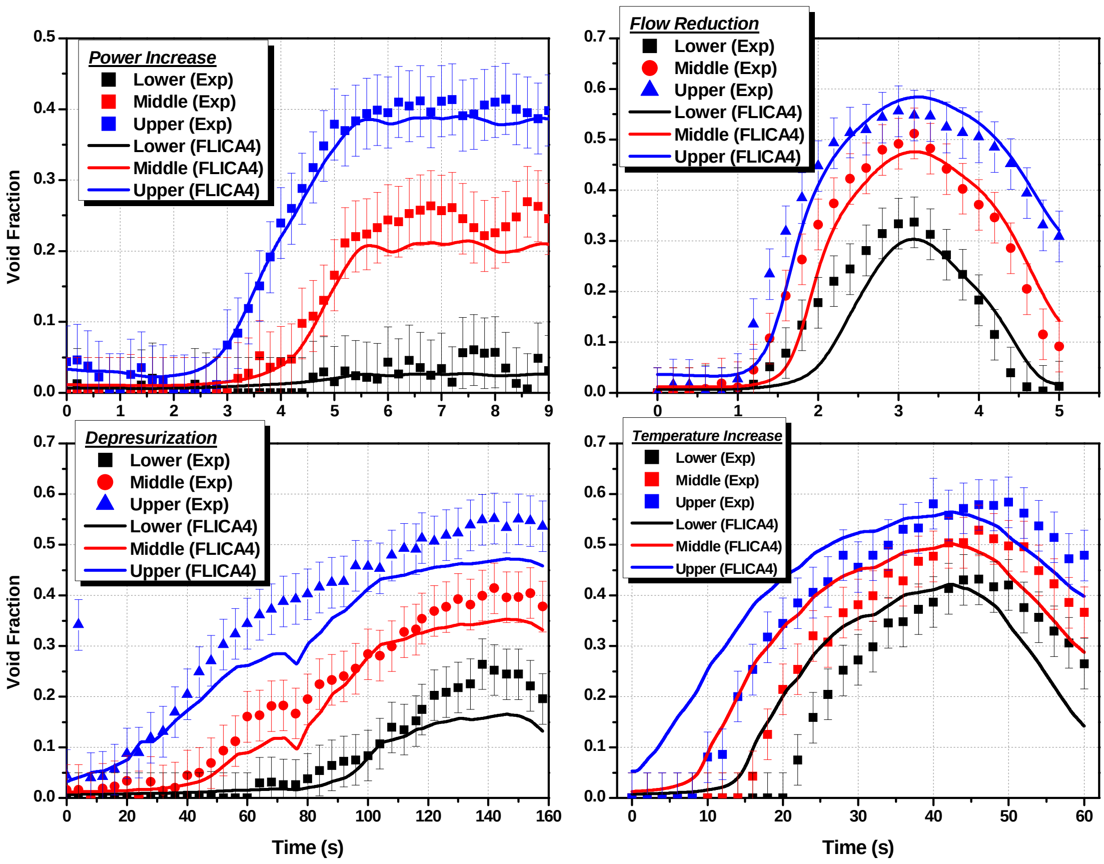


Figure 10 Void fraction of benchmark transient exercise (5T)

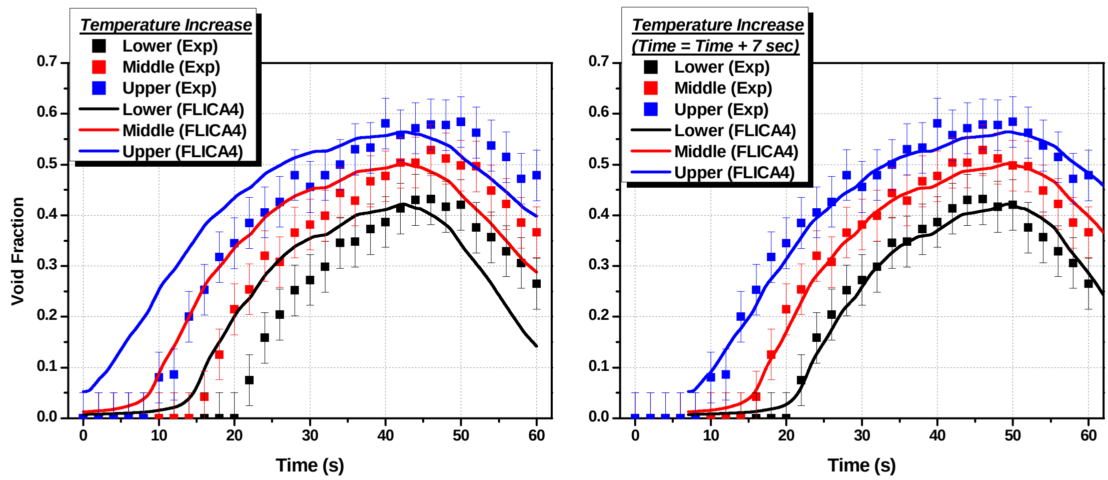


Figure 11 Calculation results with original and modified time (exercise 5T - temperature increase)

4. Conclusion

All exercises in Phase-I of the PSBT benchmark were analyzed by using the subchannel analysis code FLICA4 and the system code TRACE. The results show that FLICA4 can predict the measurements within an acceptable error range. TRACE reproduces the experimental data well in case of the single channel exercise. However, it overpredicts the void fraction when applied to the full bundle case. In particular, the comparison with the experimental data points out to the necessity of a detailed assessment of the TRACE subcooled boiling model.

5. References

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