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VOID FRACTION PREDICTION OF NUPEC PSBT TESTS BY CATHARE CODE

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Abstract

The current generation of thermal-hydraulic system codes benefits of about sixty years of experiments and forty years of development and are considered mature tools to provide best estimate description of phenomena and detailed reactor system representations. However, there are continuous needs for checking the code capabilities in representing nuclear system, for drawing attention to their weak points, for identifying models which need to be refined for best-estimate calculations. Prediction of void fraction and Departure from Nucleate Boiling (DNB) in system thermal-hydraulics is currently based on empirical approaches. The database carried out by Nuclear Power Engineering Corporation (NUPEC), Japan addresses these issues. It is suitable for supporting the development of new computational tools based on more mechanistic approaches (i.e. three-field codes, two-phase CFD, etc.) as well as for validating current generation of thermal-hydraulic system codes. Selected experiments belonging to this database are used for the OECD/NRC PSBT benchmark. The paper reviews the activity carried out by CATHARE2 code on the basis of the sub-channel (four test sections) and presents rod bundle (different axial power profile and test sections) experiments available in the database in steady state and transient conditions. The results demonstrate the accuracy of the code in predicting the void fraction in different thermal-hydraulic conditions. The tests are performed varying the pressure, coolant temperature, mass flow and power. Sensitivity analyses are carried out addressing nodalization effect and the influence of the initial and boundary conditions of the tests.

Introduction

A system code shall demonstrate that is reliable in simulating and predicting the key phenomena of properly selected scenarios. This is a necessary prerequisite for its applicability in accident analysis aimed at demonstrating that a nuclear system is safe and unlikely to fail. The current generation of thermal-hydraulic system (TH-SYS) codes benefits of about sixty years of experiments and forty years of development and are considered mature tools to provide best estimate description of phenomena and detailed reactor system representation. However, there are continuous needs for checking the code capabilities in representing nuclear system, in drawing attention to their weak points, in identifying models, which need to be refined for best-estimate calculations. Availability of good quality experimental data is necessary to address this issue, and continuously better instrumented experiments are requested not only for improving macroscopic methods but also for developing and setting up next-generation analysis techniques that focus on more microscopic processes. Prediction of void fraction and DNB in system thermal-hydraulics is currently based on empirical approaches. Advancement in understanding and modelling complex flow behaviour in rod bundles would promote the validation of the current approaches and the development of more mechanistic approaches [1].

The aim of the activity is to assess the models of CATHARE2 v2.5_1 (six-equation, two-field) code[5], [6] by means of void fraction measurements in sub-channel configurations and in full scale bundle of PWR at wide range of thermal-hydraulic boundary conditions (i.e. pressure, power, inlet temperature and mass flow rate). In particular, the present activity summarizes the results of four sub-channel test sections and presents the analysis of three bundle configurations in steady state and transient conditions. Sensitivity analyses are carried out addressing nodalization effect and the influence of the initial and boundary conditions of the tests.

1. The OECD/NRC NUPEC PSBT experimental database

The Pressurized water reactor Sub-channel and Bundle Tests (PSBT) were conducted by NUPEC within an extensive experimental campaign aimed at verifying the reliability of fuel assemblies used for commercial nuclear power plants [2]. PSBT is able to simulate the high pressure, high temperature fluid conditions, which are typical of a (Pressurized Water Reactor) PWR nuclear power plant (NPP).

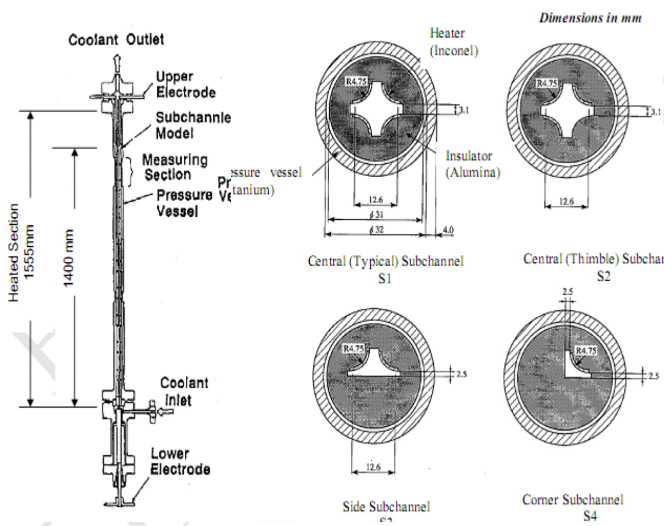
The NUPEC test facility (Fig. 1) consists of a high pressure and high temperature recirculation loop, a cooling loop, and instrumentation and data recording systems. The recirculation loop consists of a test section, circulation pump, pre-heater, steam drum (acting as a pressurizer), and a water mixer. The design pressure is 19.2 MPa and the design temperature is 362 °C. The operating conditions of the test facility are shown in Tab. 1.

The void fraction tests include steady state sub-channel as well as steady state and transient rod bundle experiments.

Four sub-channel test assemblies (TS 1, 2, 3 and 4) are used for measuring void fraction, as shown in Fig. 1. They simulate the sub-channel types (central, central with thimble, side, and corner) which are in a PWR assembly. The effective heated length is 1555 mm, and the void measurement section begins at 1400 mm from the bottom of the heated section. The overall sub-channel database includes 126 tests, under a wide range of test conditions. Among these, 43 are carried out with TS 1, and TS 2 and 20 using TS 3 and TS 4 (see Fig. 1a). Complete set of details about geometrical data, boundary conditions of the tests and experimental results are available in [4].

The rod bundle test sections simulate a partial section and full length of a PWR fuel assembly. Fig. 1b shows the test section used for the rod bundle void measurements. Three different bundles are used to perform the void distribution measurements (test section 5, 6 and 7). The effective heated length is 3.618 m. Void fraction measures are available at three different elevations 2.216 m, 2.669 m and 3.177 m, respectively. Steady state tests were carried out for a wide range of operating conditions. Transient tests were executed increasing the void generation for power increase, flow rate reduction, depressurization and coolant temperature increase. In these tests, thermal-hydraulic conditions comparable with typical scenarios were selected ranging from anticipated transients and postulated accidents.

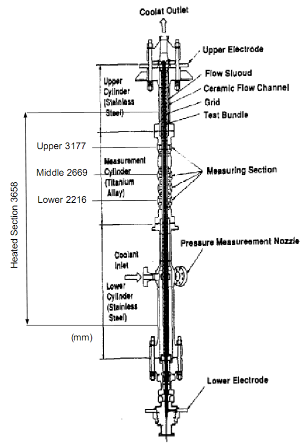
Complete set of details about geometrical data, boundary conditions of the tests and experimental results are available in [4].



(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

(a) Test sections for sub-channel void distribution measurement



0.85	0.85	0.85	0.85	0.85
0.85	1	1	1	0.85
0.85	1	1	1	0.85
0.85	1	1	1	0.85
0.85	0.85	0.85	0.85	0.85

Radial power shape A

0.85	0.85	0.85	0.85	0.85
0.85	1	1	1	0.85
0.85	1	0	1	0.85
0.85	1	1	1	0.85
0.85	0.85	0.85	0.85	0.85

Radial power shape B

Item	Data		
Assembly	B5	B6	B7
Radial power shape	A	A	B
Axial power shape	Uniform	Cosine	Cosine

○ : Heated rod ◎ : Thimble rod

(b) Test sections for rod bundle void measurement

Figure 1 Test sections of PWR Sub-channel and Bundle Tests.

Table 2 Range of NUPEC PWR test facility operating conditions.

QUANTITY	RANGE
Pressure	4.9 – 16.6 MPa
Mass Velocity	550 – 4150 kg/m^{2}s
Inlet Coolant Temperature	140 – 345 °C
Surface heat flux	37 – 186 W/cm^2

2. Modelling of PSBT test facility by CATHARE2 code

CATHARE2 models (i.e. sub-channels and bundle) are based on the following hydraulic components:

- two BCONDIT components for imposing the boundary conditions of the tests (i.e. pressure, mass flow and inlet temperature);
- two VOLUME components, which simulate the inlet and the outlet of the test section;
- one AXIAL component, which models the test section.

The electrical heaters of the sub-channel and bundle test sections are modelled with WALL components. The linear power is imposed according with the specifications of the tests.

The material properties implemented in the nodalization are provided by means of an external FORTRAN subroutine according with the specification in Ref. [4].

3. Post-test analysis void distribution PSBT tests by CATHARE2 code

3.1 Post-test analysis of steady state sub-channel tests

The analysis deals with 126 tests related the four test sections. Fig. 2 outlines the reference code results in simulating the typical central sub-channels (including the case with the thimble) and the other two test sections, referred to the side and corner geometries. The results are distinguished for the different test sections. Tab. 2 provides information about the average absolute errors at different ranges of void fractions (for the overall database and the different test sections). The table reports also the number of test cases and the corresponding standard deviations. The complete list of the sensitivities is reported in Tab. 3, which are performed for each test series. They are carried out to address nodalization effect (number of meshes) and the influence of the initial and boundary conditions of the tests. Fig. 3 reports, as sample, the results of the sensitivity analysis for the test section 2 (see Fig. 1b).

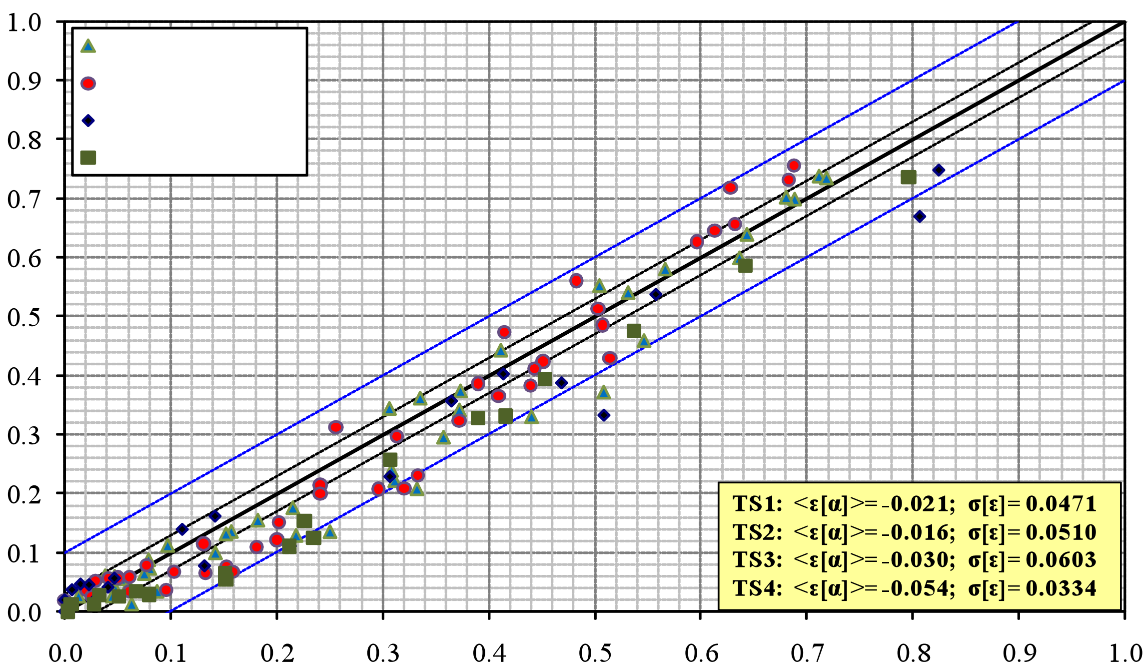


Figure 2 Overall sub-channels tests (126 tests) – CATHARE2 v2.5_1 code, reference results.

The analysis of the results of 43 test cases corresponding with the central sub-channel evidences a tendency of the code to underestimate the void fraction. The overall average error is -0.021 (in terms of void fraction) and the standard deviation is slightly lower than 0.05. The code results are less accurate and more dispersed for values of void fraction between 0.2 and 0.4. Larger errors are observed for higher values of inlet coolant temperature and of system pressure (i.e. larger than 10 MPa).

Analogous results from qualitative point of view are observed in case of test section 2 (i.e. central sub-channels with the thimble). The average error is -0.016 and the standard deviation is 0.051. The code over-predicts the void fraction up to values of void fraction equal to 0.1, then it under-estimates the test data up to about 0.6. In the range of void fraction between 0.2 and 0.6, the standard deviation increases (as in the case of the test section 1).

The analysis of the results of 40 test cases corresponding with the side and corner sub-channels confirms the results of the other test cases. However, the average absolute errors are about -0.03 and -0.05, respectively for the TS-3 and TS-4, which results higher than for the other test cases.

Table 2 Summary of sub-channels results by CATHARE2 code.

Void Fraction	**TS 1**			**TS 2**			**TS 3**			**TS 4**			**Overall**		
	<ε[α]>	**σ[ε]**	**No.**	**<ε[α]>**	**σ[ε]**	**No.**	**<ε[α]>**	**σ[ε]**	**No.**	**<ε[α]>**	**σ[ε]**	**No.**	**<ε[α]>**	**σ[ε]**	**No.**
0.0 - 0.05	0.005	*0.0161*	6	0.015	*0.0092*	5	0.013	*0.0152*	8	-0.004	*0.0088*	4	0.007	*0.0143*	23
0.05 - 0.10	-0.012	*0.0244*	9	-0.012	*0.0264*	6	--	--	--	-0.040	*0.0132*	4	-0.021	*0.0251*	19
0.10 - 0.15	-0.042	--	1	-0.040	*0.0262*	3	-0.002	*0.0455*	3	--	--	--	-0.028	*0.0365*	7
0.15 - 0.20	-0.023	*0.0037*	3	-0.079	*0.0080*	4	--	--	--	-0.091	*0.0087*	2	-0.064	*0.0313*	9
0.20 - 0.30	-0.081	*0.0384*	3	-0.030	*0.0533*	5	-0.102	--	1	-0.095	*0.0200*	3	-0.077	*0.0485*	12
0.30 - 0.40	-0.038	*0.0574*	8	-0.057	*0.0490*	5	-0.043	*0.0496*	2	-0.056	*0.0080*	2	-0.048	*0.0477*	17
0.40 - 0.60	-0.032	*0.0757*	7	-0.009	*0.0520*	10	-0.072	*0.0759*	4	-0.068	*0.0143*	3	-0.045	*0.0633*	24
0.60 - 0.80	0.007	*0.0235*	6	0.053	*0.0267*	5	--	--	--	-0.058	*0.0021*	2	0.000	*0.0446*	13
0.80 - 1.00	--	--	--	--	--	--	-0.107	*0.0429*	2	--	--	--	-0.107	*0.0429*	2

The sensitivity calculations (Tab. 3) evidence that it is possible to reduce the average absolute error varying the boundary conditions inside the accuracy of the experimental measures (see Fig. 3). In particular, the best prediction is achieved using the minimum mass flow rate as boundary condition. However, the dispersion of the results remains similar to the reference calculation and the underestimation of void fraction between 0.2 and 0.6 is only slightly improved.

Table 3 List of NUPEC PSBT code runs by CATHARE2 code.

Test section	ID	No. of axial nodes	Pressure (1)	Mass flow (1)	Note
Steady-state subchannel	RUN1	100	Nominal	Nominal	--
	RUN2	100	Nominal	Minimum	--
	RUN3	100	Nominal	Maximum	--
	RUN4	100	Minimum	Maximum	--
	RUN5	100	Maximum	Nominal	--
	RUN6	38	Nominal	Nominal	--
	RUN7	16	Nominal	Nominal	Effect of pressure drop

(1) Nominal: as specified in Ref. [4]. Minimum and Maximum: according with the estimated accuracy of the measurement system.

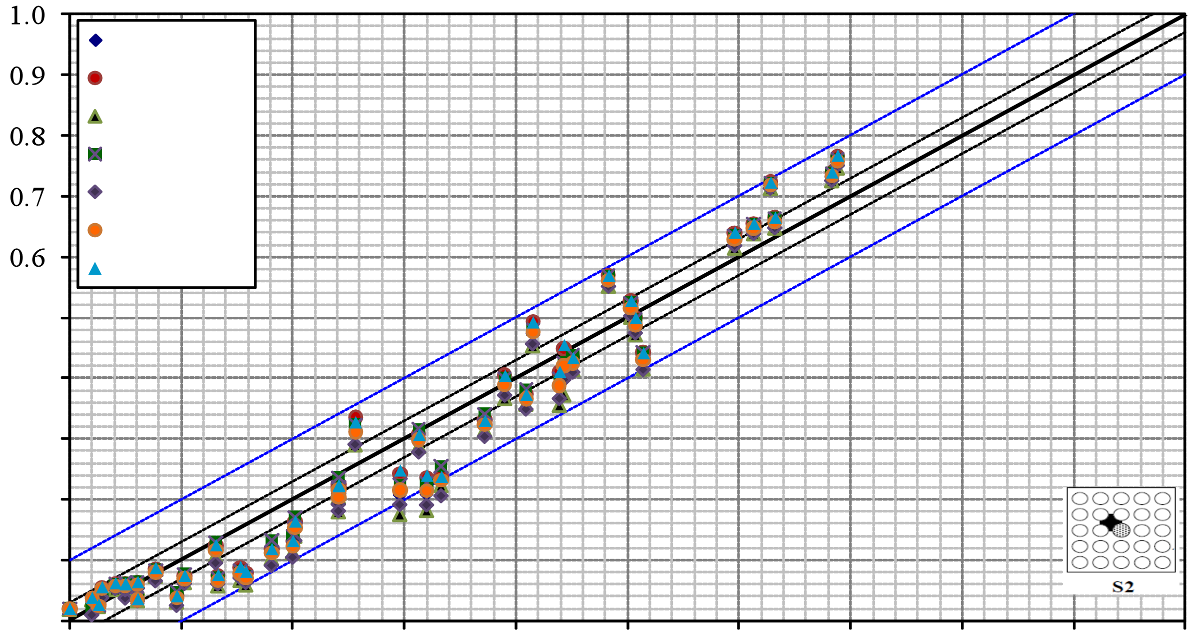
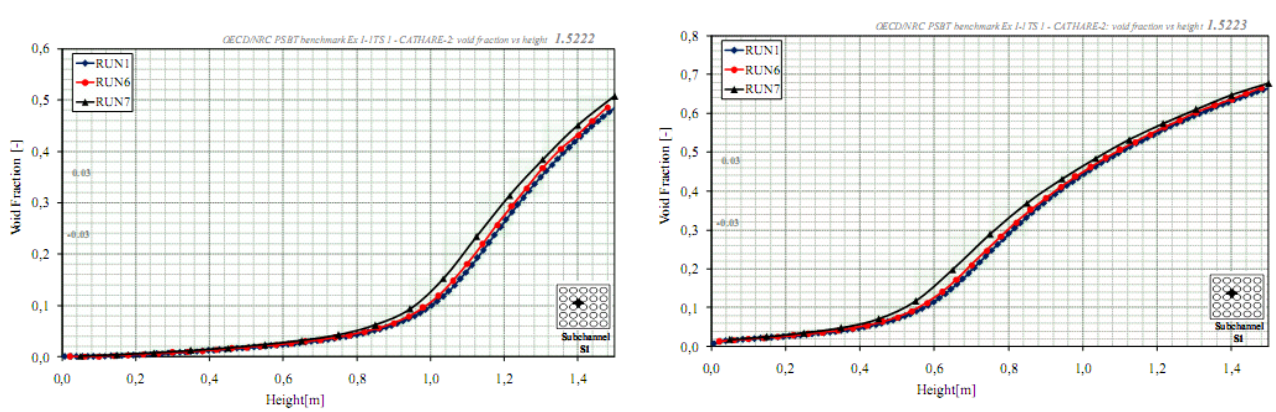


Figure 3 Test Series 2 (43 tests) – CATHARE2 v2.5_1 code, sensitivity calculations.

The sensitivity analysis related to the number of axial meshes demonstrates a dependence of the axial profile of the void fraction. This is observed in RUN 7 (see Tab. 3). Modelling the test section with 38 axial subdivisions the solutions is already converged and the void fraction distribution in axial direction corresponds with the more detailed reference solution (RUN 1). The effect is evidenced in Fig. 4, where the void fraction of two tests is reported as function of height.



(a) Test 1.5222 *(b) Test 1. 5223*

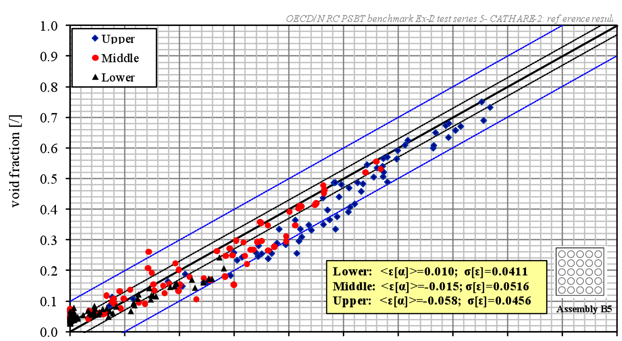
Figure 4 Test Series 1 (tests 1.5222 and 1.5223) – CATHARE2 v2.5_1 code, nodalization effect.

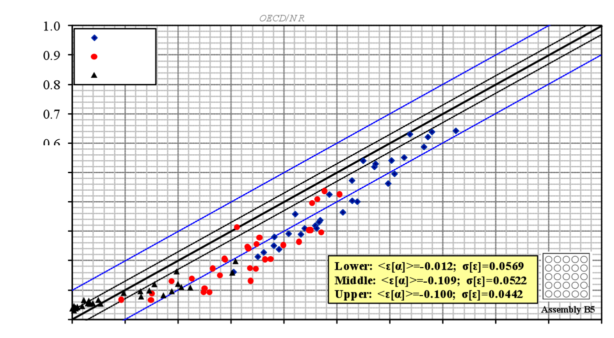
3.2 Post-test analysis of steady state bundle tests

The analysis is related to 253 tests addressing the prediction of void fraction in bundle geometry. Each test provides 3 measures at different height, thus 759 measures are available for the comparison. Four test series are analyzed: TS 5 and TS 8 are based on test section 5 with uniform axial power shape, TS 6 and TS 7 are based on test section 6 and 7, respectively, with cosine axial power shape. TS 7 has a central thimble rod.

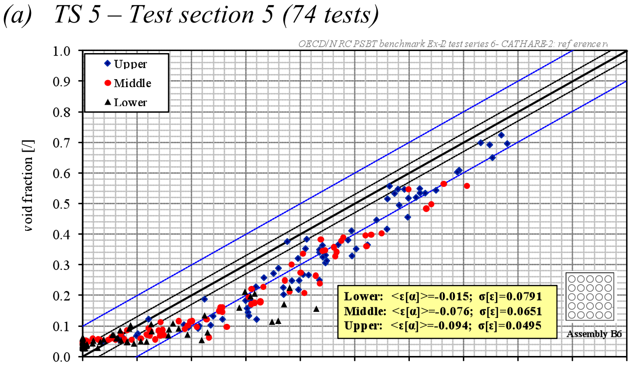
Fig. 5 reports the reference code results for the different test series. The different elevations are distinguished. Tab. 4 provides information about the average absolute errors at different ranges of void fractions (for the overall database and the different test sections), the standard deviation and the number of tests used for evaluating those values. Sensitivity calculations have been performed for evaluating the effect of the number of meshes and the influence of the initial and boundary conditions.

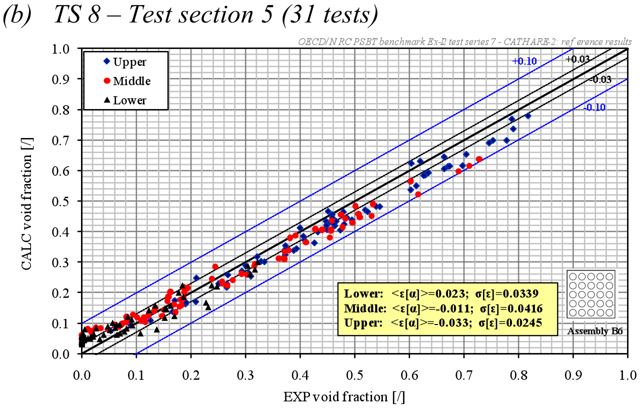
The analysis of the results confirms the tendency of the code to underestimate the void fraction. However, opposite results are observed for subcooled boiling conditions. The average absolute errors change the sign when the void fraction is in the range between 0.05 and 0.1. The maximum error calculated results for values of void fraction in the range between 0.2 and 0.4. Exceptions are the results of the test section 7, in which the average absolute errors are comparable with the standard deviation.





(a) TS 5 – Test section 5 (74 tests) *(b) TS 8 – Test section 5 (31 tests)*





(c) TS 6 – Test section 6 (74 tests) *(d) TS 7 – Test section 7 (74 tests)*

Figure 5 Overall bundle tests (253 tests) – CATHARE2 v2.5_1 code, reference results.

The different accuracy among the three different configurations (i.e. test section 5, 6 and 7) highlights the limitations of the simplified CATHARE2 model for the comparison. Indeed, the experimental data are evaluated averaging the void fraction among the four sub-channels surrounding the central rod. On the contrary, the code results represent the void fraction averaged on the bundle section for each given elevation. This explain the different performances of the code. However, from qualitative point of view the results are consistent with the sub-channel results. The analysis of the results demonstrates that the ratio of heat flux to the liquid phase and to the vapour generation and the interfacial heat transfer have opposite performances in subcooled boiling conditions and in bubbly slug and churn flow.

Table 4 Summary of bundle results by CATHARE2 code.

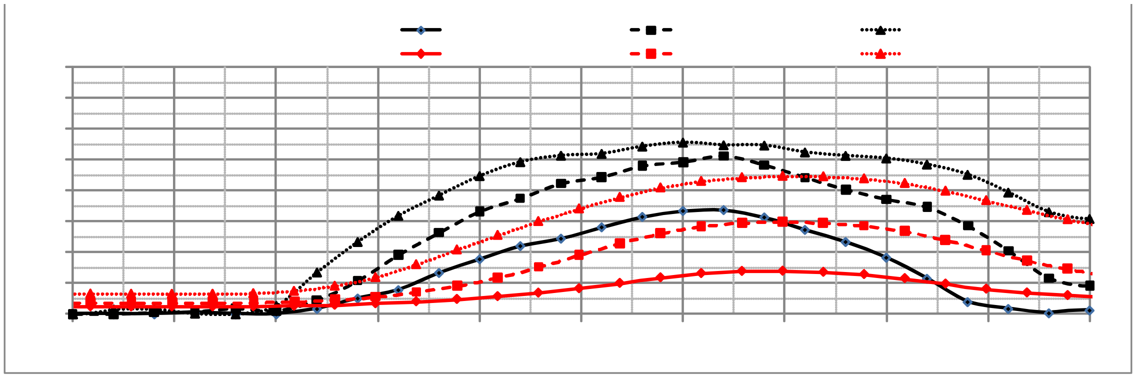
Void Fraction	TS 5 Overall			TS 6 Overall			TS 7 Overall			TS 8 Overall		
	<ε[α]>	σ[ε]	No.	<ε[α]>	σ[ε]	No.	<ε[α]>	σ[ε]	No.	<ε[α]>	σ[ε]	No.
0.0 - 0.05	0.0545	*0.0149*	54	0.0282	*0.0125*	53	0.0494	*0.0116*	51	0.0315	*0.0081*	17
0.05 - 0.10	0.0131	*0.0191*	21	-0.0095	*0.0201*	21	0.0194	*0.0155*	20	-0.0140	*0.0138*	3
0.10 - 0.15	-0.0006	*0.0461*	15	-0.0438	*0.0212*	19	-0.0099	*0.0237*	14	-0.0627	*0.0215*	4
0.15 - 0.20	-0.0278	*0.0237*	15	-0.0857	*0.0182*	11	-0.0067	*0.0245*	25	-0.0620	*0.0240*	7
0.20 - 0.30	-0.0691	*0.0337*	26	-0.1161	*0.0318*	21	-0.0270	*0.0290*	19	-0.1107	*0.0318*	10
0.30 - 0.40	-0.0716	*0.0370*	27	-0.1415	*0.0497*	33	-0.0317	*0.0192*	26	-0.1271	*0.0466*	19
0.40 - 0.60	-0.0419	*0.0455*	48	-0.1646	*0.0517*	47	-0.0411	*0.0210*	40	-0.1058	*0.0476*	25
0.60 - 0.80	-0.0325	*0.0259*	13	-0.1064	*0.0327*	17	-0.0440	*0.0290*	26	-0.0646	*0.0316*	8
0.80 - 1.00	--	--	0	--	--	0	-0.0376	--	1	--	--	0

3.3 Post-test analysis of transient bundle tests

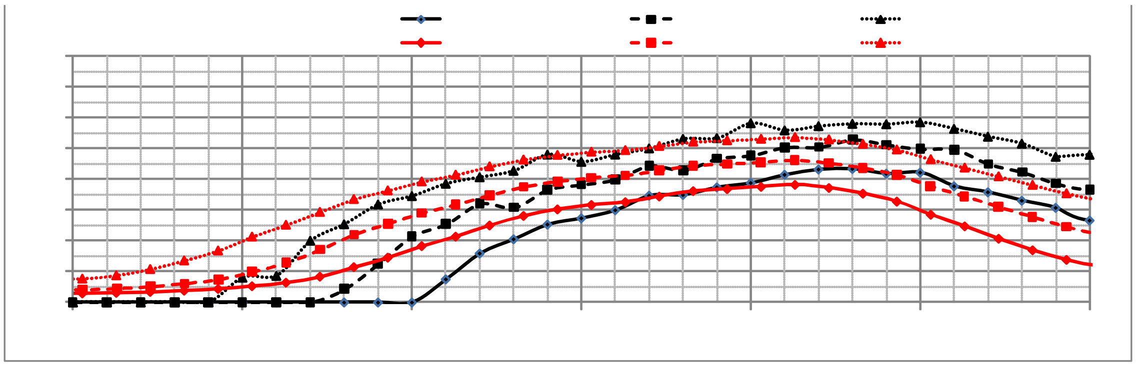
12 transient tests have been simulated, four for each bundle test section. They consist in increasing the void generation due to power increase, flow rate reduction, depressurization and coolant temperature increase.

Figs. 6 and 7 report selected results related to TS 5 and 6 in case of flow rate reduction and coolant temperature increase.

The overall results show the presence of void fraction at the beginning of the transient, which is not detected in the experiments, confirming the results of the steady state tests. In the case of flow reduction, the void fraction rises slower than in the experiment. The maximum void fraction is underestimated in the code simulation accordingly with the steady state results. Analogous results are observed in the cases of power increase and pressure reduction. Different results are obtained in the case of coolant temperature increase. The void fraction rises earlier in the code simulation than in the experiment, whereas the maximum void fraction achieved is rather well calculated.

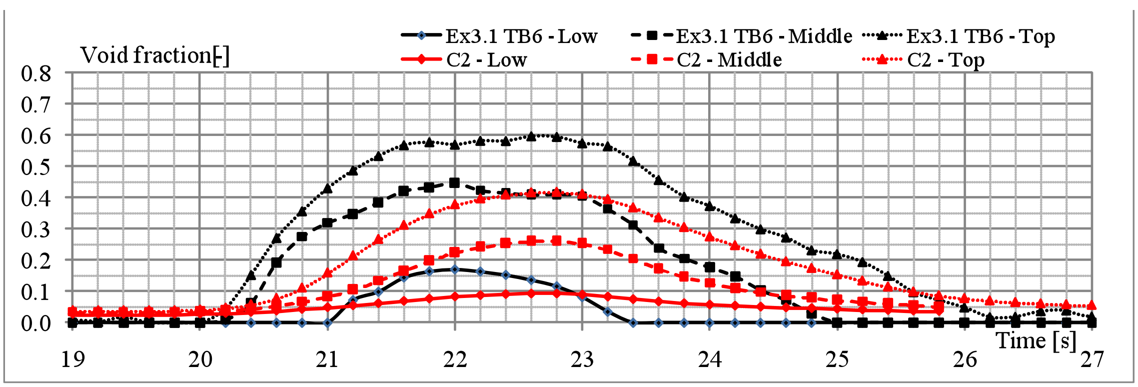


(a) Flow reduction

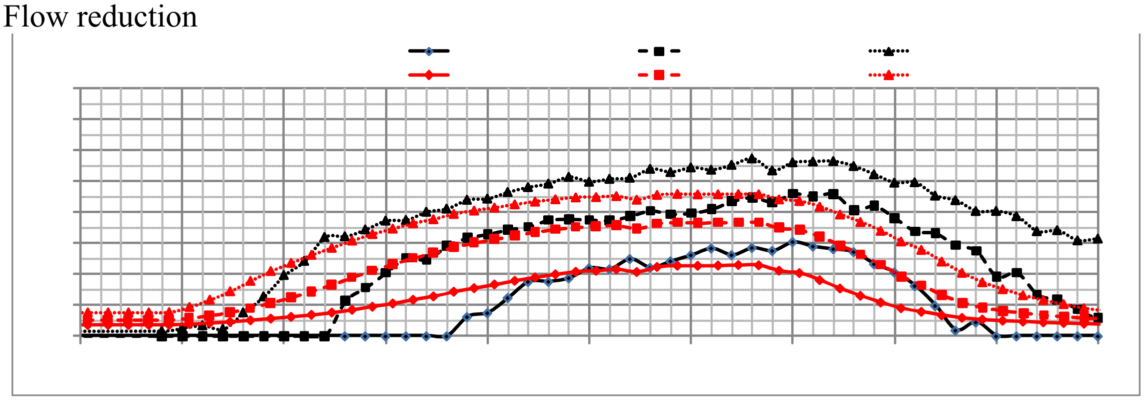


(b) *Coolant inlet temperature increase*

Figure 6 Test Series 5T, transients – CATHARE2 v2.5_1 code reference results.



(a) Flow reduction



(b) *Coolant inlet temperature increase*

Figure 7 Test Series 6T, transients – CATHARE2 v2.5_1 code reference results.

4. Conclusions

The paper presents the validation activity performed by CATHARE2 v2.5_1 code on the basis of the sub-channel experiments. The activity is part of the international benchmark NUPEC PWR Subchannel and Bundle Test (PSBT) promoted by US-NRC and OECD/NEA The experimental database is provided by NUPEC (Japan). It includes experimental measures of void fraction in a fuel assembly representative of a PWR. Four sub-channel and three bundle test sections are addressed in different thermal-hydraulic conditions (i.e. pressure, coolant temperature, mass flow and power). Sensitivity analyses are carried out investigating the effects of number of nodes and the influence of the initial and boundary conditions of the tests.

The analysis is based on 126 sub-channel tests and 253 bundle tests in steady state conditions other than 12 bundle tests in transient conditions. The analysis shows reasonable results for lower values of void fraction; underprediction for intermediate values of void fraction (i.e. $0.2 - 0.4$) and good results for higher values.

The following conclusions are pointed out.

- The void fraction is overestimated in subcooled boiling conditions. The opposite is observed in bubbly, slug and churn flow.
- The sensitivity analysis demonstrates that the prediction can be slightly improved by means of varying the boundary conditions of the simulations inside of the range of their uncertainty.
- The sensitivities addressing the effect of the number of nodes show the convergence of the mesh for number of nodes larger than 40, in case of bundle having an height of a typical PWR assembly.
- The quantitative analysis of the bundle results is affected by the simplified code modelling of the system with a single channel. Further investigations are required, for distinguishing the void fraction in the four central subchannels (e.g. applying three dimensional component).

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