PREDICTION OF VOID FRACTION IN PWR SUBCHANNEL BY CATHARE2 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, in drawing attention to their weak points, in 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. 3 field codes, 2 phase CFD, etc.) as well as for validating current generation of thermal-hydraulic system codes. Selected experiments belonging to this database are also used for the OECD/NRC PSBT benchmark. The paper presents the validation activity performed by CATHARE2 v2.5_1 (six equation, two field) code on the basis of the sub-channel experiments available in the database and performed in different test sections. Four sub-channel test sections are addressed in different thermal-hydraulic conditions (i.e. 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.*

I. 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 modeling complex flow behavior in rod bundles would promote the validation of the current approaches and the development of more mechanistic approaches [1].

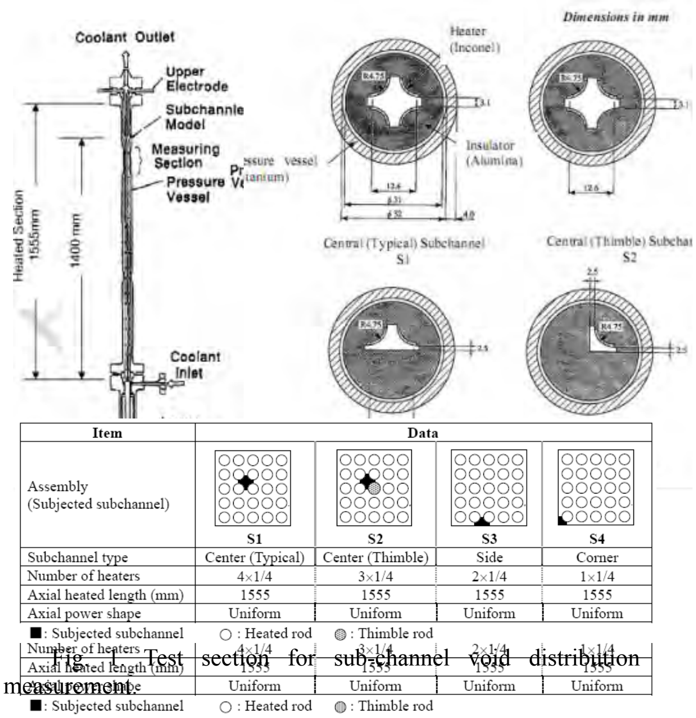
The aim of the activity is to assess the models of CATHARE2 v2.5_1 (six equation, two field) code [5, 6] on the basis of the sub-channel experiments available in the database and performed in different test sections. Four sub-channel test sections are addressed in different thermal-hydraulic conditions (i.e. 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.

II. THE 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.



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

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Fig. 1. Test section for sub-channel void distribution measurement.

TABLE I

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

The PSBT experimental database includes void fraction measurements and departure from nucleate boiling (DNB) tests, performed under steady state and transient conditions characterizing PWR operational states 3.

The void fraction tests include sub-channel experiments and the 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, among these 43 are carried out with TS 1, and TS 2 and 20 using TS 3 and TS 4 (see Fig. 1). Complete set of details about geometrical data, boundary conditions of the tests and experimental results are available in Ref. 4.

III. NUPEC PSBT void distribution post test results

III.A. modelling of PSBT test facility by CATHARE2

CATHARE2 model is 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 .

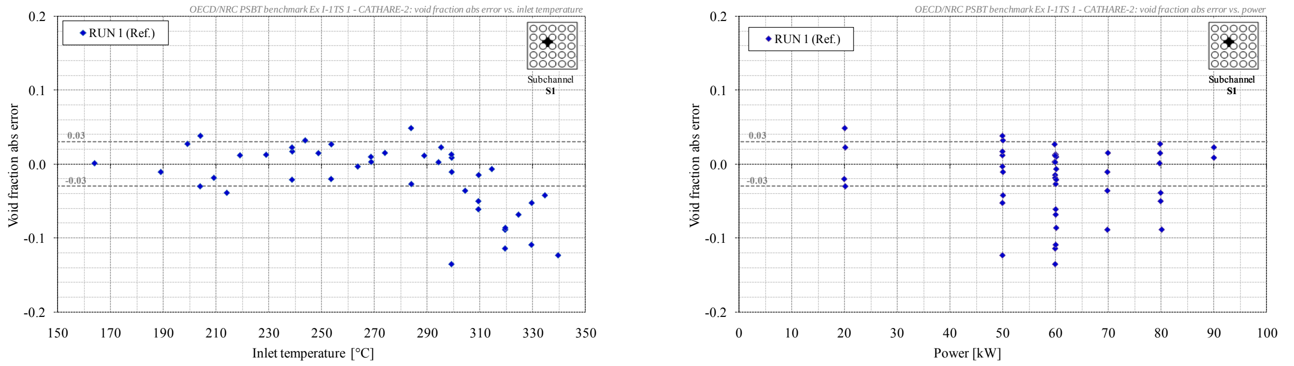
The heaters of the sub-channel test sections (TS1, TS2, TS3 and TS4) are modelled with WALL components. The linear power is constant along the axial direction.

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

III.B. CATHARE2 results

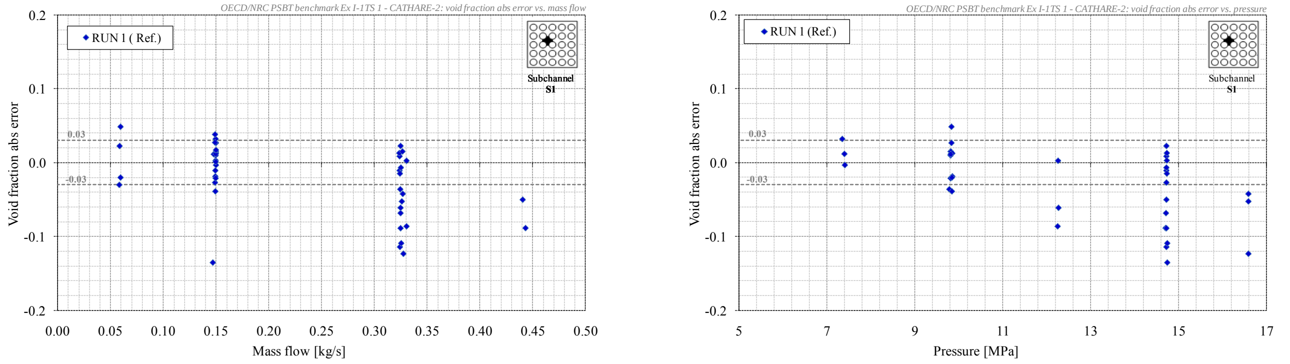
The results of four test sections are hereafter reported. Fig. 2 and Fig. 3 outline the code results in simulating the typical central sub-channels (including the case with the thimble), whereas the results of the other two test sections, referred to the side and corner geometries, are reported together in Fig. 4. The absolute void fraction errors are showed as function of the coolant inlet temperature, the subchannel power, the mass flow rate, and the system pressure in the figures (a), (b), (c) and (d), respectively. Figs. 2(e), 3(e) and 4(e) reports the absolute errors as function of the void fraction. Finally, Figs. 2(f), 3(f) and 4(f) highlights the results of the sensitivity analyses, which have been 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.

The complete list of the sensitivities performed is reported in Tab, III.



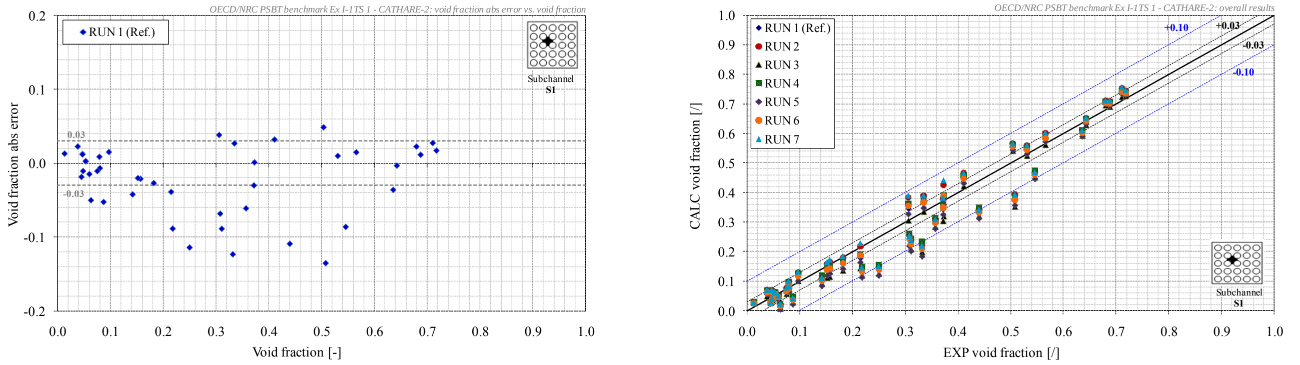
(a) void fraction absolute errors vs. inlet temperature, reference results

(b) void fraction absolute errors vs. power, reference results



(c) void fraction absolute errors vs. mass flow, reference results

(d) void fraction absolute errors vs. pressure, reference results



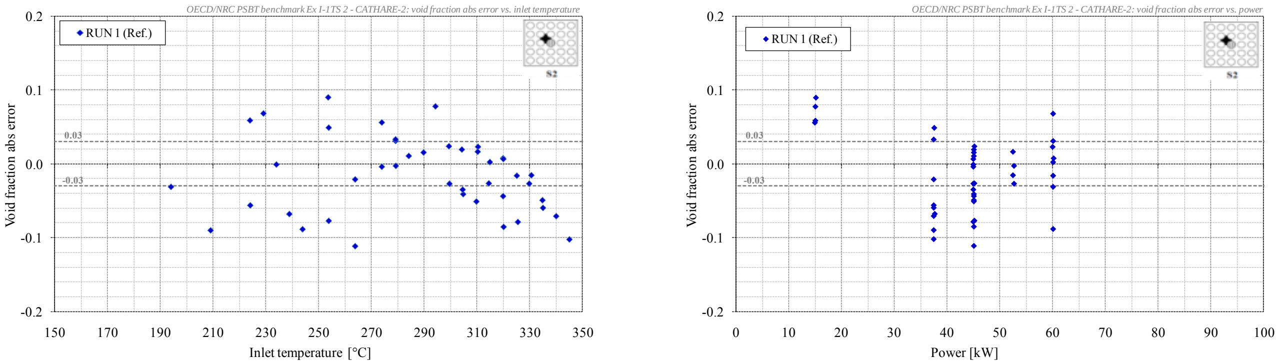
(e) void fraction absolute errors vs. void fraction, reference results

(f) void fraction exp. vs. calc., reference results and sensitivities

Fig. 2. Test Series 1 (43 tests) – CATHARE-2 v2.5_1 code, reference results and sensitivities.

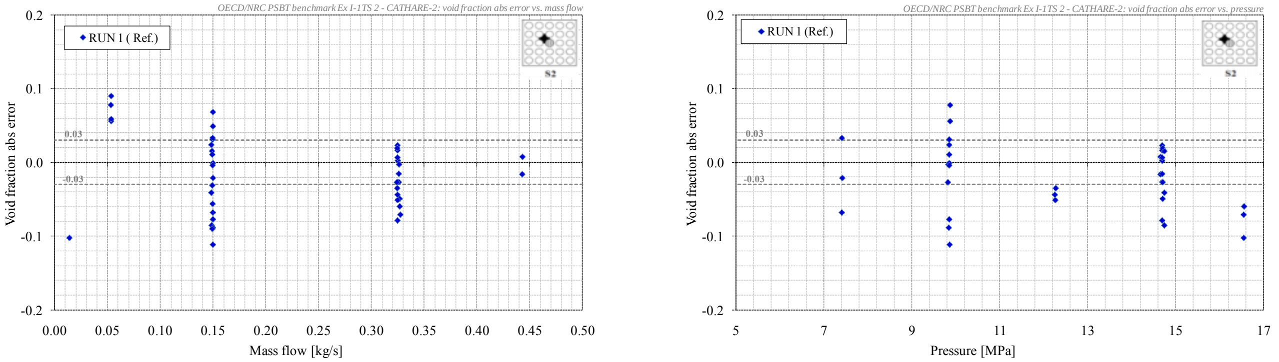
The reference results are then summarized in Fig. 5, where the results are distinguished for the different test sections. Those results are complemented with Tab. II, which provides information about the average absolute errors at different ranges of void fractions (for the overall database and the different test sections. The table reports also the number of test cases and the corresponding standard deviations.

The 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.



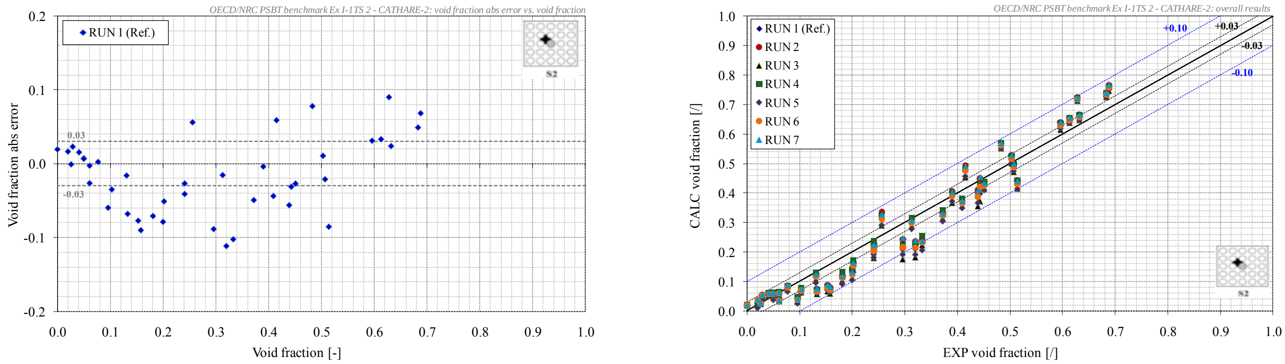
(a) void fraction absolute errors vs. inlet temperature, reference results

(b) void fraction absolute errors vs. power, reference results



(c) void fraction absolute errors vs. mass flow, reference results

(d) void fraction absolute errors vs. pressure, reference results



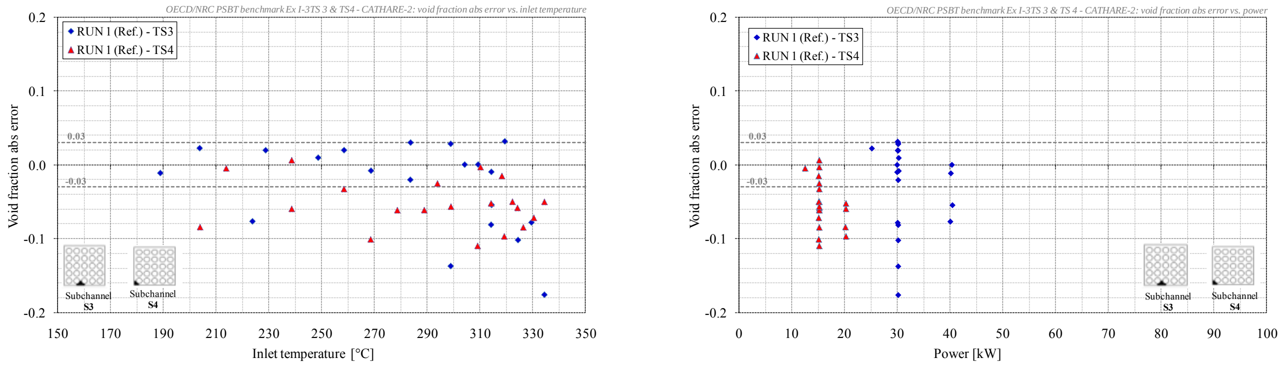
(e) void fraction absolute errors vs. void fraction, reference results

(f) void fraction exp. vs. calc., reference results and sensitivities

Fig. 3. Test Series 2 (43 tests) – CATHARE-2 v2.5_1 code, reference results and sensitivities.

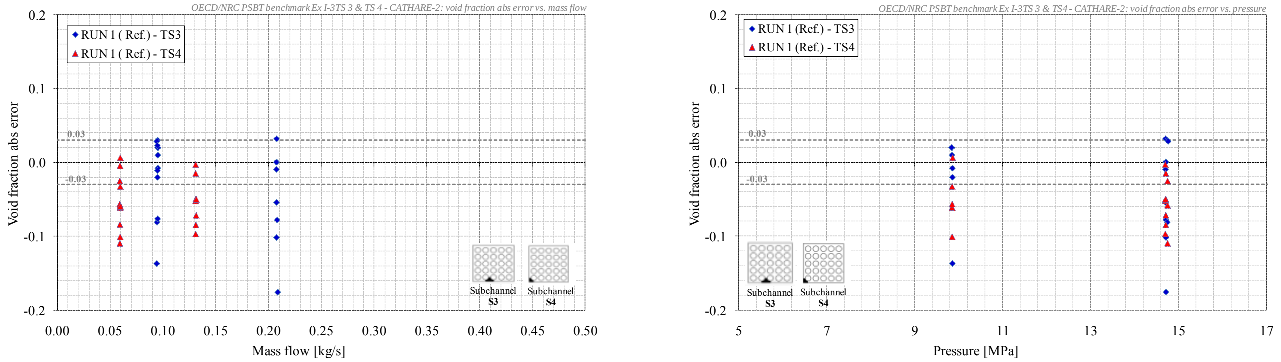
The code results are less accurate and more dispersed for values of void fraction between 0.2 and 0.6. Larger errors are observable for higher values of inlet coolant temperature and of system pressure (i.e. larger than 10 MPa).

The sensitivity analysis evidences that is possible to reduce the average absolute error up to -0.006 by means of a single variant sensitivity based on the uncertainty in the experimental boundary conditions. In particular, this result is achieved in RUN2 (Tab. III), using the minimum mass flow rate as boundary condition. However, the excellent average absolute error derives from a compensation of errors. Indeed, the dispersion of the results remains as in the reference calculation and the underestimation of void fraction between 0.2 and 0.6 is only slightly improved.



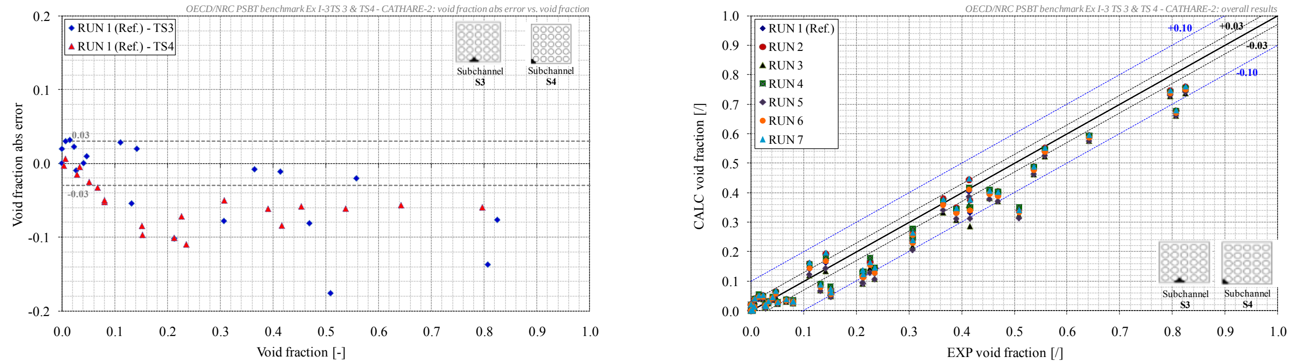
(a) void fraction absolute errors vs. inlet temperature, reference results

(b) void fraction absolute errors vs. power, reference results



(c) void fraction absolute errors vs. mass flow, reference results

(d) void fraction absolute errors vs. pressure, reference results



(e) void fraction absolute errors vs. void fraction, reference results

(f) void fraction exp. vs. calc., reference results and sensitivities

Fig. 4. Test Series 3 and 4 (40 tests) – CATHARE-2 v2.5_1 code, reference results and sensitivities.

The sensitivity analysis related with the number of axial meshes demonstrates a dependence of the axial profile of void fraction. This dependence is observed in the case of the RUN 7 (see Tab. III). In the case of 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).

Analogous results from qualitative point of view are observed in the 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 about values of void fraction equal to 0.1, then it highlights a tendency to under-estimate the test data up to about 0.6.

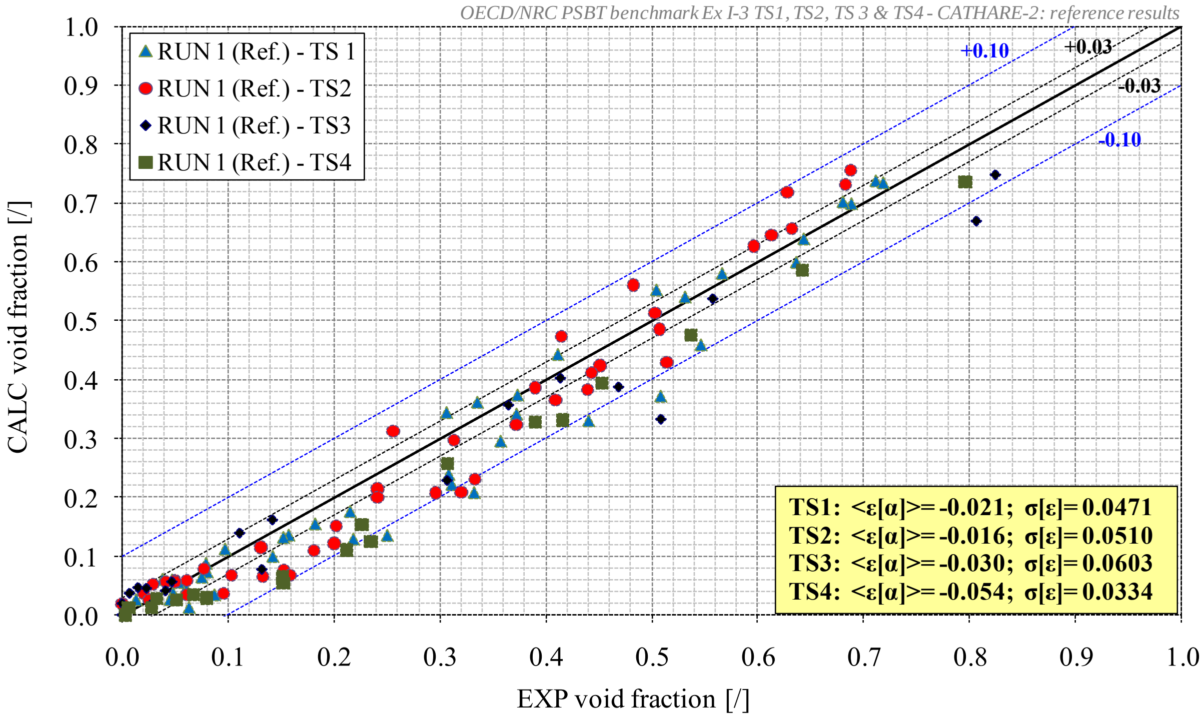


Fig. 5. Test Series 3 and 4 (40 tests) – CATHARE-2 v2.5_1 code, reference results and sensitivities.

TABLE II

Summary of results by CATHARE-2 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

TABLE III

List of NUPEC PSBT code runs by CATHARE-2 code

Test section	ID	No. of axial nodes	Pressure (1)	Mass flow (2)	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.
(2) Nominal: as specified in Ref. 4. Minimum and Maximum: according with the estimated accuracy of the measurement system.

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), demonstrating the large scatter of the results. Fig. 3(f) reports the results of the sensitivity analysis.

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.

IV. CONCLUSIONS

The paper presents the validation activity performed by CATHARE2 v2.5_1 (six equation, two field) code on the basis of the sub-channel experiments. The indentified database is developed by NUPEC (Japan) and is currently adopted for a OECD/NRC benchmark, namely PSBT. It includes experimental measures of void fraction in a fuel assembly representative of a PWR. Four sub-channel 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.

On the basis of the 126 tests simulated, the following conclusions are applied:

- the code highlights a underestimation of the void fraction. The absolute error increases with the void fraction up to the range 0.2 – 0.3 and then it slightly decreases for higher values of void fraction. For values of void fraction (>0.2), the dispersion of the results is large.
- The sensitivity analyses (sub-channel tests) demonstrate an improvement of the prediction can be achieved by means of varying the boundary conditions of the simulations inside of the range of their uncertainty. However, this is only an effect of errors compensation as testify by the standard deviation of the results, which is not affected.
- A dependence of the axial profile of void fraction from the number of axial subdivisions is also identified.

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