

VOID FRACTION PREDICTION BY CATHARE 2 OF THE OECD/NRC BFBT AND PSBT BENCHMARKS

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Abstract

The objective of the current study is to evaluate the performance of the last version of the French best estimate thermal-hydraulic code CATHARE 2 regarding void fraction prediction, comparing the analytical results with the experiments in the framework of International OECD/NRC Benchmarks based on NUPEC (Nuclear Power Engineering Corporation) BWR Full-size Fine-mesh Bundle Tests (BFBT) and PWR Subchannel and Bundle Tests (PSBT). The results show reasonable prediction of the void fraction distribution in broad range of variation of the operational parameters: pressures, mass fluxes, power and inlet subcooling, which characterize the operation of Light Water Reactors.

Introduction

The CATHARE strategy of qualification is based on: Verification, Validation procedure on separate effect tests, Validation on integral tests.

The BWR Full-size Fine-mesh Bundle Tests (BFBT) and PWR Subchannel and Bundle Tests (PSBT) Benchmark are appropriate exercises for CATHARE qualification, based on void fraction and critical heat flux predictions on the level of fuel assemblies (separate effect tests) with a typical reactor power and fluid conditions

The current paper describes the IRSN activity on CATHARE 2 void fraction predictions in the framework of both benchmarks. In BFBT benchmark the modeling and results of Exercise I-3 Transient macroscopic grade benchmark of assembly void fraction distribution for two transients: Turbine trip without bypass and Recirculation pump have been calculated. In PSBT benchmark the CATHARE 2 calculations have been carried out for Phase I - Void Distribution Benchmark, Exercise1: Steady-state Single Subchannel Benchmark.

1. CATHARE computer code

CATHARE (Code for Analysis of Thermal-Hydraulics during an Accident of Reactor and safety Evaluation) is an advanced, two-fluid, thermal-hydraulic code. It is developed in France by the French Atomic Energy Commission (CEA), Electricité de France (EDF), AREVA and Institut de Radioprotection et Sûreté Nucléaire (IRSN).

CATHARE is designed to perform best-estimate calculations of accidents in pressurized water reactor in 0D, 1D and 3D geometries. Specific modules have also been implemented to allow modeling of other reactors like VVER, boiling water reactors or gas cooled reactors. Its range of application covers all loss-of-coolant accident (LOCA), all degraded operating conditions in steam generators secondary systems, following ruptures or system malfunctions [1].

Two-phase flows are described using a two-fluid six-equation model. These equations represent conservation of mass, energy and momentum, for separate processing of liquid and steam. The presence of non-condensable gases can be taken into account by additional transport equations. This system of equation is closed by a complete set of momentum, mass and energy transfer laws for exchange at liquid/steam interfaces or at walls. Specific models are also available to represent fuel rods thermomechanics, core neutronics, reflooding, etc. [2].

In the prediction of void fraction distribution NVGP (Net Vapor Generation Point) plays an important role together with the condensation phenomena in subcooled region. Improved CATHARE modeling is applied [3, 4] based on the KIT experiments [5] with axial gamma attenuation measurements at constant and nonuniform heat flux distribution. In the last Revision 6.1 of CATHARE 2 the modified Saha-Zuber correlation, obtained as a result of KIT data statistical processing, yields the correlations (1) and (2) in two domains of Peclet number:

$$\delta_{hc} = \frac{q}{G} \times \frac{Pe}{Pe_0 + Pe} \times \frac{5.0}{65.10^{-4}}, \quad 0 < Pe/Pe_0 < 0.52 \quad (1)$$

$$\delta_{hc} = \frac{q}{Pe_0} \times \frac{2.0}{65.10^{-4}} \times \frac{1.0}{(Pe/Pe_0)^{1.4}} \times \frac{D_h \times C_{pL}}{\lambda_L}, \quad 0.52 < Pe/Pe_0 < 3.25 \quad (2)$$

Where $\delta_{hc} = (H_{Lsat} - H_L)_{SB}$ defines the beginning of the subcooled boiling. $Pe_0 = 7.10^4$, q is the heat flux (W/m^2), G is the mass flow rate ($kg/m^2.s$).

The condensation term q_{Lc} in CATHARE has been decreased for the heated pipe for better prediction (more steep void fraction profile at NVGP).

2. BFBT Full-size Fine-mesh Bundle Test

The BWR Full-size Fine-mesh Bundle Test (BFBT) consists of 2 phases with several exercises each [6]. In this paper we present the modeling and results of Exercise I-3 Transient macroscopic grade benchmark of assembly void fraction distribution for two transients: Turbine trip without bypass and Recirculation pump trip.

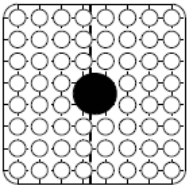
2.1 Test assembly BFBT and modeling with CATHARE

In the transient void distribution tests the assembly type 4 (see Table 1) was used with high burn-up 8×8 fuel bundle, large water rod in the centre of the bundle and uniform axial power profile. The axial heated length is 3.708 m, the fuel rod diameter is 0.0123 m.

Two types of void distribution measurements were employed: X-ray densitometers and X-ray CT scanner. The X-ray densitometers measurements were carried out in several axial positions inside the fuel assembly, providing cross-sectional averaged transient void distributions. The CT scanner measured the exit void fraction distribution (0.05 m above the heated length) with higher resolution.

Parameters of the test assembly are provided in the Table 1.

Table 1 Test assembly parameters

Item	Data			
Test assembly				
	4	C2A	C2B	C3
Simulated fuel assembly type	High burn-up 8×8			
Number of heated rods	60			
Heated rods outer diameter (mm)	12.3			
Heated rods pitch (mm)	16.2			
Axial heated length (mm)	3708			
Number of water rods	1			
Water rods outer diameter (mm)	34.0			
Channel box inner width (mm)	132.5			
Channel box corner radius (mm)	8.0			
In channel flow area (mm ²)	9463			
Spacer type	Ferrule			
Number of spacers	7			
Spacer pressure loss coefficients	1.2			
Spacer location (mm)	455, 967, 1479, 1991, 2503, 3015, 3527 (distance from bottom of heated length to spacer bottom face)			
Radial power shape	A	A	B	A
Axial power shape	Uniform	Cosine	Cosine	Inlet-peak

○ Heated rod, ● Water rod – no flow in water rods

A: Simulation pattern for beginning of operation.

B: Simulation pattern for middle of operation.

The fuel assembly is modeled by CATHARE with axial element, inlet and outlet boundary conditions and connected with junctions (Fig.1). The axial element is of the type rod bundle with 24

axial segments, which correspond to the axial meshes of the experimental power distribution if a cosine profile has to be used. The boundary conditions are imposed functions of power, flow rate, temperature and pressure.

In CATHARE the heat structures (fuel simulators) (Fig.2) are represented also with 24 axial segments as the hydraulic channel.

In radial direction the fuel rod is divided in 3 parts: heater, insulator and cladding, where the volumetric power is calculated over the whole volume, based on the external heater diameter $d=0.0073$ m.

The 7 grid spacers are modeled according to the specification of the benchmark.

The fuel rod simulator is presented in Figure 2.

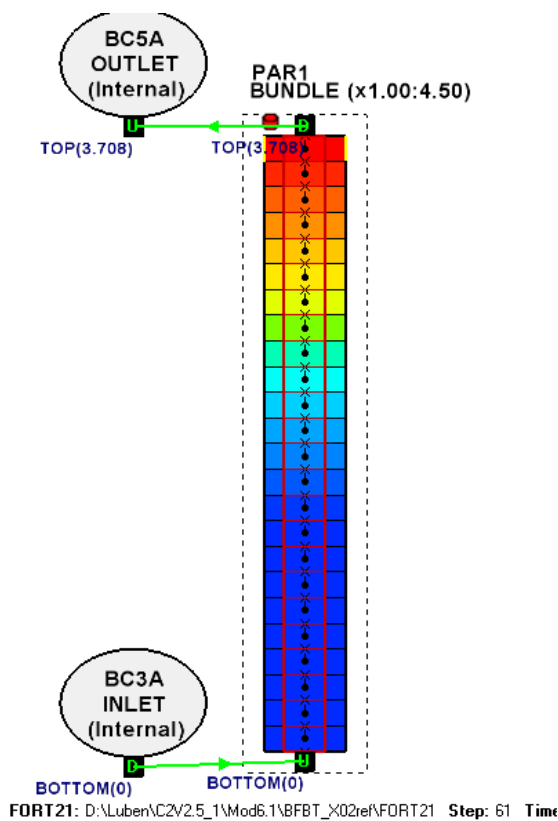


Figure 1. CATHARE model of the hydraulic assembly channel

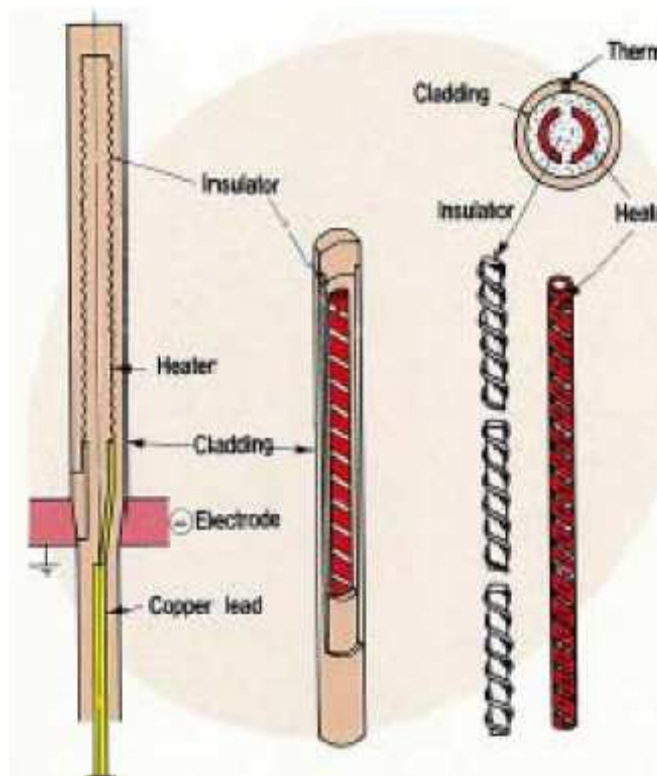


Figure 2. Fuel rod simulator

2.2 Turbine trip without bypass (Test N°4102-001~009)

The normalized boundary conditions are presented in Figure 3. These are the imposed functions of power, flow rate, temperature and pressure.

The Figure 4 provides the comparison of the transient void fraction prediction by CATHARE with the X-ray measurements at axial position 0.682m, 1.706 m and 2.73 m (averaged cross section void fraction). The void fraction distribution is reasonably predicted by CATHARE code, especially the NVGP (Net Vapor Generation Point) and the initial region of the boiling with lower void fractions. Some underprediction is observed at higher void fractions in the upper part of the fuel assembly, especially in the initial steady state period of the transient, but then the transient void distribution agrees well with the experiment. It should be noted that for comparison reasons we used the raw measurement data (no corrections). There is higher uncertainty of the experimental results of the X-ray densitometer compared to CT scanner data. The CT scanner provided lower exit void fraction than the upper most X-ray densitometer. The standard deviation of CATHARE results $\sigma = 1.12$ is among the other code predictions:

MATRA (KAERI)	MARS (KAERI)	RELAP3D (UNIP)	F-COBRA-TF (AREVA)	COBRA-TF (UPM)	RELAP5 (KTH)	CATHARE 2 (IRSN)	TRACE (KTH)
2.06	1.82	1.56	2.21	2.32	0.77	1.12	1.40

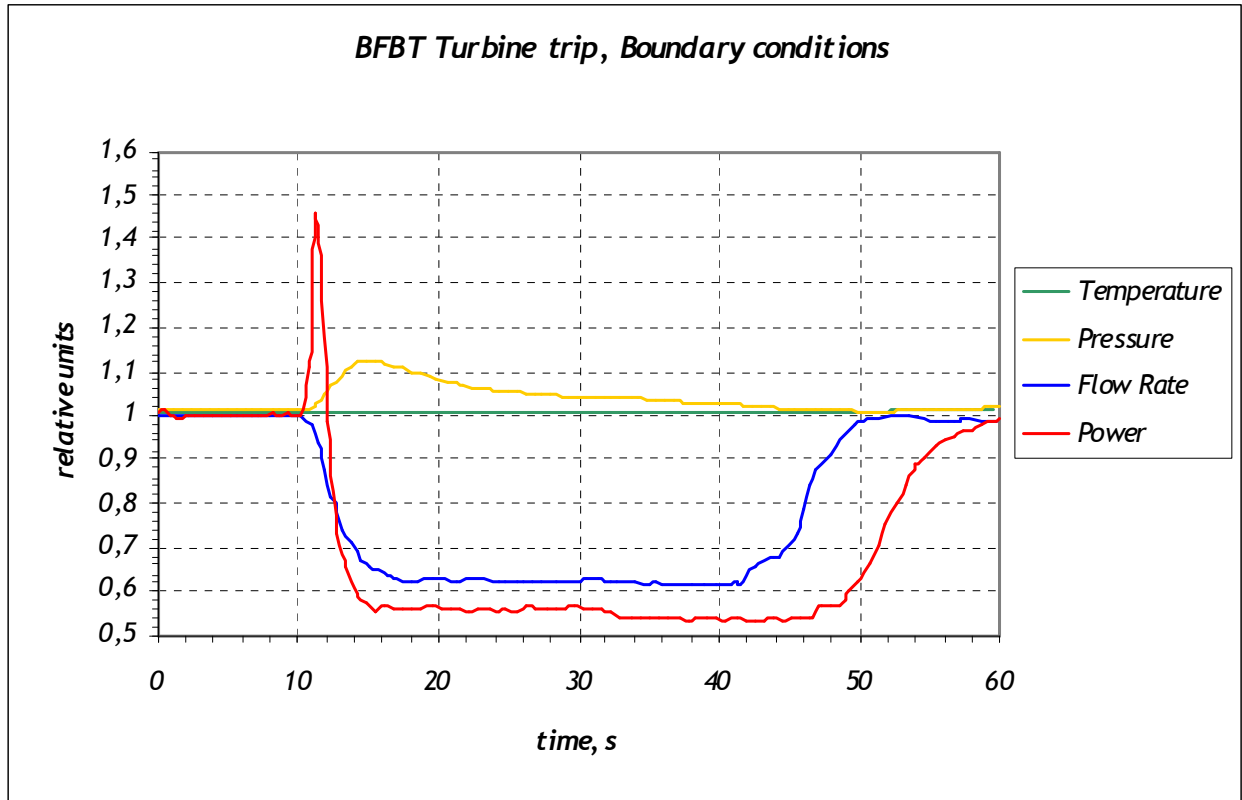


Figure 3. Normalized power, flow rate, temperature and pressure.

Void fraction, BFBT Turbine trip (4102-001~009)

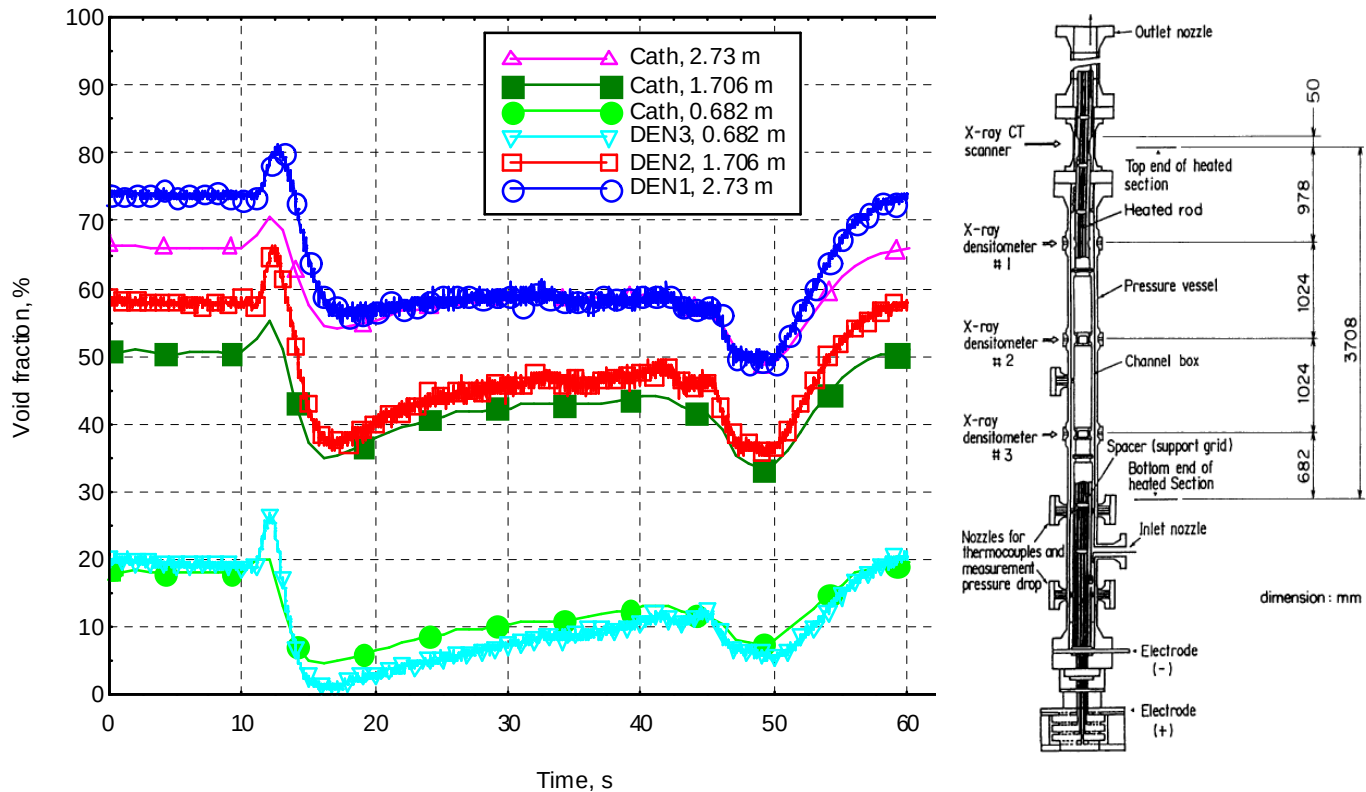


Figure 4. Comparison of transient void fraction prediction CATHARE vs. experiment

2.3 Recirculation pump trip (Test N°4102-019~027)

The normalized boundary conditions of the Recirculation pump trip transient are presented in Figure 5. These are the imposed functions of power, flow rate, temperature and pressure. The comparison of the transient void fraction CATHARE vs. measurements is given in Figure 6. The same trend of the prediction can be observed as in Turbine trip transient. The void fraction distribution is reasonably predicted by CATHARE code, especially the NVGP (Net Vapor Generation Point) and the initial region of the boiling with lower void fractions. Some underprediction is observed at higher void fractions in the upper part of the fuel assembly, especially in the initial steady state period of the transient. Then during the transient the prediction is better but remains below the measurements. There is a high uncertainty of the experimental results of the X-ray densitometer.

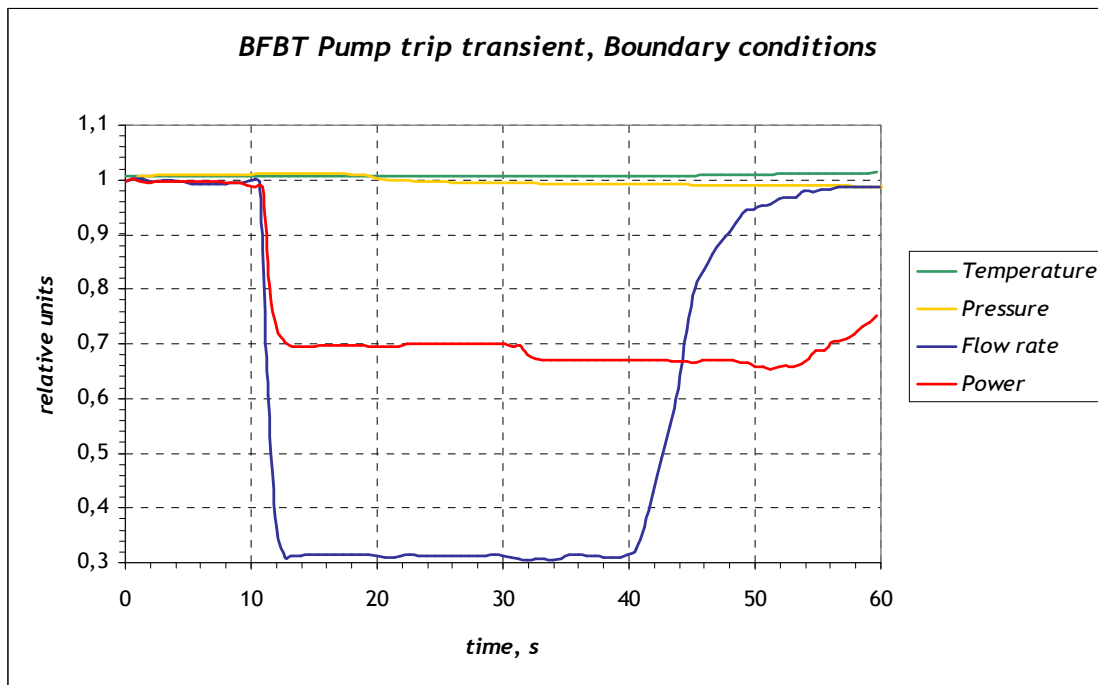


Figure 5. Normalized power, flow rate, temperature and pressure.

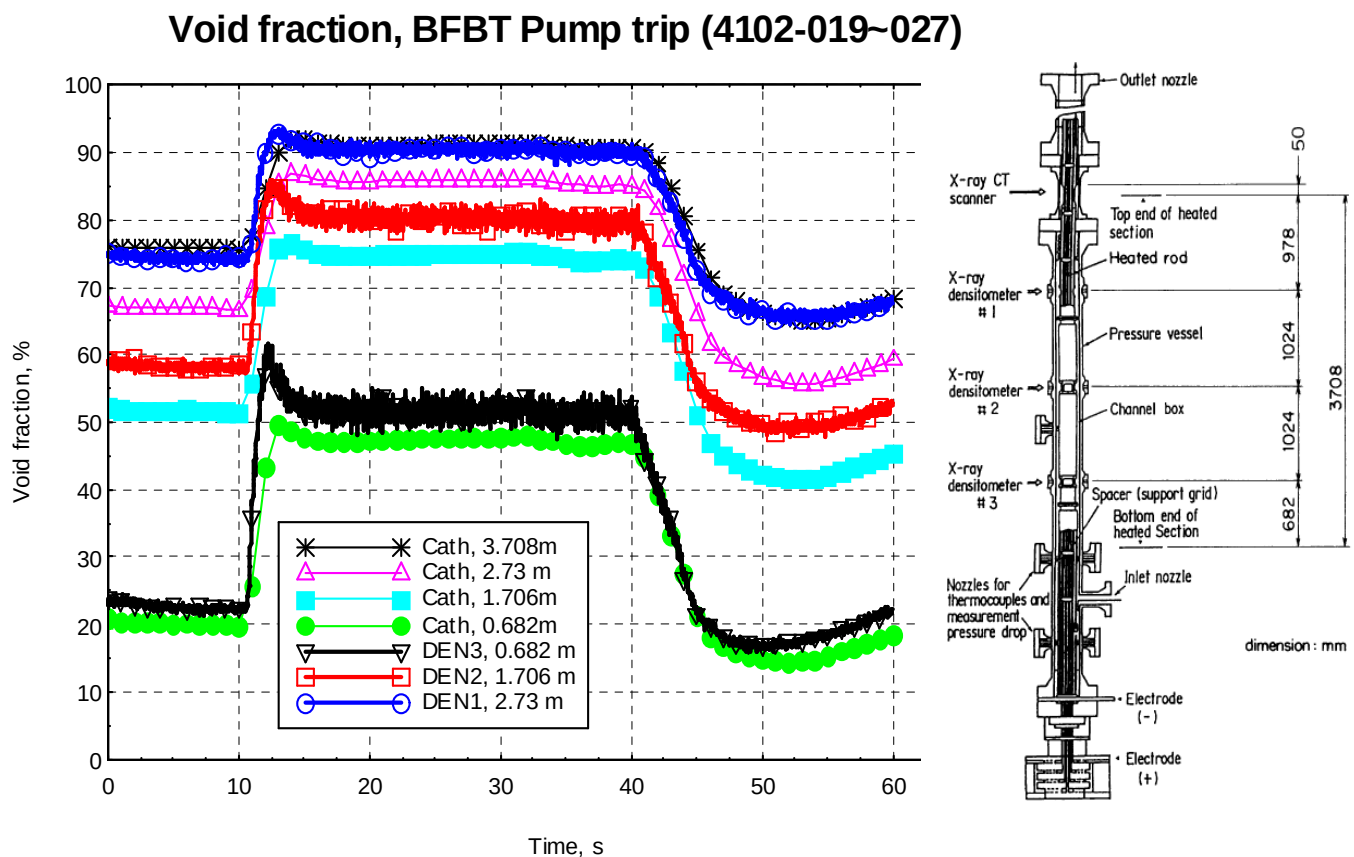


Figure 6. Comparison of transient void fraction prediction CATHARE vs. experiment

3. PSBT PWR Subchannel and Bundle Tests

The NUPEC PSBT benchmark consists of two parts (phases), each part considering different exercises:

► Phase I – Void Distribution Benchmark

► Phase II – DNB Benchmark

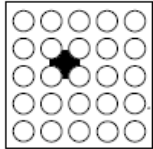
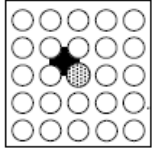
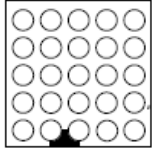
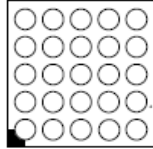
The current CATHARE 2 calculations have been carried out for Phase I - Void Distribution Benchmark, Exercise1: Steady-state Single Subchannel Benchmark.

3.1 PSBT test subchannels and modeling with CATHARE

Four different subchannel test section configurations have been calculated and compared with the experiments. The subchannels represent the flow area geometries, which can be observed in the PWR assembly: central, side, thimble and corner cells (Table 1) [7].

Table 1. Subchannel parameters

Assembly	Reference fuel type	Type of cell		Power distribution	
				Radial	Axial
S1	17×17 M	Subchannel	Center (Typical)	-	Uniform
S2			Center (Thimble)	-	Uniform
S3			Side	-	Uniform
S4			Corner	-	Uniform

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

The subchannels are modeled in CATHARE with axial elements, inlet and outlet boundary conditions and connected with junctions (Fig.7) The axial elements (heated length of 1.555m) are of the type **tube channel geometry** with 24 axial segments, which correspond to the axial meshes of the experimental power distribution if a cosine profile has to be used. Parametric study was performed also with **rod bundle** option (in CATHARE according to the geometry the physical models consider pipe, rod bundle and annular flows in the correlations)

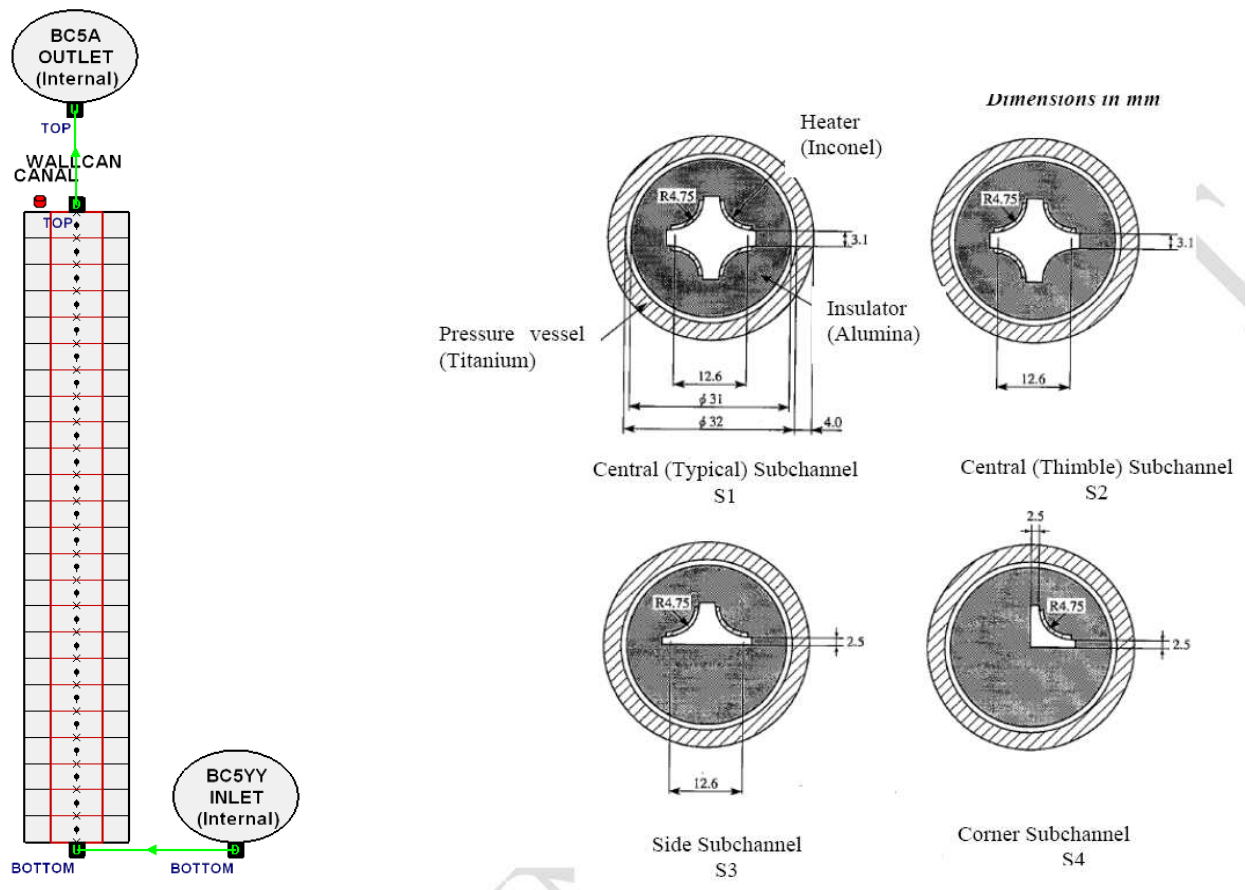


Figure 7. CATHARE model of the subchannel

In CATHARE the heat structures (fuel simulators) are represented also with 24 axial segments as the hydraulic channel.

In radial direction the fuel rod is divided in 2 parts: heater and insulator, where the volumetric power is calculated over the annular volume, based on the external and internal heater diameter respectively, $D_{ext}=9.5$ mm and $D_{int}=7.8$ mm.

3.2 CATHARE subchannel void fraction results (S1, S2, S3, S4)

The next graphics illustrate the predictions of the void fraction by CATHARE 2 code for the single cell geometries characterizing the assembly of PWR reactors: central, side, thimble and corner cells for different combination of pressures, powers, temperatures and mass flow rates (42 calculated cases).

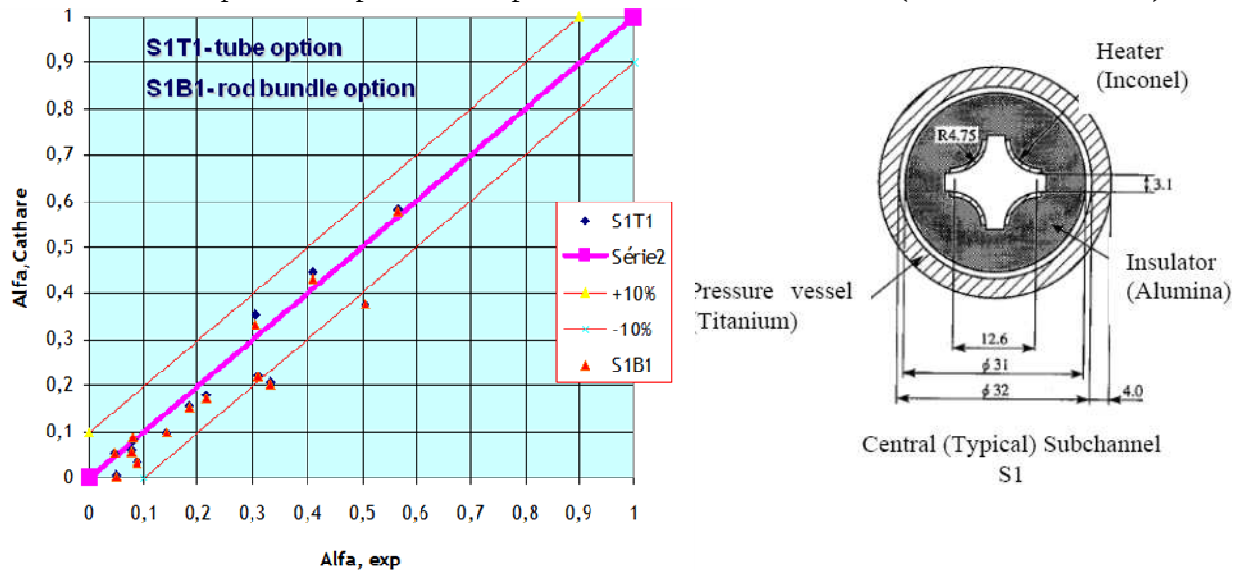


Figure 8. CATHARE void prediction vs. experiment (Test subchannel S1, Central Typical)

Illustration of the axial void fraction distribution is given in Fig.9.

(S1, Run No 1.4312 ($P = 100.2 \text{ kg/cm}^2$, $MF = 5.10^6 \text{ kg/m}^2 \cdot \text{h}$, $Pow = 79.8 \text{ kW}$, $T_{in} = 248.9^\circ \text{C}$))

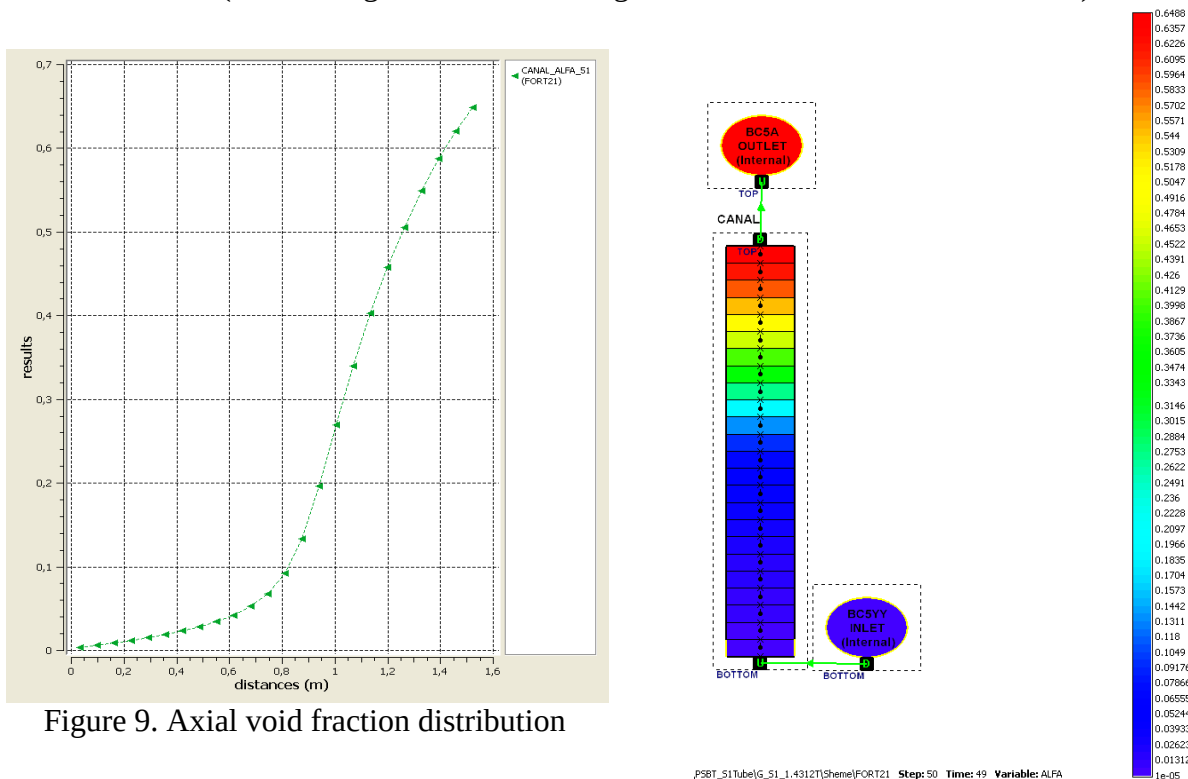
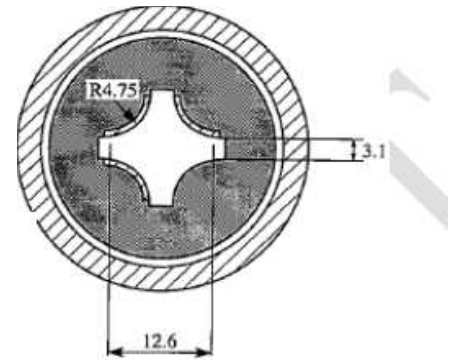
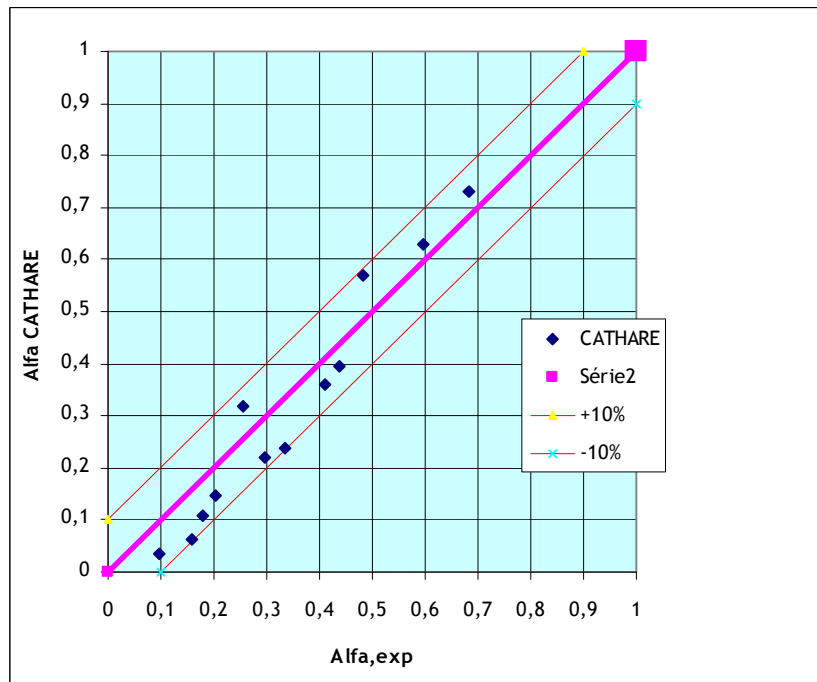


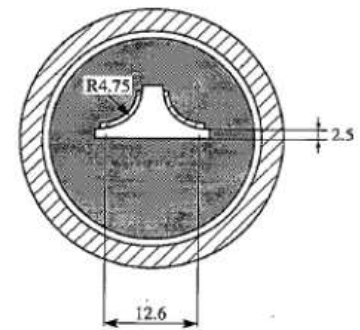
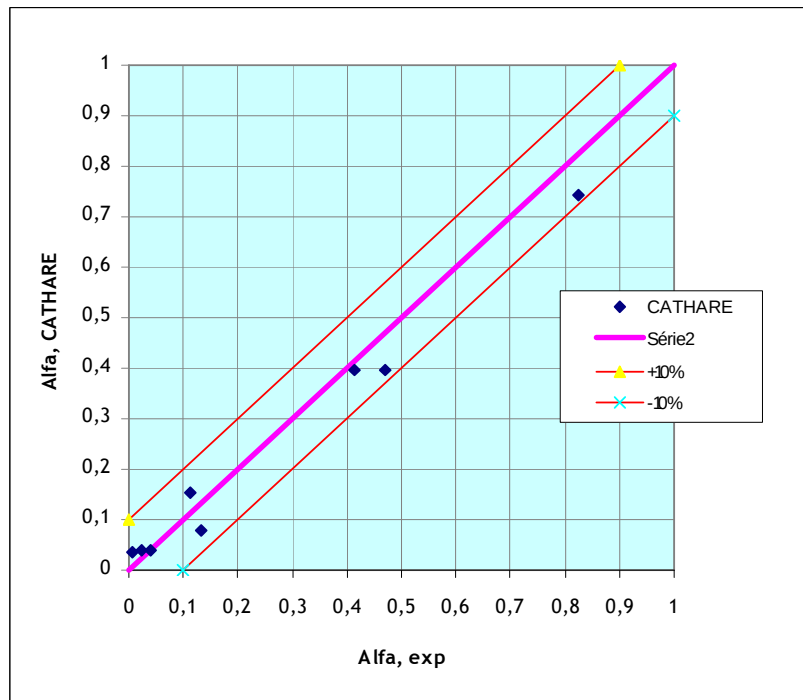
Figure 9. Axial void fraction distribution

4.



Central (Thimble) Subchannel
S2

Figure 10. CATHARE vs. experiment, Test subchannel S2, Central (Thimble)



Side Subchannel
S3

Figure 11. CATHARE vs. experiment, Test subchannel S3, Side

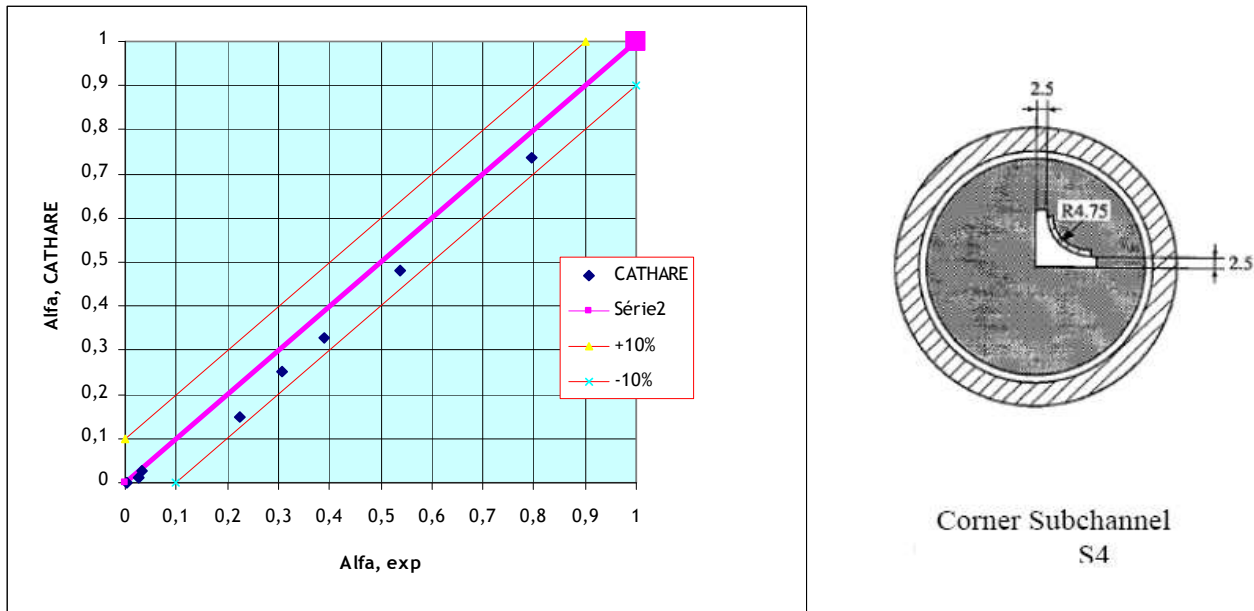


Figure 12. CATHARE vs. experiment, Test subchannel S4, Corner

5. Conclusion

The OECD BFBT and PSBT benchmarks provide excellent opportunity for system, subchannel and CFD codes validation and code to code comparison. The predictions of the French thermal-hydraulic code CATHARE 2 are generally in good agreement with the transient void fraction tests of BFBT (turbine trip and recirculation pump trip) regarding especially the NVGP (Net Vapor Generation Point) and the initial region of the boiling with lower void fractions (subcooled boiling). Some underprediction is observed at higher void fractions in the upper part of the fuel assembly in the initial steady state period of the transient, but then the transient void distribution is in reasonable agreement with the experiment (measurement uncertainties have to be taken into consideration). The stationary single subchannel tests (central, thimble, side and corner cells) of PSBT benchmark with typical reactor parameters and flow conditions of PWR are relatively well predicted by CATHARE especially in subcooled regions with low void fractions. Higher deviation is observed at higher void fractions. As a whole the deviations of the calculated void fractions are in the domain less than 10% (the measurement uncertainty is evaluated to be about 4%). In the current study cases recommended by the benchmark team have been considered. For better statistics all experimental results provided by NUPEC should be calculated.

6. Acknowledgement

The study is carried out for the assessment of CATHARE 2 code jointly developed by the French Atomic Energy Commission (CEA), Electricité de France (EDF), AREVA and Institut de Radioprotection et Sûreté Nucléaire (IRSN). The experimental results are provided in the framework of the International OECD/NRC Benchmarks based on the Japanese NUPEC (Nuclear Power Engineering Corporation) BWR Full-size Fine-mesh Bundle Tests (BFBT) and PWR Subchannel and Bundle Tests (PSBT). Special thanks to the Benchmark Team of the Penn State University for the good organization and coordination of the activity.

7. References

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