# VALIDATION OF CATHARE 3 CODE ON THE PIERO EXPERIMENT

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**ABSTRACT**

The CATHARE 2 code is the French reference code for safety analysis. The new version of the code CATHARE 3, still in development, will allow a better simulation of thermal hydraulic flows in a nuclear power plant. The CATHARE 3 code has to be validated on several kinds of accidents that can occur. Plus, its results shall also be compared to the CATHARE 2 code ones, to avoid any physical regression.

For the validation and verification of the 3D module of the CATHARE 3 code, the PIERO experiment has been used. This experiment has been carried out to study phases' separation in the lower plenum and the downcomer of a Pressurized Water Reactor (PWR) during the end of the depressurization phase of a Large Break Loss of Coolant Accident (LB-LOCA). The good calculation of these phases is of prime importance for establishing the initial conditions of the core reflooding phase, especially concerning the amount of water remaining in the lower plenum.

The results given by the CATHARE 2 code are not satisfactory due to an overestimation of the liquid entrainment in the lower plenum through the use of a coarse meshing for modelling the PIERO experiment.

To evaluate the meshing effect on the CATHARE 2 and CATHARE 3 codes, three different meshing were used. Sensitivity studies using a thinner meshing gives a better estimation of the water level with the CATHARE 2 and CATHARE 3 codes. Nevertheless, with the CATHARE 3 code the method used for determining the water level remaining gives differences.

**KEYWORDS**

CATHARE 2, CATHARE 3, PIERO, PWR, LB-LOCA

## 1. INTRODUCTION

In the framework of Pressurized Water Reactor (PWR) safety studies, Large Break Loss of Coolant Accident (LB-LOCA) prediction is still one of the most important and one of the most difficult problems to solve. For the validation and the verification of the 3D module of the CATHARE 3 code, the refill phase of the LB-LOCA concerning the lower plenum voiding has been studied. The good calculation of this phase is of prime importance for establishing the initial conditions of the core reflooding phase, especially concerning the amount of water remaining in the lower plenum.

During a LB-LOCA, the lower plenum voiding occurs during the blowdown phase. The steam generated in the reactor flows out of the bottom of the core through the lower plenum towards the downcomer and the broken cold leg. If the steam flow rate is high enough, it can extract water from the lower plenum and empty it partially or totally.
The 3D module of the CATHARE 3 code has been assessed on the PIERO experiment [1] which was conducted to simulate lower plenum voiding and to study phases separation in the lower plenum but the results are not very conclusive.
This document presents an overview of the CATHARE code, the PIERO experiment and the assessment results.

## 2. CATHARE PRESENTATION

### 2.1. CATHARE 2 General Description

CATHARE 2 [2] is an advanced best estimate code used for PWR safety analyzes, accident management, definition of plant operating procedures and for research and development. The code is developed in Grenoble (France) by a joint effort of *Commissariat à l'Énergie Atomique* (CEA), *Électricité De France* (EDF), AREVA and *Institut de Radioprotection et de Sûreté Nucléaire* (IRSN). Two-phase flows are described using a two-fluid six-equation model and the presence of one to four non-condensable gases can be taken into account. CATHARE 2 can model any water-cooled reactor or test facility using several available modules (0D, 1D, 3D module).
The code allows a three-dimensional modelling of mainly the pressure vessel. The main purpose of the 3D module of the CATHARE 2 code is the representation of large scale thermal-hydraulic 3D effects in nuclear power plants. The 3D module is based on the two-fluid six-equation model. The basic set of equation consists of ten thermal-hydraulic differential equations. The mass and energy balance equations are of primary form whereas the momentum equations are of secondary form. The presence of one to four non-condensable gases can be taken into account by adding one to four transport equations. The numerical choices are finite volume discretization with structured mesh, first order discretization in space and time, staggered spatial mesh and donor cell principle, a semi-implicit scheme is used. Two coordinate options are available: either Cartesian coordinates, or cylindrical coordinates.
A qualified set of constitutive relationships is directly extrapolated from those of the 1D element, extended over the three directions and with some specificity: no stratification, nor added mass terms. Inertial force and interfacial friction play a dominant role in the phase distribution as well as interfacial heat and mass transfer.
A specific validation program has been developed for the 3D vessel application considering both separate effect tests and integral tests. It includes PIERO tests for lower plenum voiding, UPTF tests for downcomer refill and upper plenum behavior during a LB-LOCA [3], and PERICLES tests for core uncover and for core reflood [4].

### 2.2. CATHARE 3 Presentation

In 2006, CEA, EDF, AREVA and IRSN launched the development of CATHARE 3 and defined the main targets for the new code in terms of physical models, numerical methods and software architecture [5]. The roadmap of CATHARE 3 was defined in order to achieve a smooth transition between CATHARE 2 and CATHARE 3 for all the users. The new code includes all CATHARE 2 physical models, and modeling options, and has the same level of validation, robustness, performances and qualification. The main objectives for the CATHARE 3 code are:

- Advanced physical modelling of two-phase flows, mainly by using multi-field and turbulence models,
- Improved 3D modeling by using thinner and non-conforming structured meshes,
- Generalized coupling abilities with other thermal-hydraulic scales and other disciplines (core physics, structural mechanics, …),

- Extension of the applicability to new Gen IV reactors (Sodium Cooled Fast Breeder Reactors, Gas Cooled Reactors, Supercritical Light Water Reactors),
- True oriented-object code architecture.

## 3. PIERO PRESENTATION

The PIERO experiment [6] has been carried out to study phases' separation in the lower plenum and the downcomer of a PWR during the end of the depressurization phase of a LB-LOCA. This PIERO experiment focused on mechanical phenomena like water entrainment from the lower plenum towards the downcomer. The fluids are water and air under atmospheric pressure unlike the reactor case where fluids are liquid and steam water under few bar.

### 3.1. PIERO test facility

The PIERO test section, which is shown on Figure 1, represents a two-dimensional cross section of the lower plenum and the downcomer. The scaling factor is ¼ of a French PWR for the geometry.
The thickness of the test section is equal to 150 mm. The lower core plate is 100 mm thick and ten holes (I.D. 55 mm) are pierced. The downcomer is 50 mm width and its bottom is located at 625 mm under the exit. The exit cross section is 100 mm high and 150 mm thick. The radius of the lower plenum is 500 mm (scaling factor ¼ applied to a 2 m radius of the reference reactor). The lower face of the lower core plate is located at 434 mm from the bottom of the lower plenum. An air-water mixture can be injected at the top of the system.

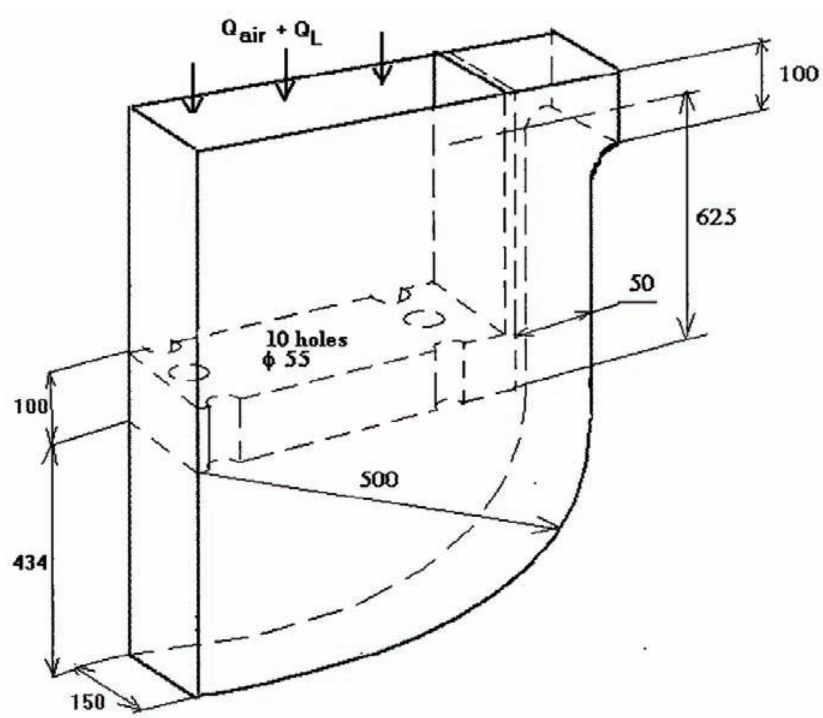


**Figure 1. Scheme of the PIERO test facility.**

### 3.2. Experimental Conditions

Several tests have been carried out on PIERO facility in order to analyze phases' separation in the lower plenum. For each test, the fluids are water and air under atmospheric pressure. Air or air-water

mixture is injected at the top of the system, above the core tie plate, by a fan at a given flowrate which can vary from 50 to 3500 $m^3$/h.
Each test carried out on the PIERO facility follows the same scenario. At the beginning of one test, there is no air and liquid flowrates injected, and the liquid level in the lower head is high enough in order to have water entrainment when the air flowrate is imposed. After that, constant air and liquid flowrates are imposed until an equilibrium state is obtained. Such as, there is a balance between the inlet liquid flowrate and the driven liquid flowrate at the exit of the system. For the tests with no inlet liquid flowrate, the equilibrium is reached when no more liquid is dragged along the exit of the facility. Finally, the height of the water level in the lower plenum has been measured for each test.

### 3.3. Instrumentation

At the inlet, air flowrate has been measured with an error not greater than 5%. The water flowrate is also measured, and then the computed liquid fraction is given with an error inferior to 1%. Both air and water flowrates corresponds to inlet boundary conditions of the PIERO test facility.
The key parameter, which is the level in the lower head, has been measured by visualization since the front plate of the experiment is transparent. Given that this level was not horizontal in the lower plenum at the end of the test, its determination was made only by measure of a medium level. This medium level is acquired after cutting the air and water flowrates at the inlet of the facility. In fact, it represents the water inventory in the lower head after reaching the equilibrium state.

### 3.4. Experimental Results

The experimental results [6] are given by triplets composed of the inlet air flowrate, the inlet water fraction, and the measured level in the lower plenum at the equilibrium.
Three main conclusions were carried out on the PIERO experiment, the level in the lower plenum drops when the inlet air flowrate increases, the influence of the water title is weak, and the results of the tests were able to be found by using a model proposed by Wallis [7].

## 4. CATHARE 3 VALIDATION RESULTS

### 4.1. PIERO Modeling with CATHARE

The PIERO test section is modelled with the 3D CATHARE module sing a two-dimensional Cartesian meshing. The qualification work [1] is conducted with a meshing having 10 meshes along Z direction, 5 meshes along Y direction, and 1 mesh along X direction (Figure 2), for a total of 50 meshes.

It was shown in the reference [7] that assessment with the CATHARE 2 for the PIERO experiment needed a refined mesh or the development of a model of stratification to take into account the evaluation of the level in the lower plenum.
Using a Cartesian meshing, the fluid volume has to be calculated for each cell and also the available fluid face area on each face of the cells to simulate the circular shape of the lower plenum. The air flowrate and eventually a droplet liquid flowrate are imposed at the inlet boundary conditions.

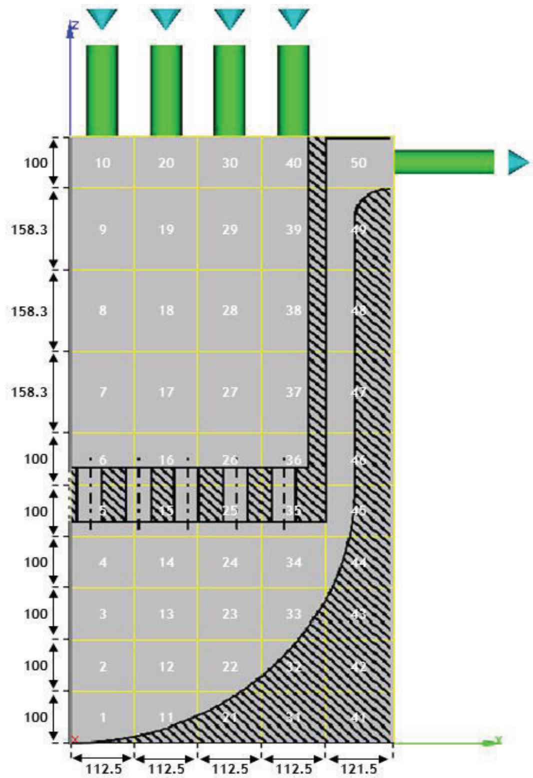

**Figure 2. CATHARE modelling of the PIERO experiment.**

### 4.2. Calculation's Procedure

For the calculations, the experimental procedure described in 3.2 is exactly reproduced: a sufficient amount of liquid is initially brought in the lower plenum in order to locate the water level at approximately 420 mm above the bottom of the lower head. The calculation is run until stabilization of thermal-hydraulic parameters (void fraction) and equality of the inlet and outlet liquid flowrates. The stabilized liquid level and the mass in the lower plenum are then calculated and then compared to the experimental ones.

### 4.3. Level and mass calculation

The water level in the 3D module isn't directly accessible either in CATHARE 2, or in CATHARE 3. In order to calculate the level and the mass remaining in the experiment at the end of each test, two methods were used [8].
The first one, so called void fraction method, uses the void fraction field in the 3D element. For each mesh, the void fraction is retrieved at the end of the test. Then, the water level is determined by averaging the filling of the five columns of the meshing, as shown by equation (1).

$$\mathrm{H} = \frac{1}{5}\sum_{j=1}^{5}\left[\sum_{i\in\mathrm{Column}\,j}(1-\alpha_i)\mathrm{Z}_i\right] \qquad (1)$$

where H is the level of water remaining in the lower plenum, $\alpha_i$ is the void fraction of mesh i, and $Z_i$ is the height of mesh i. The mass calculation (2) also uses the void fraction field with the volume of each mesh ($V_i$) and the liquid density of water ($\rho_{water}$).

$$\mathrm{m_{tot}} = \sum_{i\in \mathrm{mesh}} \rho_{\mathrm{water}}.\mathrm{V_i}.(1-\alpha_i) \qquad (2)$$

The second one, called the flowrate method, calculate the level and mass remaining using the mass balance. The total mass at the end of each test is calculated (3) by integrating on the whole test the difference between the inlet water flowrate ($q_{inlet}$) and the outlet water flowrate ($q_{outlet}$).

$$m_{tot} = \int_{t_{begin}}^{t_{end}} (q_{outlet} - q_{inlet}) dt \tag{3}$$

For each test, the functional point of the test is far from the saturation point, there is no phase change during the tests. Knowing the geometry of the test section, the level in the lower plenum can be directly calculated from the liquid mass (4).

$$m_{tot} = \frac{l_X \rho_{water} R^2}{2} \left[ \arcsin\left[\frac{H}{R} - 1\right] + \frac{\pi}{2} + \frac{1}{2} \sin\left(2 \arcsin\left[\frac{H}{R} - 1\right]\right)\right] \tag{4}$$

where $l_X$ is the width of the test section and R is the curvature's radius of the lower plenum.

### 4.4. Validation Results

A total of 89 tests has been performed experimentally, corresponding to different air and liquid inlet flowrates. The results presented in this paper concern exclusively the tests without liquid flowrate in entrance. Five different tests have been selected for the calculations. A comparison between CATHARE 2 results, CATHARE 3 results and the experiment is shown on Figure 3 for the level calculated.

On the following figures, C2 refers to calculations done with CATHARE 2, and C3 refers to calculations done with CATHARE 3.

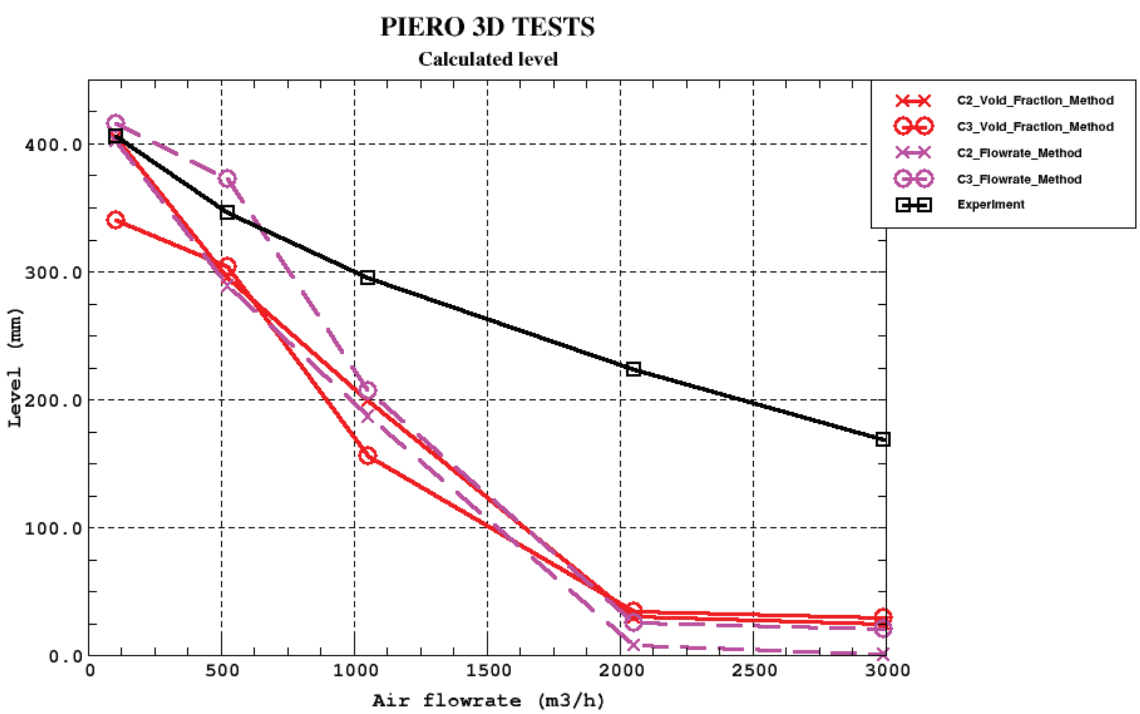


**Figure 3. Comparison of the level measurement.**

Except at the lower air flowrates, the calculated water levels are systematically underestimated by both CATHARE 2 and CATHARE 3 in comparison with the experiment. For the higher air flowrates, the calculated water level is almost zero, indicating that no liquid is remaining in the bottom of the lower head for both codes with both methods. This clearly shows that CATHARE 2 and CATHARE 3 underestimate the water level in particular for the higher air flowrates.

In one hand, this tendency can be explain by a too strong liquid entrainment in the calculation. The liquid entrainment is the result of a competition between the interfacial friction force and the gravity force. So, several sensitivity tests [1] have been computed where the interfacial friction force has been reduced in order to improve the CATHARE code prediction, but results were not conclusive. Moreover, it appeared that a free surface localization model is necessary to predict the PIERO experiment well, model being missing both in CATHARE 2 and CATHARE 3 nowadays.

In the other hand, in the CATHARE 2 and CATHARE 3 calculations, the liquid water in the lower head is drained step by step, each step corresponding to the drainage of one horizontal mesh layer. This causes a strong sensitivity to the meshing used to describe the lower head of the lower plenum.

Finally, two ways of improvement are possible: the first one, and the most complicated, is to introduce a stratification model (or a free surface localization model) in the 3D module of CATHARE [7]. The other one is a possibility to use a thinner meshing. The second way has been performed and results are presented in this paper.

Moreover, unless CATHARE 2 shows no difference in the results between both methods, CATHARE 3 results vary much more with the method used for calculating the level. The level calculated is mainly affected by the liquid mass remaining in the lower plenum. In this case, CATHARE 3 presents an important mass default. The mass calculated with the flowrate method leads to a better estimation of the water level at least for the low-air-flowrate tests. As for the level, the mass default is strongly affected by the meshing used.

### 4.5. PIERO Meshing Refinement

The meshing sensitivity consists in refining the 3D vessel meshing only in the Z direction in the lower plenum. Two meshing have been tested and are presented on Figure 4. First, the experiment has been meshed with 13 axial meshes along the Z direction, for a total of 65 meshes. The refinement is located underneath the core support plate in the area where the free surface should be located and the main entrainment phenomena occur. The second meshing is based on 20 meshes along Z direction, for a total of 100 meshes. The refining mainly concerns the hemispherical part of the lower plenum which has most impact on PIERO results.

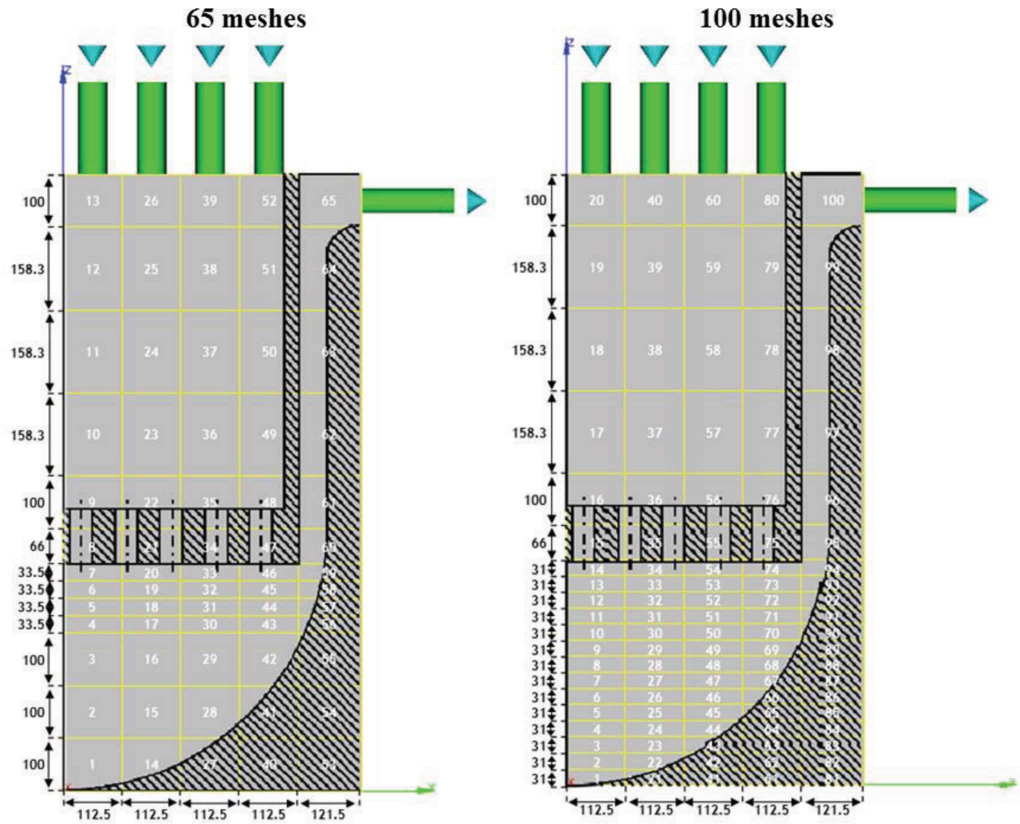


**Figure 4. PIERO meshing refinements.**

The results of the calculations with CATHARE 2 and CATHARE 3 for the three different meshing are compared to the experimental results. The calculated level using the void fraction method is shown on Figure 5 and the calculated level using the flowrate method is shown on Figure 6.

The results show that the thinner the meshing is, the better the CATHARE 2 and CATHARE 3 prediction is. In fact, the results with the thinnest meshing with 100 meshes are close to the experimental results for the lower air flowrate tests and tend to slightly overestimate the experimental results for the higher air flowrate tests. However, the thinner the meshing is, the greater the CPU time is. In fact, for both codes, the CPU time is 3 times greater for the meshing with 100 meshes than for the meshing with 50 meshes. But, as the calculus are quite fast (the maximum CPU time recorded is about half an hour), this time growth is considered reasonable in the sight of the sharp improvement of the obtained results.

In terms of non-regression, the best method to calculate the water level is the void fraction method. For all the meshing used, the results given by CATHARE 3 are close to the CATHARE 2 ones. Furthermore, the thinnest meshing used gives the best results with a difference not greater than 0.05% between CATHARE 2 and CATHARE 3 except for the lowest air flowrate test.

Nevertheless, in terms of physical representation, the flowrate method is the most suitable method. Indeed, by using this method, the mass balance is strictly applied to the system whereas the void fraction method just controls the presence of water in each mesh. Theoretically, if the mass balance is well calculated by the code, the two methods should give the same results. It is actually the case for CATHARE 2, but this isn't for CATHARE 3

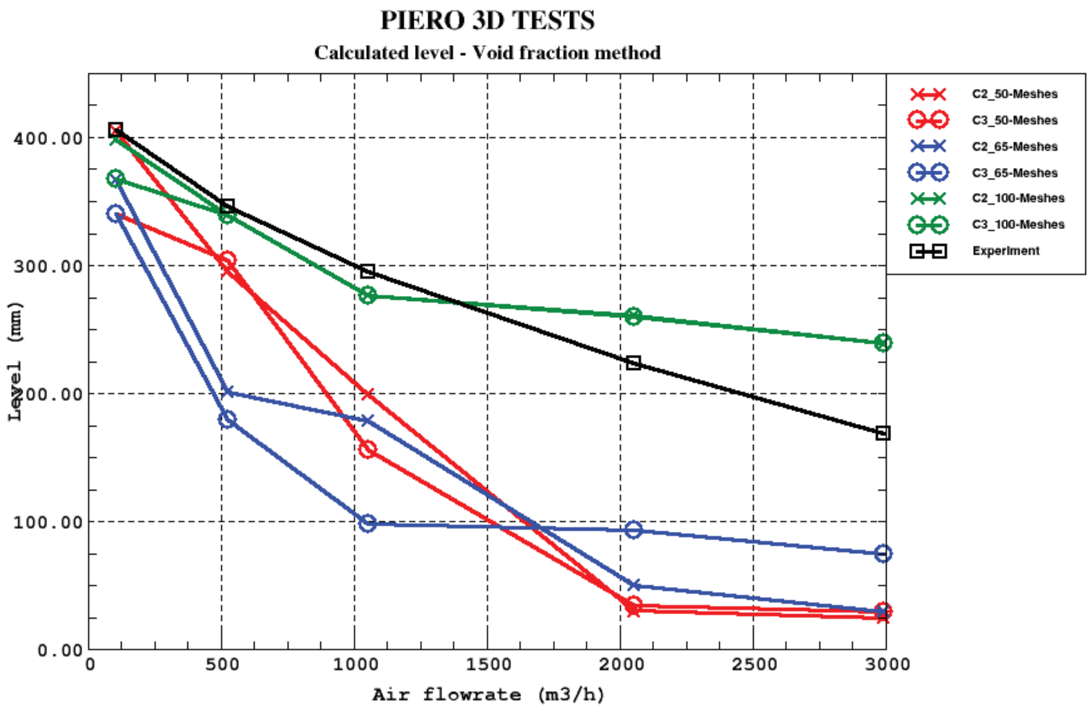


**Figure 5. Comparison of the level measurement – Void fraction method.**

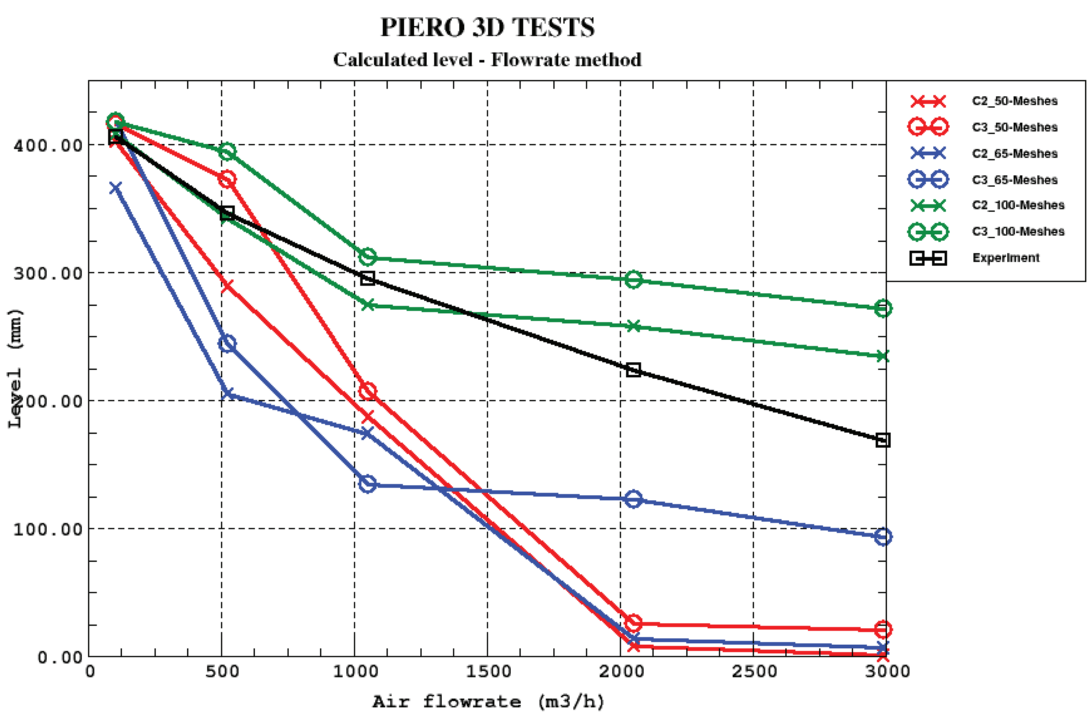


**Figure 6. Comparison of the level measurement – Flowrate method.**

On the whole, for all the tests, the results given by CATHARE 3 show a mass default between the two methods used, and this mass default affects directly the level calculation. The evolution of this mass default with the air flowrate is shown on Figure 7. For CATHARE 3, whilst this mass default is growing as the air flowrate is important for the meshing with 50 and 65 meshes, this mass default remains constant for the meshing with 100 meshes. For CATHARE 2, the thinner the meshing is, the lower the mass default is. CATHARE 2 gives the same mass default for the three meshing used and the error is lower than 10% indicating the two methods give the same results.

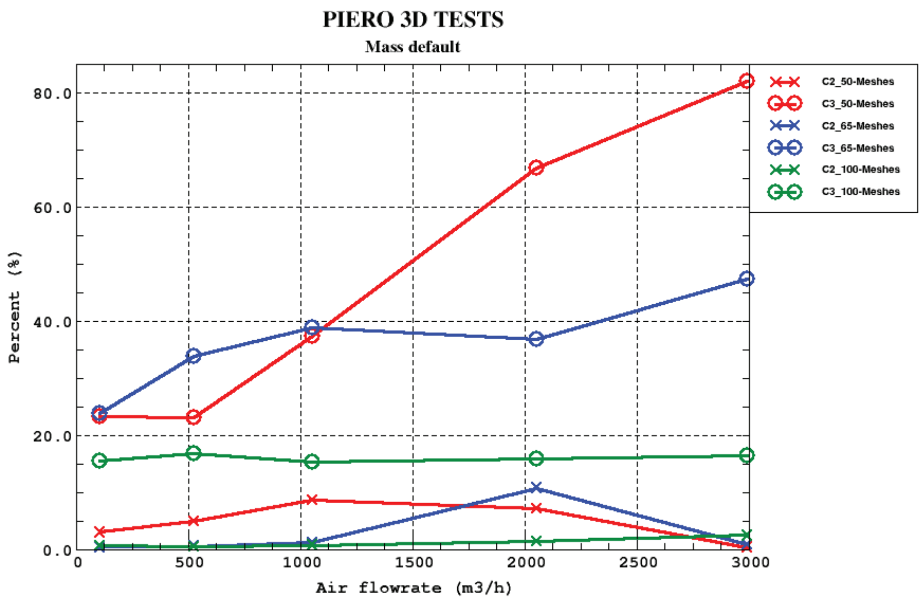


**Figure 7. Mass difference between the two methods used.**

Finally, except for the lowest air flowrate test, the water level calculated by CATHARE 2 and CATHARE 3 consistently underestimated compared to the experiment for the meshing with 50 and 65 meshes. Though, for the two higher air flowrate tests, the water level calculated is approximately zero, indicating that no more water is remaining in the lower plenum. Only the meshing with 100 meshes gives a better estimation of the water level remaining in the lower plenum.

## 5. CONCLUSIONS

On the whole, validation results of the CATHARE 3 code on the PIERO experiment modelled with the 3D module were not conclusive because there is no identification model of the free surface localization available either in CATHARE 2, or in CATHARE 3. Indeed, both codes tend to overestimate in an important way the water pulled out of the lower plenum.

Two ways of results' improvement are possible. The first one consists in developing a stratification model, or a free surface localization model, which would be integrated to the 3D module of CATHARE 2 and CATHARE 3. But this way of resolution turns out to be difficult and long to set up. The second way of improvement consists in refining the axial meshing of the 3D element modelling the PIERO experiment. This last way was investigated within the framework of this study. Indeed, by meshing the lower plenum with 15 meshes, the physical response of CATHARE 2 and CATHARE 3 on the PIERO experiment is more acceptable than using a coarser meshing. Moreover, for all the simulated tests, only the thinnest meshing presents no regression between CATHARE 2 and CATHARE 3.

Furthermore, it appeared that CATHARE 3 presents a mass default when using incondensable. Thus, the main variables of CATHARE 3 do not concord with the mass balance. This default also varies with the meshing used: the thinner the meshing is, the less important the default is.
In conclusion, the use of refined axial meshing with CATHARE 2 and CATHARE 3 is necessary to well reproduce the PIERO experiment, particularly to represent the hemispherical part of the lower plenum.

## NOMENCLATURE

| | |
|---|---|
| $H$ | Water level |
| $l_X$ | Width |
| $m_{tot}$ | Total mass |
| $q$ | Mass flowrate |
| $R$ | Curvature's radius of the lower plenum |
| $V_i$ | Volume of mesh i |
| $Z_i$ | Height of mesh i |
| $\alpha_i$ | Void fraction of mesh i |
| $\rho_{water}$ | Liquid water density |

| | |
|---|---|
| CATHARE | Code of Analysis of Thermal-Hydraulics during an Accident of Reactor safety Evaluation |
| PWR | Pressurized Water Reactor |
| LB-LOCA | Large Break Loss Of Coolant Accident |

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