5th Europlexus User Meeting

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Numerical and experimental parametric investigation of rarefaction wave propagation across an orifice plate

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Context

Loss of Coolant Accident (LOCA) in a Pressurized Water Nuclear Reactor (PWR)

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Propagation of a transient rarefaction wave within the primary circuit

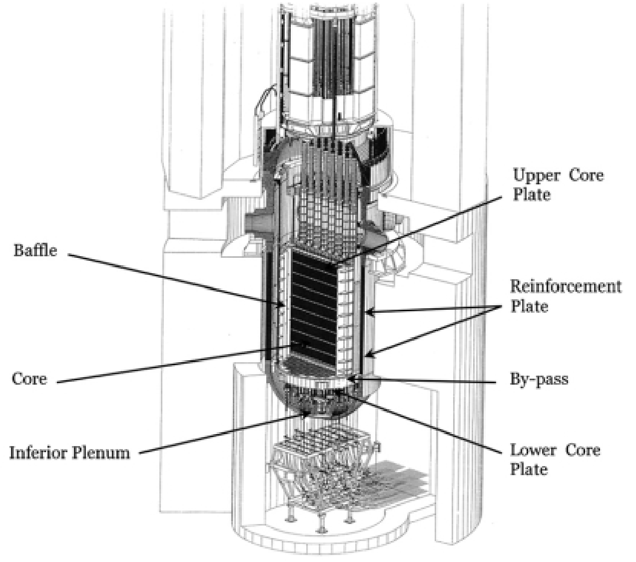


Figure 1: *PWR vessel and internal components.*

- Rarefaction wave crosses **two zones of the reactor vessel with different geometric characteristics**: the **reactor core** itself (fuel assemblies) and the **by-pass zone** → nonidentical travel times of the rarefaction wave in the two zones → transient pressure load on the baffle surrounding the reactor core.
- **Out-of-reach accurate geometric representation of obstacles in simulations** → development of simplified models to be implemented in the **EUROPLEXUS software** and validated through experimental facilities.

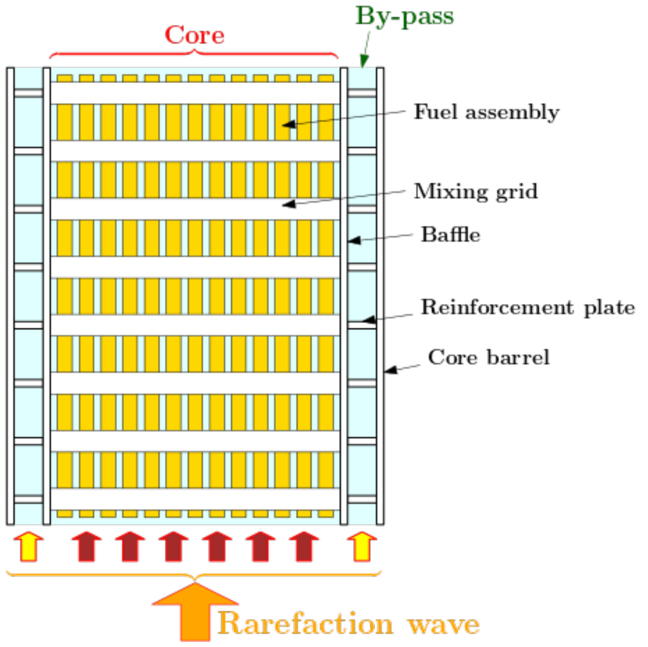


Figure 2: *Simplified scheme.*

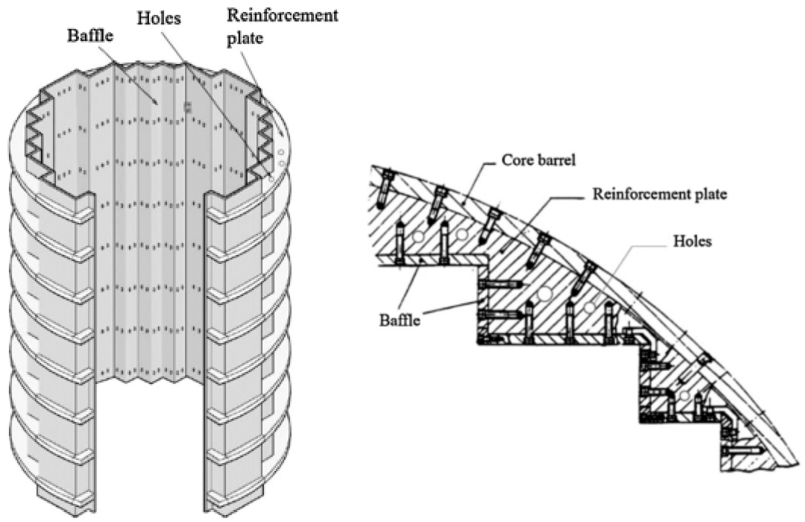


Figure 3: *Baffle and perforated plates.*

Outline

1. MADMAX experimental facility

MADMAX = **M**odélisation de l'**A**ccident de **D**épressurisation - **M**aquette **A**nalytique-e**X**périmentale
(*Depressurisation Accident Modelling - Analytical-Experimental Mock-up*)

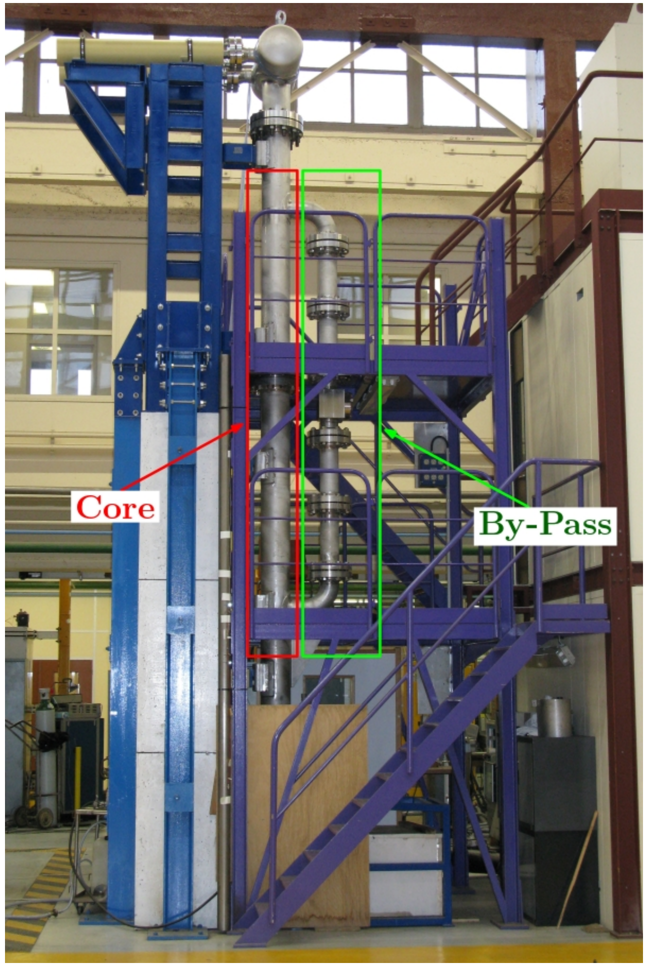


Figure 4: *MADMAX experimental facility at DYN (CEA Saclay, France).*

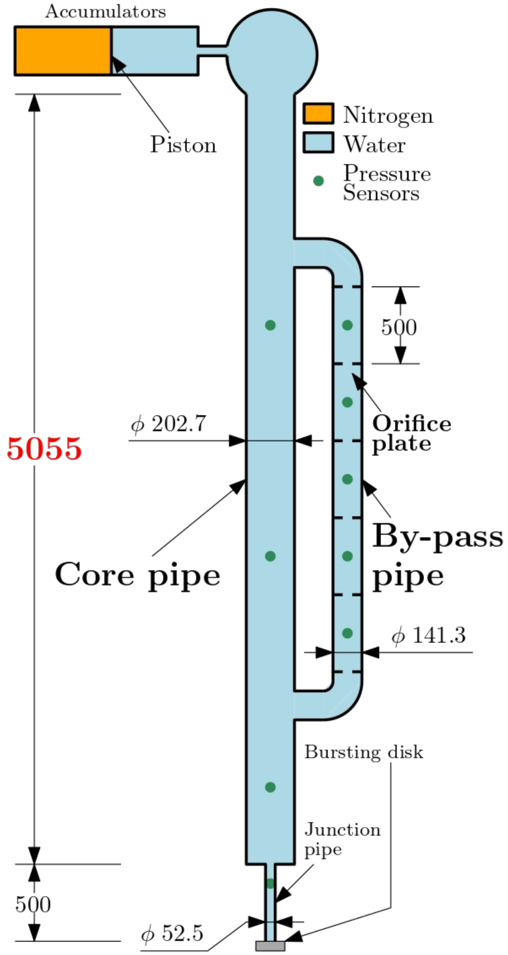


Figure 5: *Experimental set-up* (***dimensions in mm***).

- Two connected parallel pipes: a main core pipe representing the reactor core and an auxiliary by-pass pipe, equipped with several orifice plates, representing the by-pass and perforated reinforcement plates.
- The pipes are initially filled with water that is then pressurized until it triggers the bursting of a graphite bursting disk (failure pressure at about 70 bar) located at the bottom of the core pipe.
- Pressure sensors placed along the pipes measure the pressure of the fluid at the inner wall of the pipes during the fast transient.

1. Numerical models

- **EUROPLEXUS** → Fast transient fluid-structure interaction (FSI) calculations.
- Arbitrary Lagrangian-Eulerian (ALE) description for fluids and structures.

In this work:

Fluid calculations with fixed structures

↓

Euler equations for the fluid

- Mass conservation equation
- Momentum equation
- Energy transport equation

- Spatial discretization: **Finite Elements Method** (FEM)
- Time discretization: **Centered Differences** (explicit)

2D axisymmetric model (expensive reference)

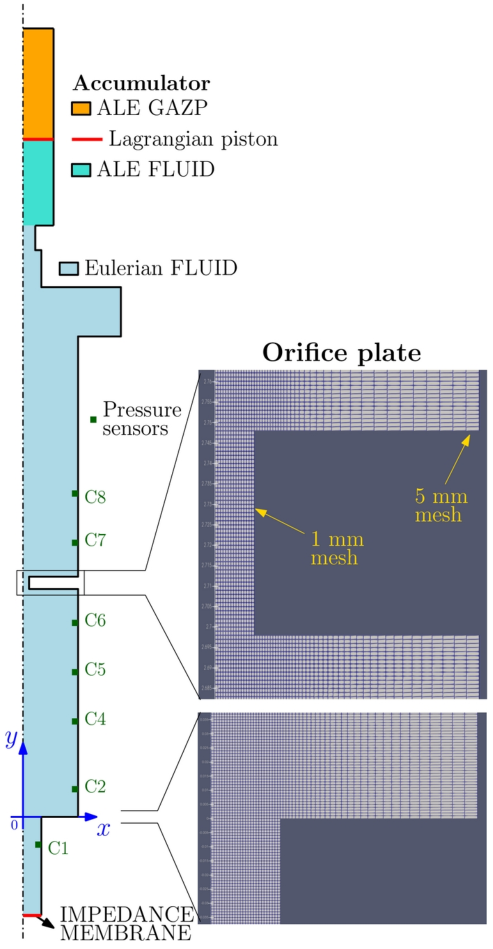


Figure 6: *2D axisymmetric mesh.*

1D model with impedances (simplified model)

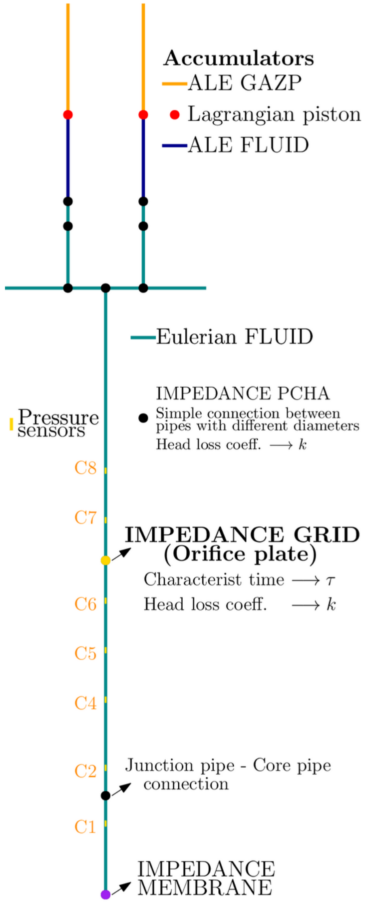


Figure 7: *1D with impedances mesh.*

1. Numerical models

Simplified 1D model to represent the geometric obstacles

- **Grid impedance = Acoustic term + Head loss term**

Pressure drop

$$\Delta p = -\frac{L_{eq}}{s}\dot{q} - \frac{1}{2} k \frac{q^2}{\rho_0 S_t^2}$$

Acoustic term

Characteristic time

$$\tau = \frac{S_t}{s}\frac{L_{eq}}{2c}$$

Equivalent length

$$L_{eq} = 2\left[0.85 - \frac{r}{R} + 0.15\left(\frac{r}{R}\right)^2\right] r + e$$

Head loss term

Head loss coefficient

$$k$$

Calculated from Idel'Cik correlations.

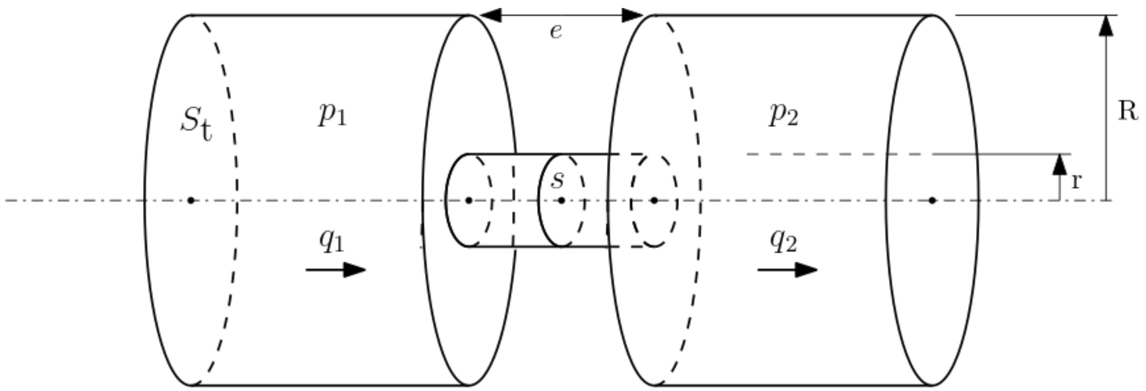


Figure 8: *Orifice plate scheme.*

2. Experimental set-up

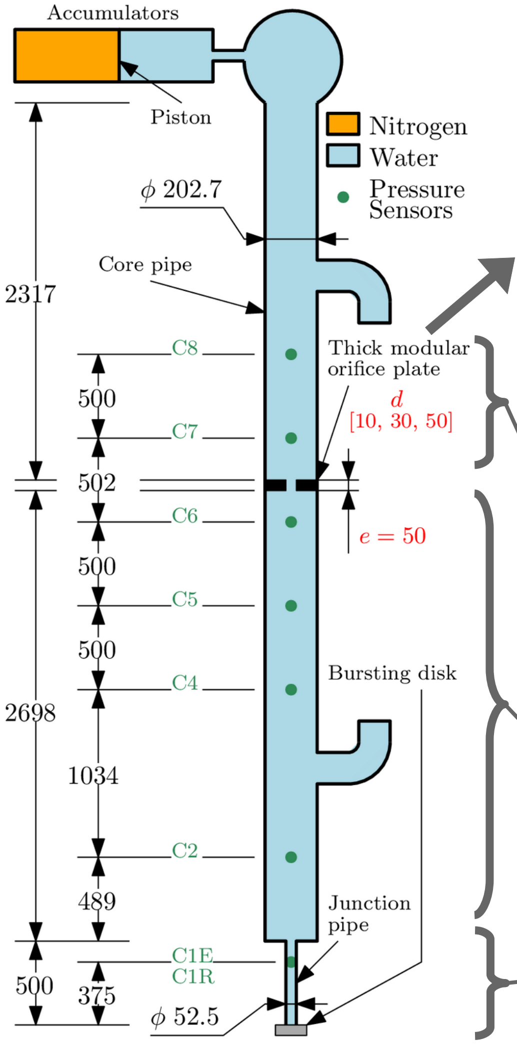


Figure 9: *Experimental set-up (dimensions in mm).*

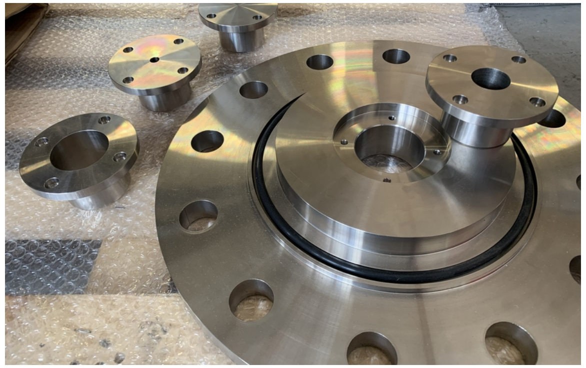


Figure 10: *New modular orifice plate.*

- **MADMAX simplified configuration**:
  - no by-pass pipe
  - thick modular orifice plate in the middle of the core pipe
- **Three configurations (parametric investigation):**
  - **e = 50 mm, d = 10 mm**
  - **e = 50 mm, d = 30 mm**
  - **e = 50 mm, d = 50 mm**

- **Three different pressure sensor zones:**

1	**Core pipe (above the orifice plate)** *upstream*	2 piezoelectric pressure sensors (**C7 and C8**)
2	**Core pipe (below the orifice plate)** *downstream*	4 piezoelectric pressure sensors (**C2, C4, C5 and C6**)
3	**Junction pipe**	1 piezoelectric pressure sensor (**C1E**) 1 piezoresistive pressure sensor (**C1R**)

2. Experimental results

Table 1: Experimental bursting pressure

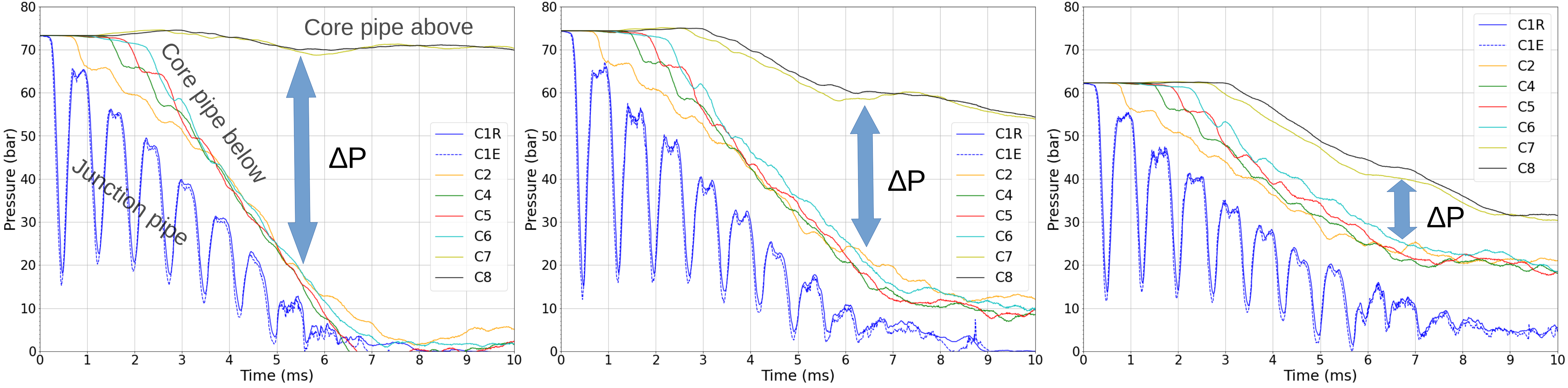
EXP	e = 50 mm d = 10 mm	e = 50 mm d = 30 mm	e = 50 mm d = 50 mm
P_{burst} (bar)	**73.3**	**74.3**	**62.3**

Effect of the geometry:

d ↑ ➡ ΔP ↓

Pressure evolution for all sensors

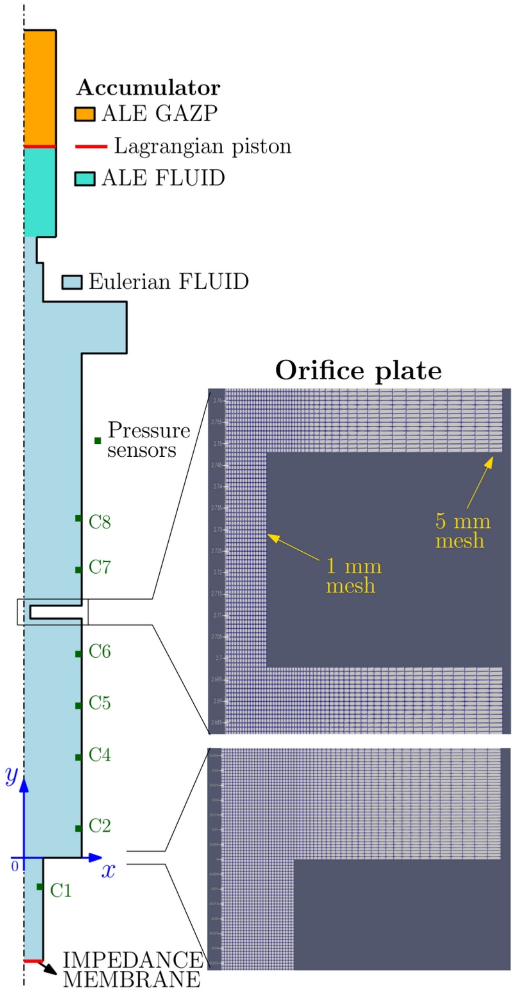
e = 50 mm, **d = 10 mm** e = 50 mm, **d = 30 mm** e = 50 mm, **d = 50 mm**



2. Numerical simulations

EUROPLEXUS Finite Elements fluid calculations with fixed structures

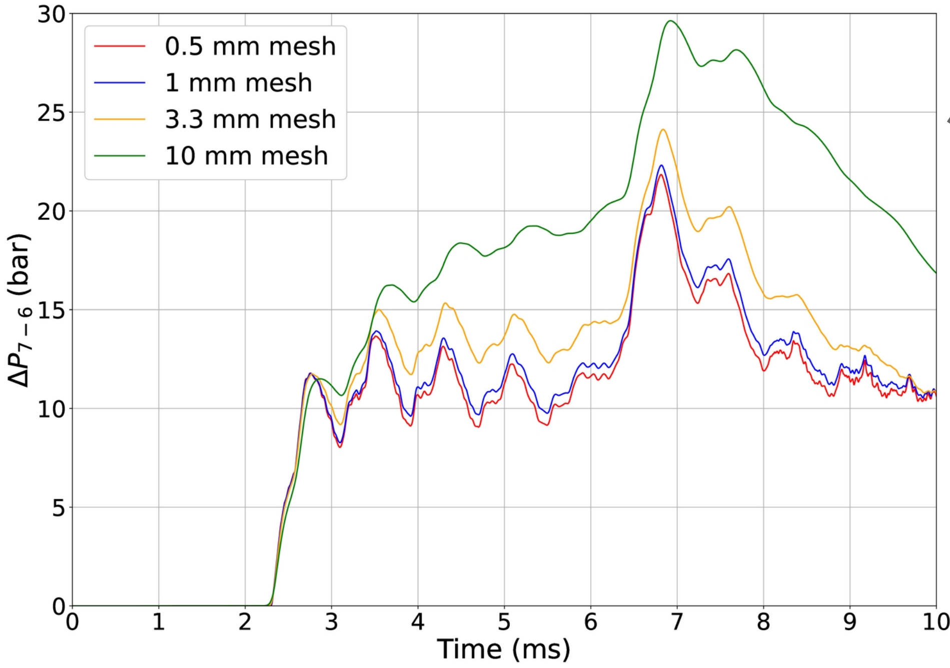
Two models:
- 2D axisymmetric (expensive reference)
- 1D with impedances



2D axisymmetric model

Mesh convergence for $\Delta P_{7\text{-}6}$

Config.: e = 50 mm, d = 50 mm



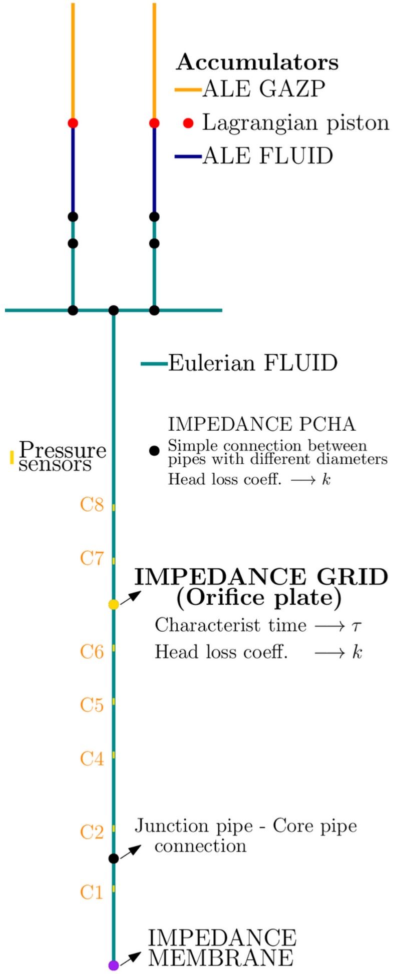
Selected mesh
1 mm

About 230 000 elements

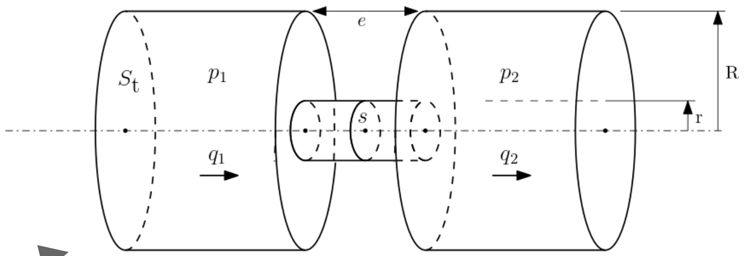
2. Numerical simulations

EUROPLEXUS Finite Elements fluid calculations with fixed structures

Two models:
- 2D axisymmetric (expensive reference)
- 1D with impedances



1D model with impedances



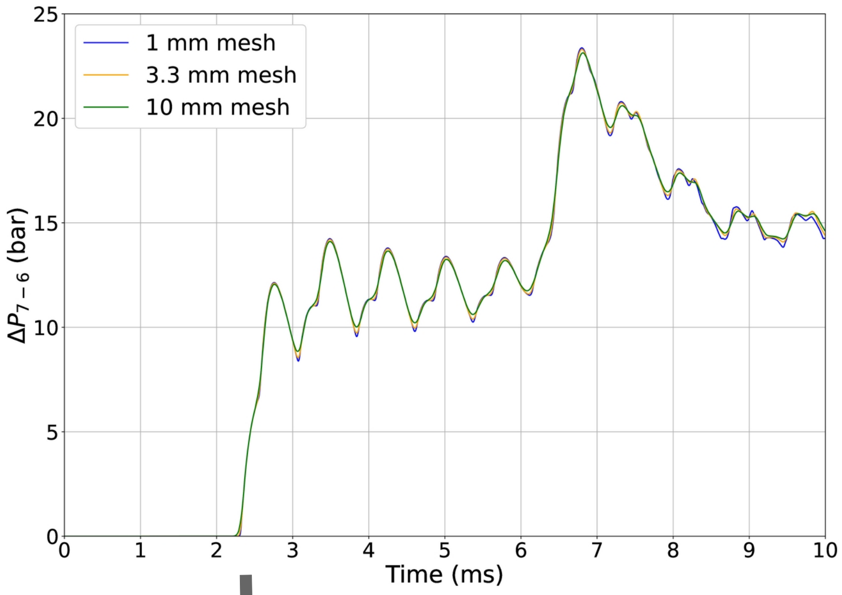
$$\tau = \frac{S_t}{s} \frac{L_{eq}}{2c}$$

$$k$$

From Idel'Cik correlations

Calculation of τ and *k* for each of the three geometric configurations to be used as input in the simulations

Mesh convergence for $\Delta P_{7\text{-}6}$
Config.: e = 50 mm, d = 50 mm
(Uniform meshes)

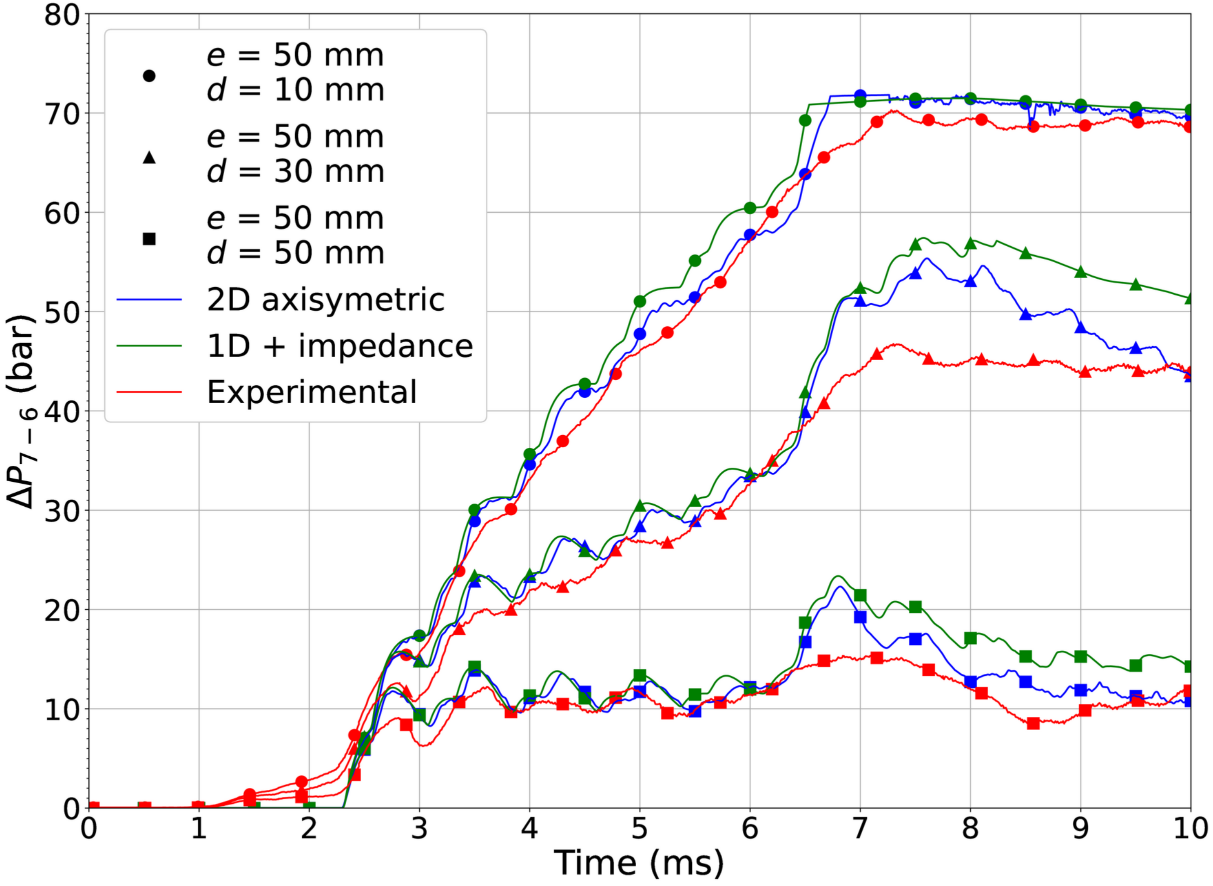


Selected mesh
10 mm

About 1500 elements

2. Experiments/Simulations Comparison

Pressure difference between sensors C6 and C7 for all orifice plate configurations.

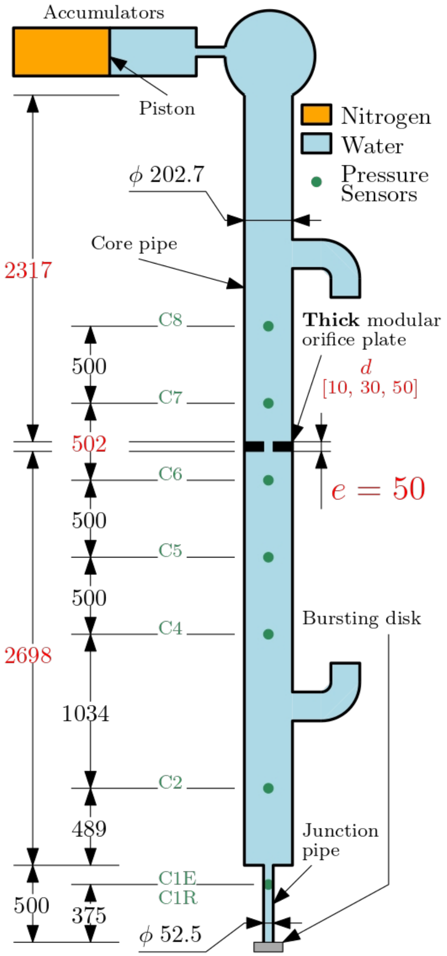


- Both models are able to reproduce the experimental results with fair accuracy and, as one would expect, with greater agreement for the 2D axisymmetric model.
- Effect of the orifice plate geometry: the smaller the orifice plate diameter, the greater the pressure difference between the two sensors.
- Small phase shift which may be attributed to an inaccurate bottom outlet condition and to the absence of acoustic impedance to account for transient effects of the sudden enlargement between the junction pipe and the core pipe (for the 1D model).
- A major influence is also given by the value of the speed of sound, considered uniform throughout the fluid, but which actually depends not only on the material of the pipe, but also on its diameter and thickness.

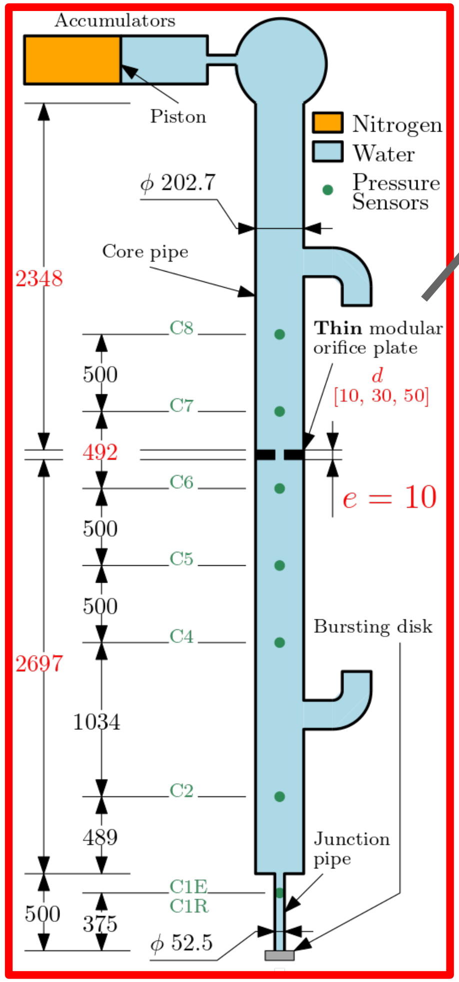
3. Latest results

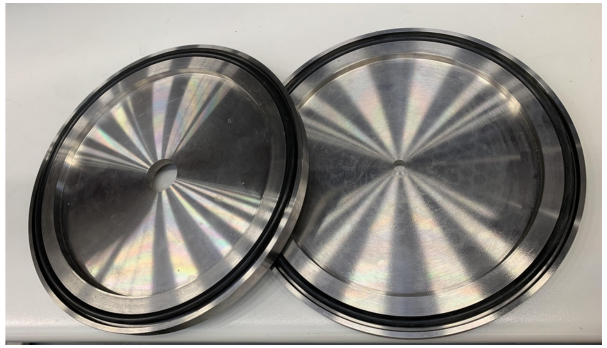
- **New experimental set-up**

e50dxx



e10dxx

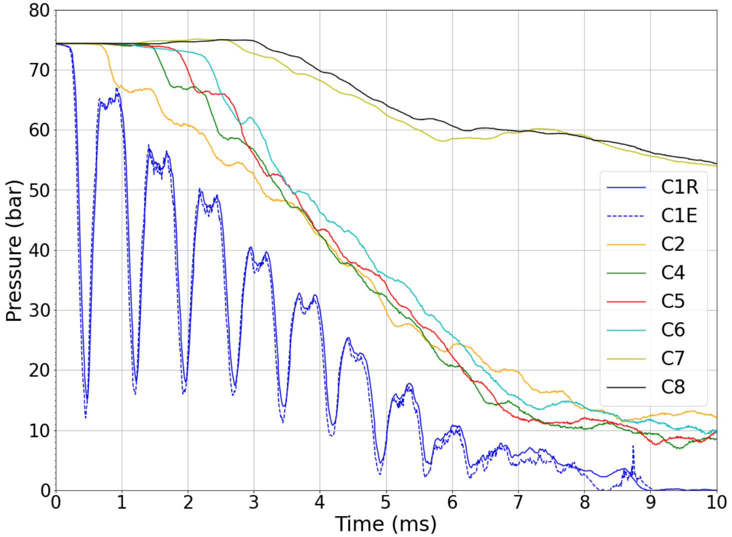




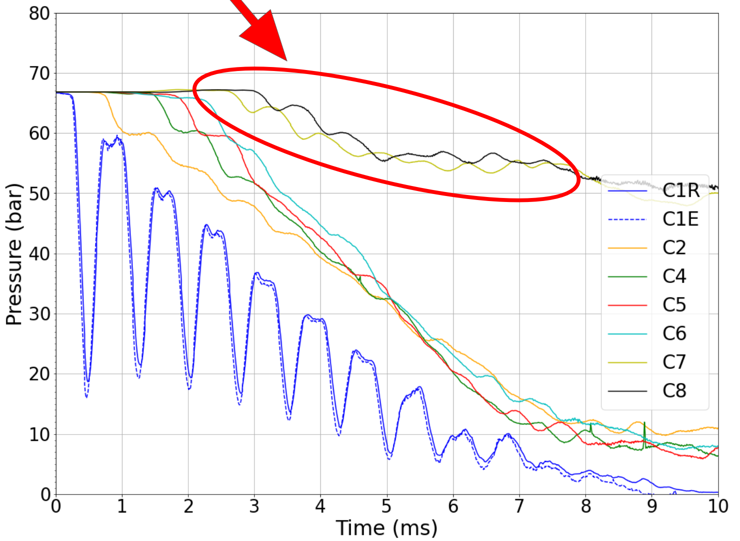
- Study of the **influence of orifice plate thickness**.

e ↓ → Pressure signal transmitted more effectively from one side of the obstacle to the other

e50d30



e10d30

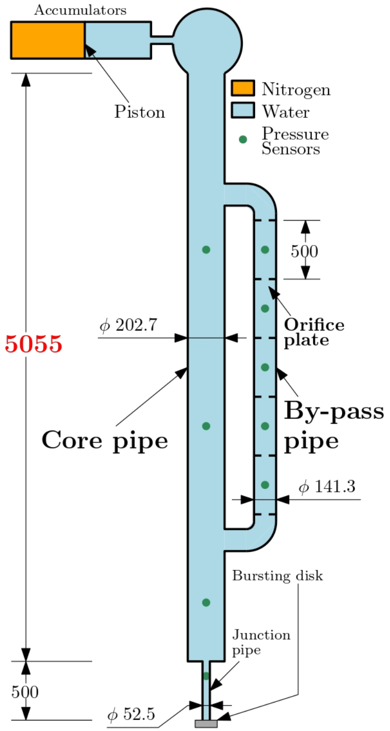


4. Conclusions and perspectives

- The reference 2D Euler axisymmetric model correctly reproduces the physics of rarefaction wave propagation.
- The 1D simplified model with impedances also produces satisfactory results, while at the same time allowing a significant gain in terms of calculation time (reduction by a factor 100 for this single obstacle configuration) and greater simplicity of representation (mesh creation).
- Perspectives:
  - Full validation of the numerical models (variation of orifice plate thickness and diameter)

    ➔ **Experimental results available (latest results)**
  - Assessment of a 1D simplified model for multiple obstacle configuration (by-pass pipe reinstallation)

    ➔ **By-pass pipe recently reinstalled** (next experimental campaign June-July 2023)
  - Carry out Fluid-Structure Interaction (FSI) calculations.



Thank you for the attention

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Annexes

ALE Euler equations for the fluid

- Mass conservation equation

$$\frac{\delta}{\delta t}\int_{V(t)} \rho(\underline{x},t)\, dV = \oint_{S(t)} \rho(\underline{x},t)(\underline{w}-\underline{v})\cdot \underline{n}\, dS$$

- Momentum equation

$$\frac{\delta}{\delta t}\int_{V(t)} \rho(\underline{x},t)\underline{v}\, dV + \oint_{S(t)} \left[\rho(\underline{x},t)\,\underline{v}\otimes(\underline{w}-\underline{v})\right]\cdot \underline{n}\, dS = \int_{V(t)} \rho(\underline{x},t)\underline{g}\, dV + \oint_{S(t)} \underline{\underline{\sigma}}\cdot \underline{n}\, dV$$

- Energy transport equation

$$\frac{\delta}{\delta t}\int_{V(t)} \rho(\underline{x},t)\, i\, dV = \oint_{S(t)} \rho(\underline{x},t)\, i\,(\underline{w}-\underline{v})\cdot \underline{n}\, dS - \oint_{S(t)} p\,\underline{v}\cdot \underline{n}\, dS$$

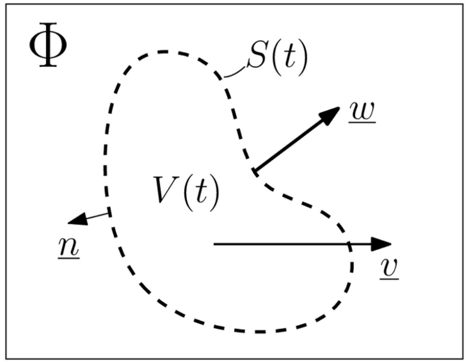
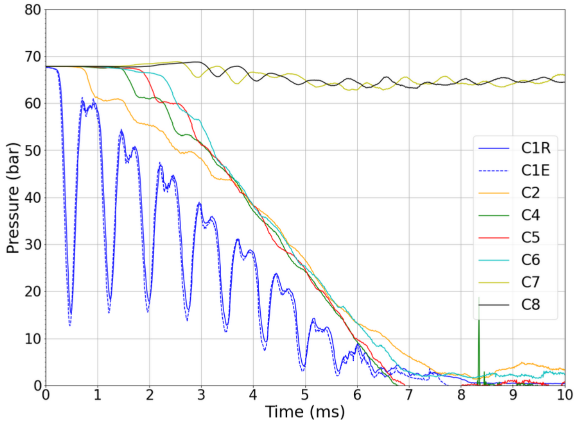


Figure: *Fluid domain.*

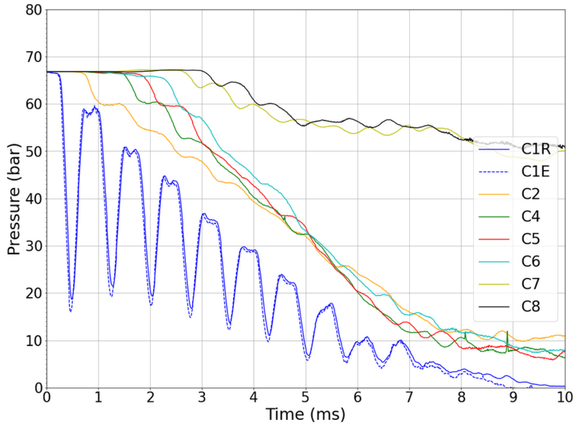
Annexes

Full experimental results and bursting pressure

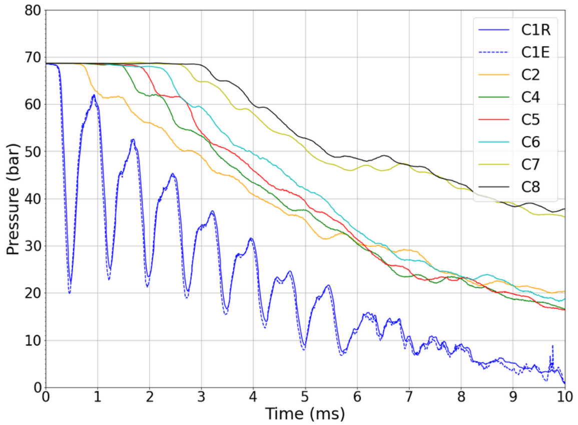
e10d10



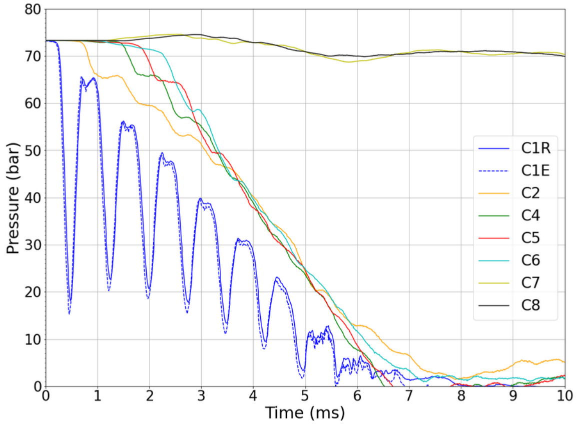
e10d30



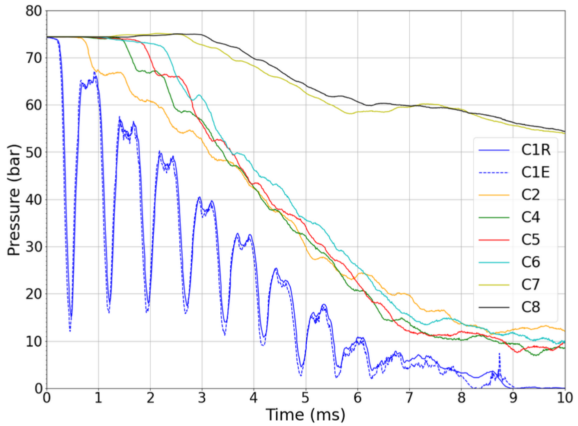
e10d50



e50d10



e50d30



e50d50

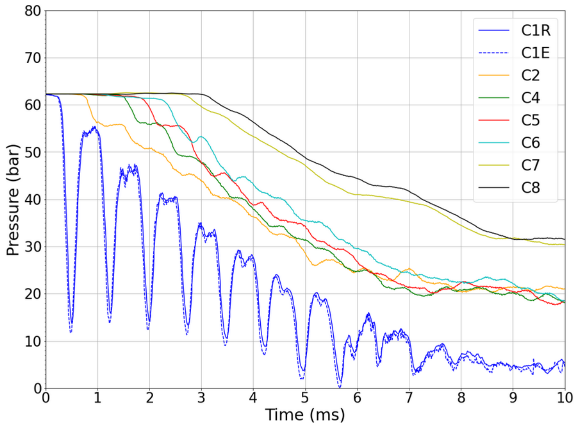


Figure: *Graphite bursting disk and failure cone.*

EXP	P_{burst} (bar)
e = 10 mm d = 10 mm	**67.8**
e = 10 mm d = 30 mm	**66.8**
e = 10 mm d = 50 mm	**68.7**
e = 50 mm d = 10 mm	**73.3**
e = 50 mm d = 30 mm	**74.3**
e = 50 mm d = 50 mm	**62.3**

Annexes

2D axisymmetric mesh convergence analysis

Table: Mesh characteristics for convergence analysis

Mesh name	Mesh type	Smallest element (mm²)	Largest element (mm²)
0.5 mm mesh	Progressive	0.5 x 0.5	5.0 x 0.5
1 mm mesh	Progressive	1.0 x 1.0	5.0 x 1.0
3.3 mm mesh	Progressive	3.3 x 3.3	5.0 x 3.3
10 mm mesh	Uniform	10.0 x 10.0	10.0 x 10.0

1D model with impedances coefficients

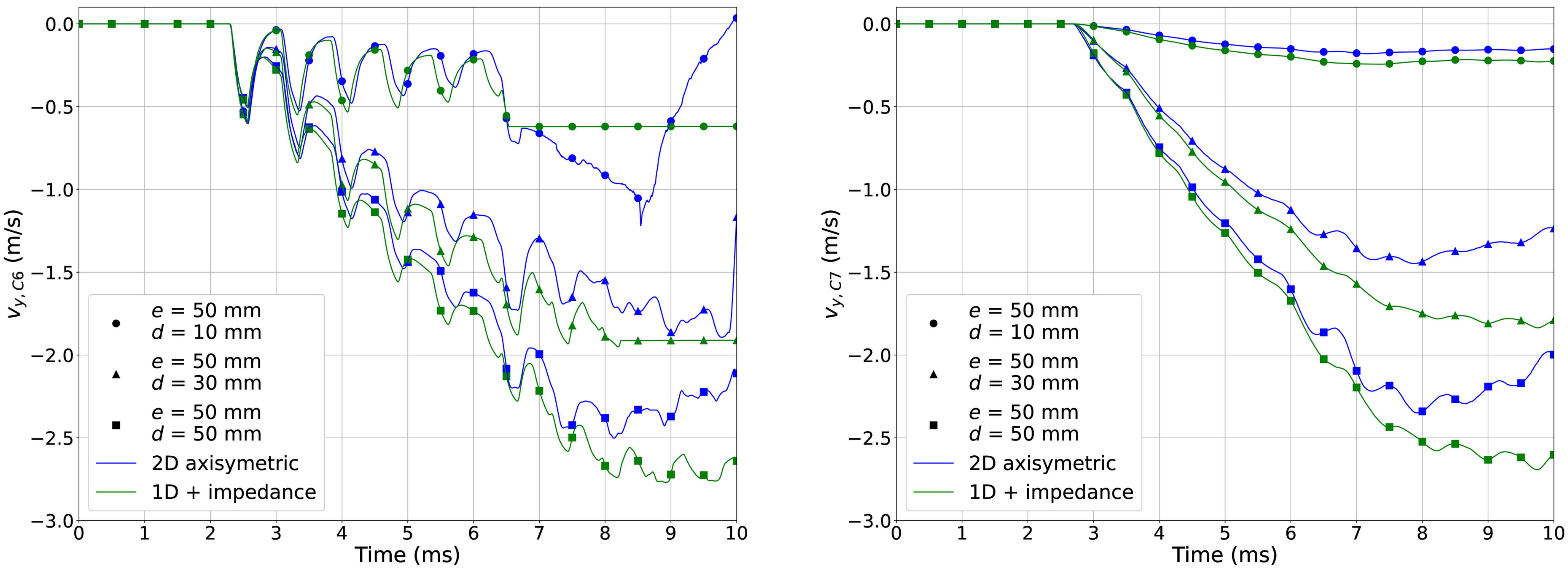
Table: Characteristic time and head loss coefficient for IMPEDANCE GRID

Orifice plate geometry	e = 50 mm d = 10 mm	e = 50 mm d = 30 mm	e = 50 mm d = 50 mm
τ (ms)	7.94	1.08	0.44
k (-)	261874	3178	427

Annexes

Numerical cavitation (1/3)

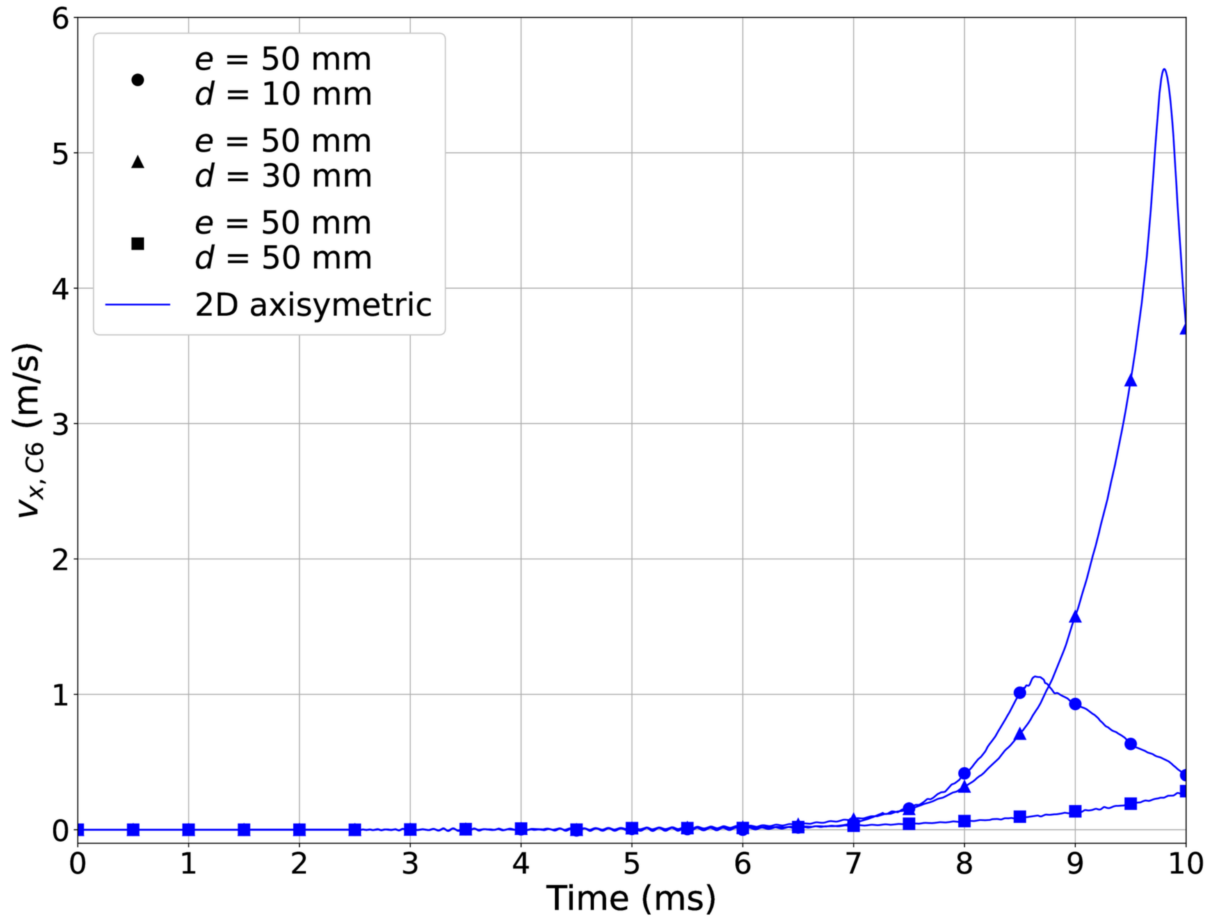
Fluid velocities (axial component *y*) at position C6 ant C7 for the two numerical models.

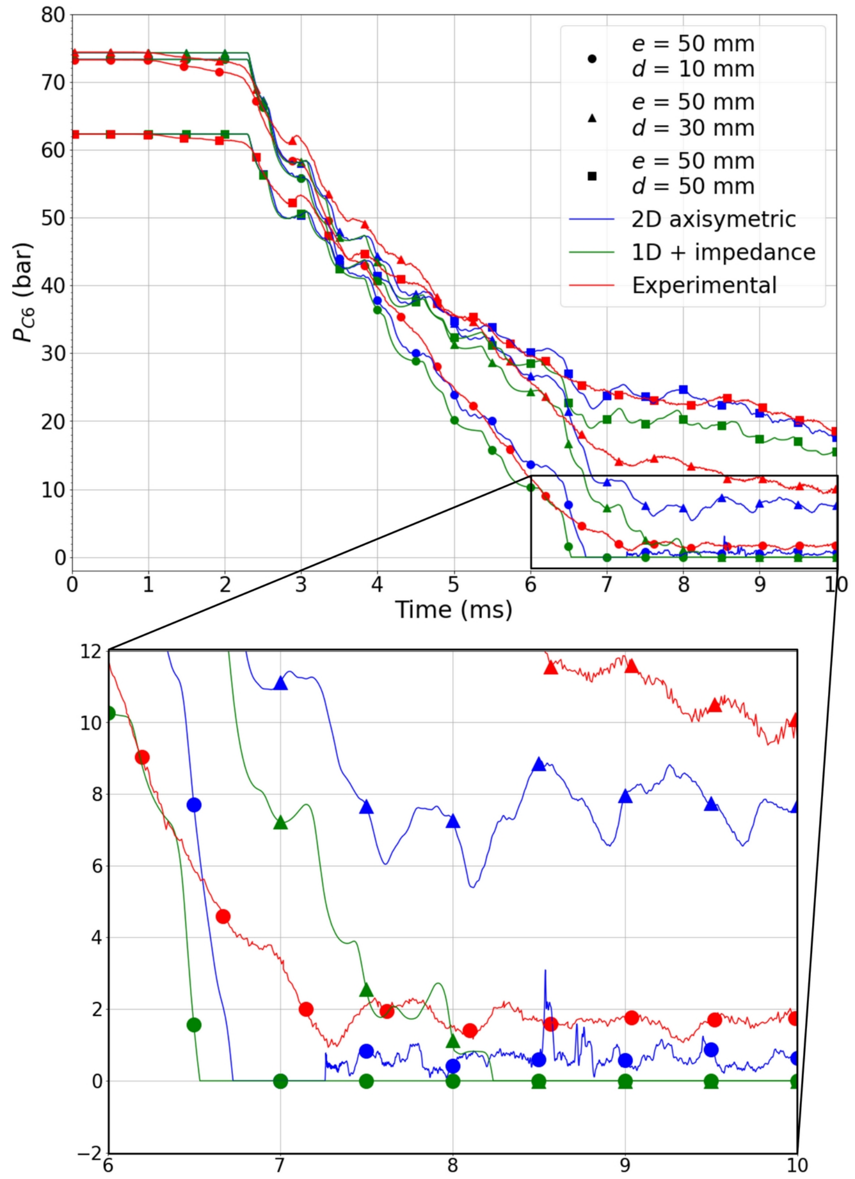


Annexes

Numerical cavitation (2/3)

Fluid velocity (radial component *x*) at position C6 for the 2D axisymmetric model.





Annexes

Numerical cavitation (3/3)

NOW ➞ Fluid model (no phase change)

$$\Delta P = c^2 \Delta\rho$$

$$\rightarrow \text{Cavitation} = \downarrow\rho$$

P_{min} imposed by the user

To take into account **pipe deformation** on the speed of sound in water → Allievi correction

$$c_{Allievi} = 1310 \text{ m/s} \quad (\text{instead of } 1500 \text{ m/s})$$

PERSPECTIVE ➞ Use WATER model (with TABULATED EQUATIONS OF STATE) to take into consideration phase change

→ Speed of sound computed through EoS → **FSI calculations to take into account pipe deformation**