Comparative study of the flow within water mist and sprinkler fire protection systems by means of CFD

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Context and objectives

Calculation of the air/water flow within water-mist and sprinkler systems

Usual procedure (**NFPA 750**):

- **Hazen-Williams** (low-pressure: <12bar, 175psi)
- **Darcy–Weisbach** (intermediate and high pressure: >12 bar, 175 psi)
- **Pneumatic calculation procedure** (gas/water flow)

Other possibility: Navier-Stokes equations and **turbulence** modelling by means of **Computational Fluid Dynamics** (**CFD**)

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☞ **Detailed study (CFD) on Dry-pipe Low pressure Water-mist system and Sprinkler system**

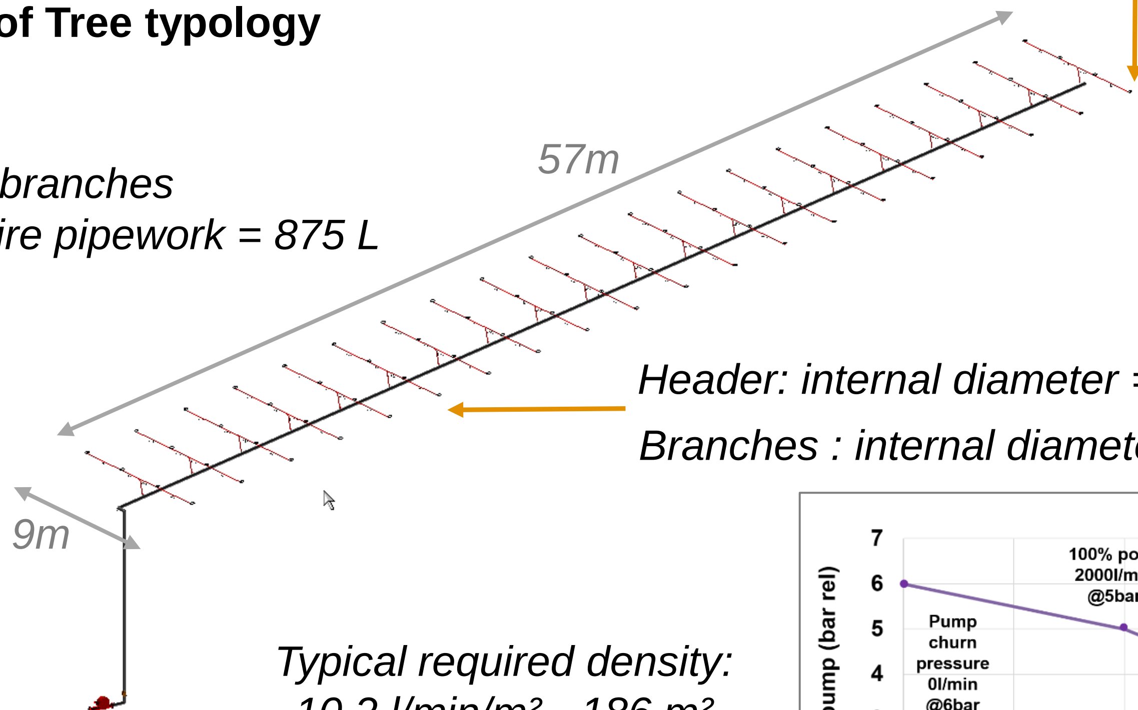
- Impact on valve activation time ?
- Impact on delay to obtain steady-state water flow ?
- Location and size of the air pockets ?

Modelled system

Typical outside conveyor protection: system of Tree typology

Outlet: most remote Water-mist nozzle or Sprinkler head $Q=f(p,\alpha_{water})$

20 branches
Volume of entire pipework = 875 L



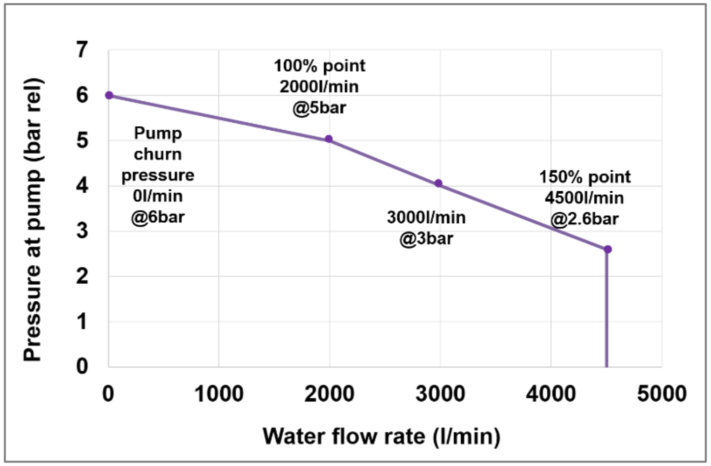
Header: internal diameter = 108mm (4”)

Branches : internal diameter = 37.2mm (1 1/4”)

Inlet: Main fire pump Ptot=f(Q)

Typical required density: 10.2 l/min/m² - 186 m²
⇒ minimum pump flow = 1897.2 l/min

Pump curve



Modelled system

Sprinkler head

Required water density defined according to hazard : 10,2 l/min/m² - 186 m² => minimum pump flow = 1897.2 l/min

K115 (8.0 US) Sprinkler head
115 l/min/bar$^{1/2}$
Orifice size: 14mm

Water-mist nozzle

Relationship between drop size distribution and extinguishing capacity of water mist not straight-forward

<u>Assumptions for this study:</u>
K43.2 (3.0 US) Water-mist nozzle
43.2 l/min/bar$^{1/2}$
Orifice size: 8.33mm
Low pressure (<12bar) water-mist system: identical distribution piping and pump

Modelling approach: resolved equations

OpenFOAM (CFD opensource code/C++ library)

Navier-Stokes equations for a turbulent, isothermal, two-phase flow.

Liquid phase : **water** (incompressible) ; Vapor phase : **air** (compressible: perfect gas)

VOF (volume of fluid) phase-fraction based interface capturing approach.

1. **Continuity equation**

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho U) = 0 \qquad \rho = \alpha_l \rho_l + \alpha_v \rho_v \qquad U = \alpha_l U_l + \alpha_v U_v$$

2. **Momentum equation**

$$\frac{\partial \rho U}{\partial t} + \nabla.(\rho U U) = -\nabla(P_{rgh}) - gh\nabla\rho + \nabla.\tau + \rho g + F_s$$

3. **Energy equation**

$$\frac{\partial(\rho T)}{\partial t} + \nabla.(\rho U T) - \nabla.(K\nabla T) + \left[\nabla(PU) + \frac{\partial(\rho K)}{\partial t} + \nabla(\rho U K)\right]\left(\frac{\alpha_l}{c_{vl}} + \frac{\alpha_v}{c_{vv}}\right) = 0$$

4. **Phase continuity equation**

$$\frac{\partial(\alpha_l)}{\partial t} + \nabla.(\alpha_l U) + \nabla.(\alpha_l \alpha_v U_r) = \alpha_l \alpha_v \left(\frac{\psi_1}{\rho_l} - \frac{\psi_v}{\rho_v}\right)\frac{DP}{Dt}$$

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+ 2 transport equations for turbulence modelling (k-ε realizable with wall-law)

Timesteps: 1e-5s to 1e-4s (CFL condition <0.5)

Modelling approach: pump and nozzle/sprinkler head routines

Inlet : pump model

- **$0 \leq t < t_{activation}$ (wall)**

U=0

p=zeroGradient

- **$t \geq t_{activation}$**

p_calculated=f(Q)

Relaxation factor = 0,0001 (for increased calculation stability), ie:

p_current_timestep=0,0001*p_calculated+0,9999*p_previous_timestep

- **$t \geq t_{activation}+0.1s$**

p_calculated=f(Q)

Nomenclature

α : water mass fraction (-)
(1=water, 0=air)
U : velocity magnitude (m/s)
p : absolute pressure (Pa)

Outlet: nozzle/sprinkler model

- **$0 \leq t < t_{activation}$ (wall)**

U=0

p=zeroGradient

- **$t \geq t_{activation}$**

α =0 (=100% air)

p=101325 : U=0

101325<p<191801 : U=Upositivepressure (formula)

p>191801 : U=Uchoked=340m/s (choked flow)

α =1 (=100% water)

U=Uwater=Kfactor/S (p-101325)

0<α<1 (air and water mix)

U= αUwater + (1- α)Upositivepressure

$$U_{\text{positive pressure}} = \sqrt{\frac{2\gamma}{\gamma-1} RT\left(1-\left(\frac{p_{atm}}{p}\right)^{\frac{\gamma-1}{\gamma}}\right)}$$

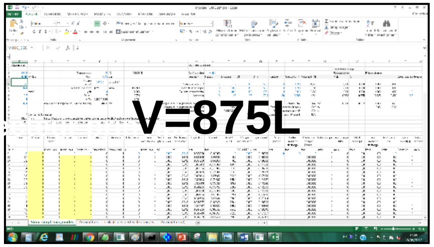
Modelling approach: 2D assumption

Tank of a given volume

Analytic calculations based on system volume V

+ *: low computational cost*

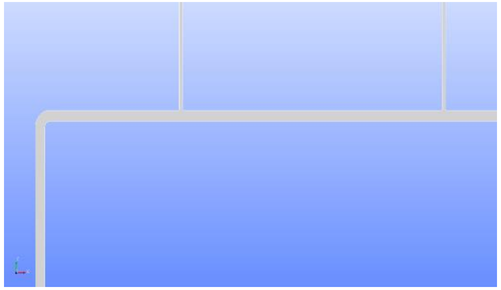
-*: water distribution in the system not available*



2D simulations on simplified geometry

+*: more precise, and water distribution available*

-*: friction underestimated, gravity neglected (no hydrostatic pressure)*



3D simulations with complete system details

+*: quantitative results with full details*

-*: very high computational cost*

Accuracy ↘
Computational cost ↘

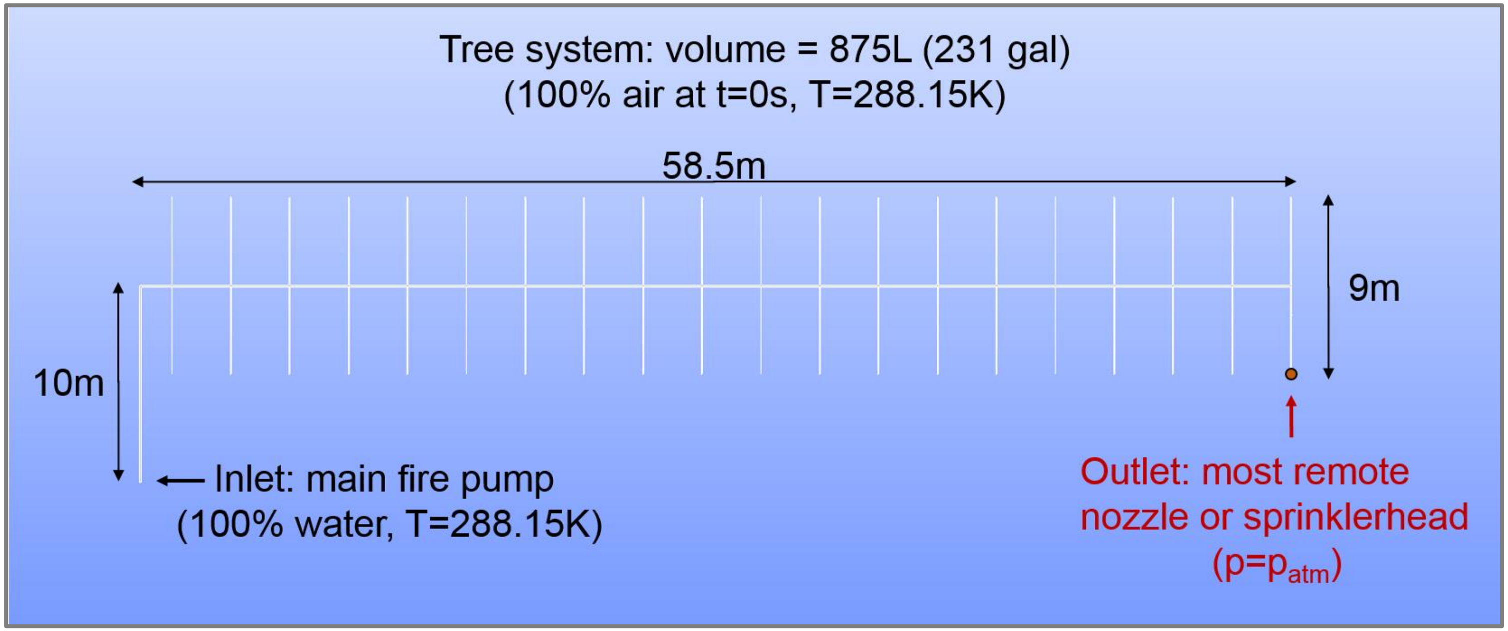
Retained Choice

Accuracy ↗
Computational cost ↗

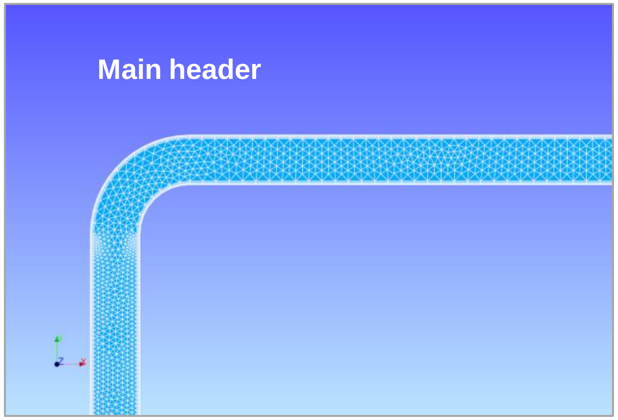
☞ **Comparative study flow for a simplified geometry (2D + 1cell in the Z direction)**

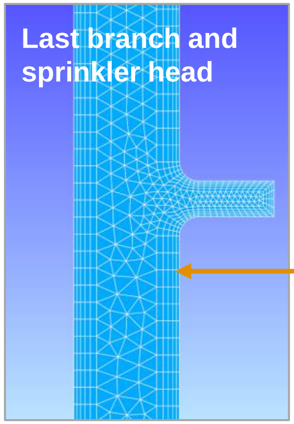
Geometry and mesh

Geometry



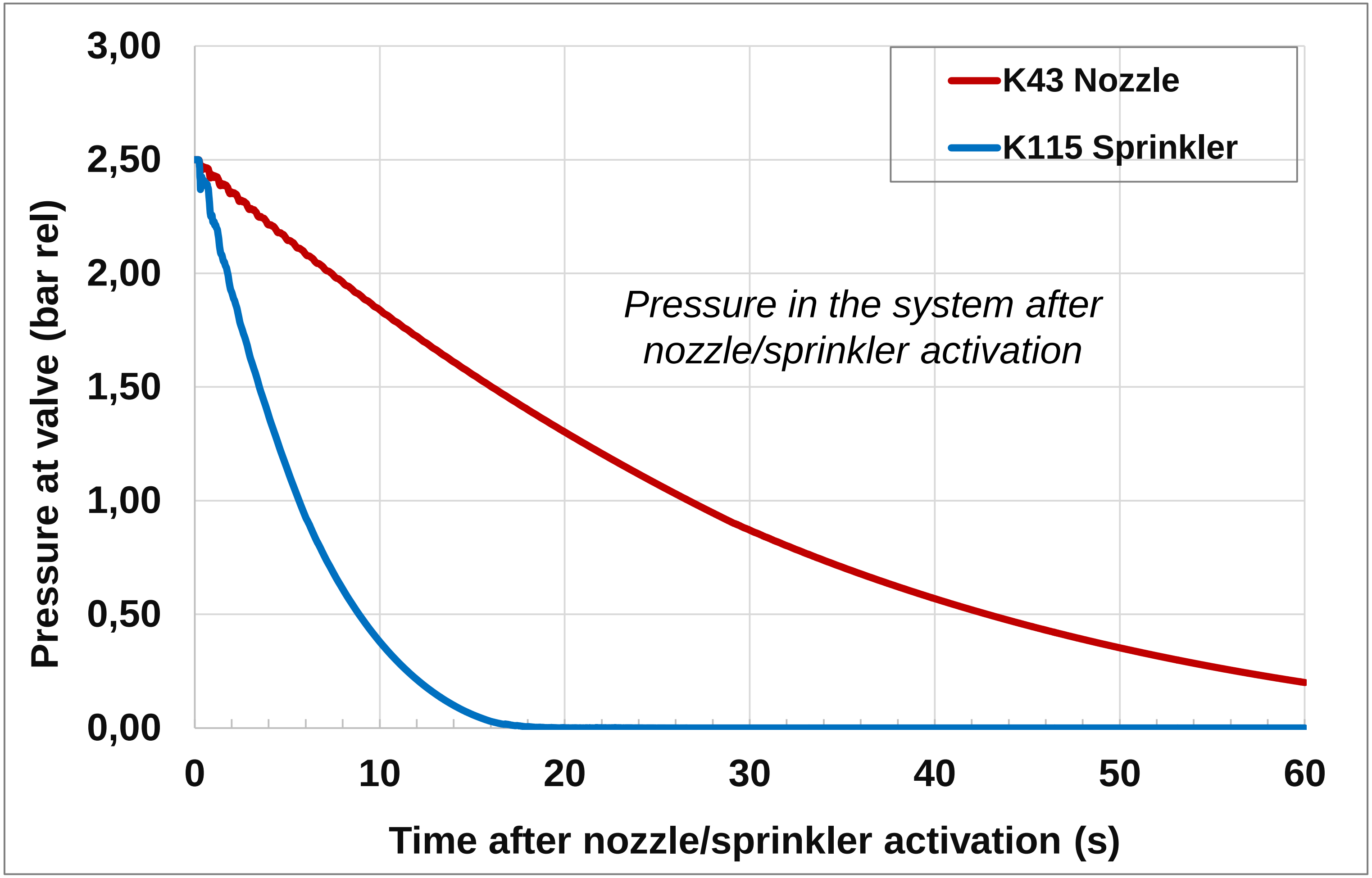
Tetrahedral mesh with viscous layer (~300k cells)





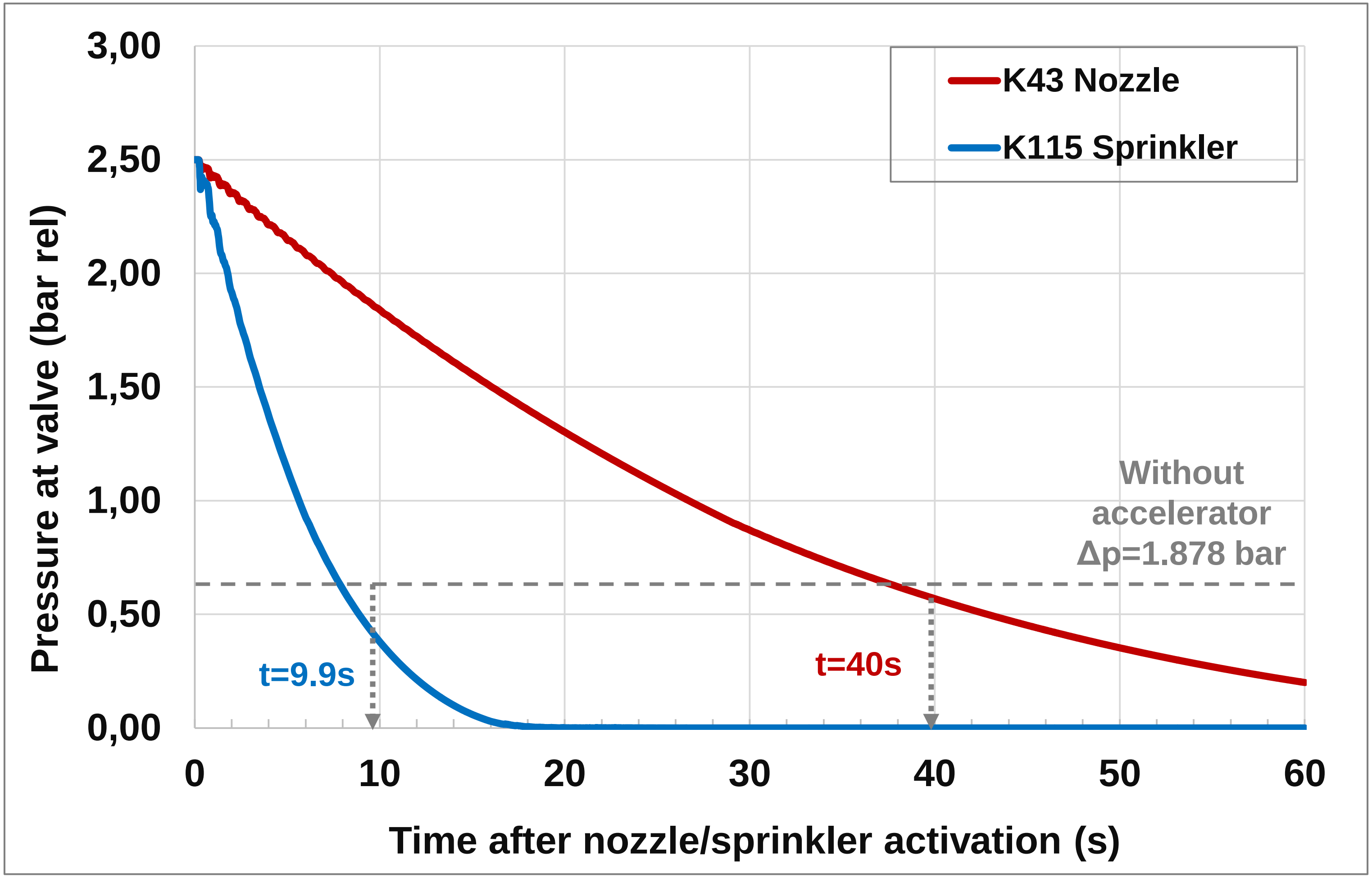
0.0008m (first node in the log-layer) to 0.015m

Results : valve activation time



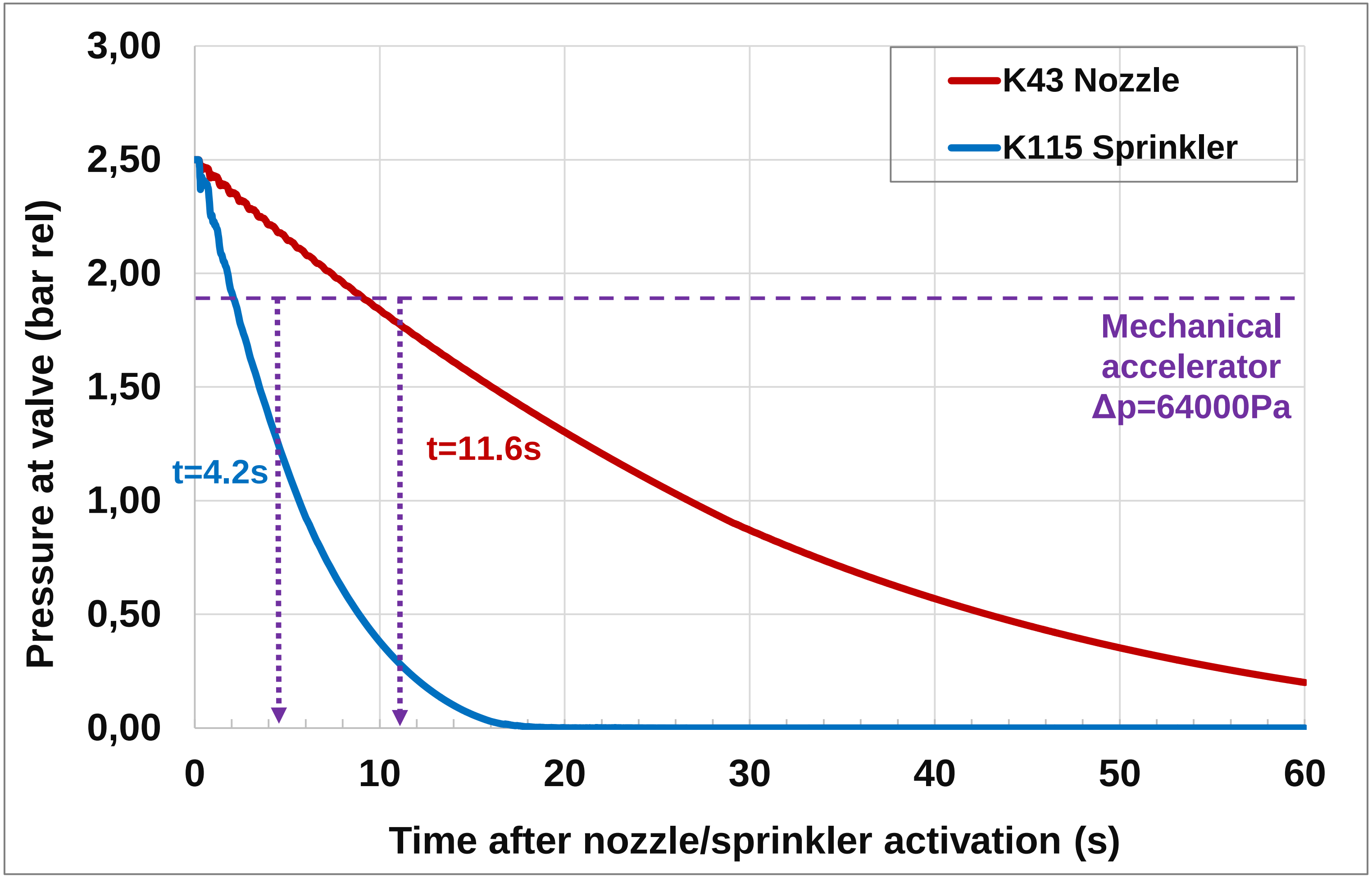
- Patm reached in the system after **20s for K115 Sprinkler** vs **more than 60s for K43 Nozzle**

Results : valve activation time



- 2s delay between detection and valve activation

Results : valve activation time



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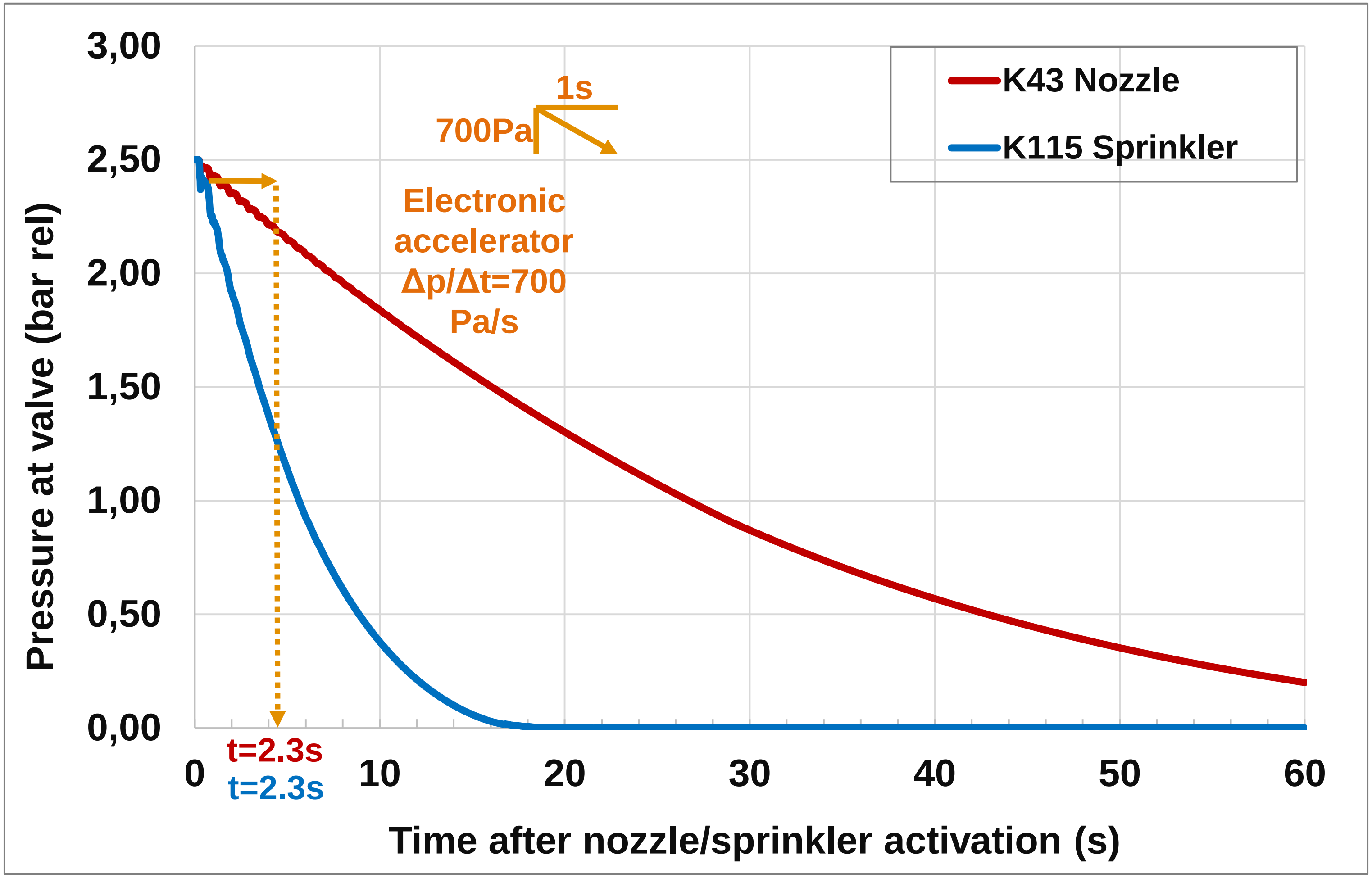


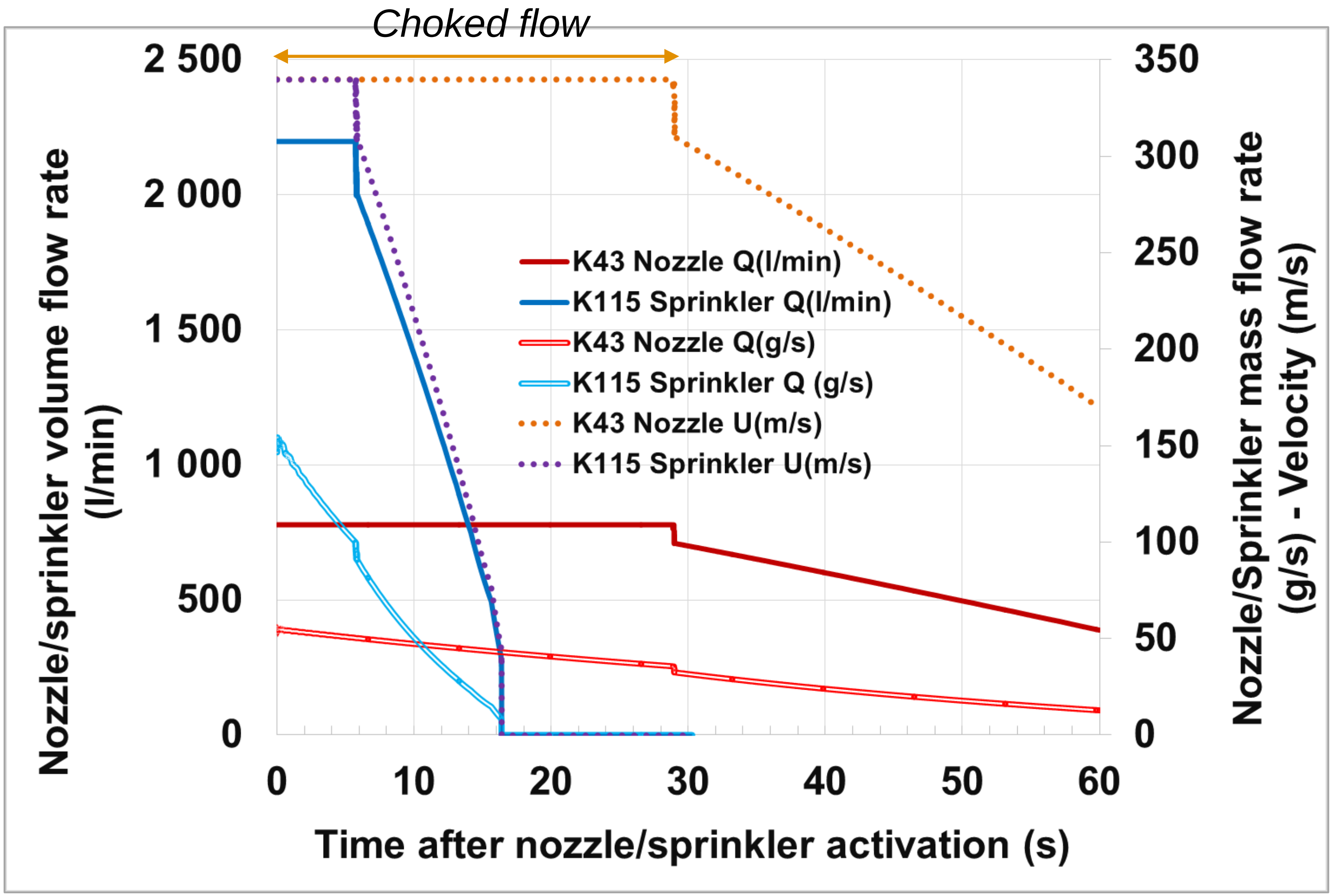
- 2s delay between detection and valve activation

Results : valve activation time

	Accelerator	Detection time (s)	Valve activation time (=detection time +2s)	Pressure at valve activation (bar rel)
Water-Mist (K43)	**W/O**	**38.02**	**40**	**0.57**
	MECH	**9.63**	**11.6**	**1.74**
	ELEC	**0.26**	**2.3**	**1.84**
Sprinkler (K115)	**W/O**	**7.94**	**9.9**	**0.36**
	MECH	**2.23**	**4.2**	**1.32**
	ELEC	**0.23**	**2.3**	**2.34**

- The slower the technology, the larger the difference in valve activation time
- Lower pressure in the system at activation for **K115 Sprinkler** than for **K43 Nozzle**

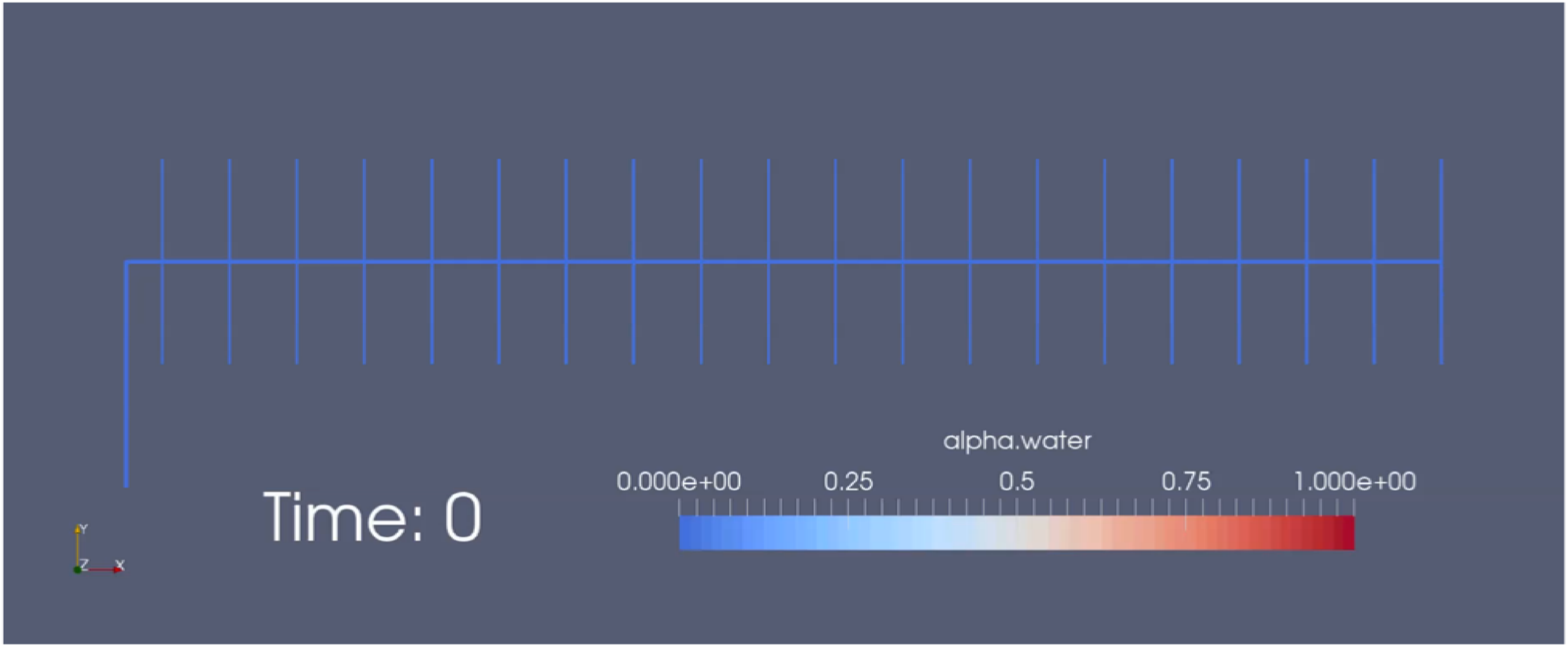
Results : valve activation time



Velocity, mass flow rate and volume flow rate at sprinkler head: illustration of the choked flow modelling

Results : Scenario 1 – electronic accelerator

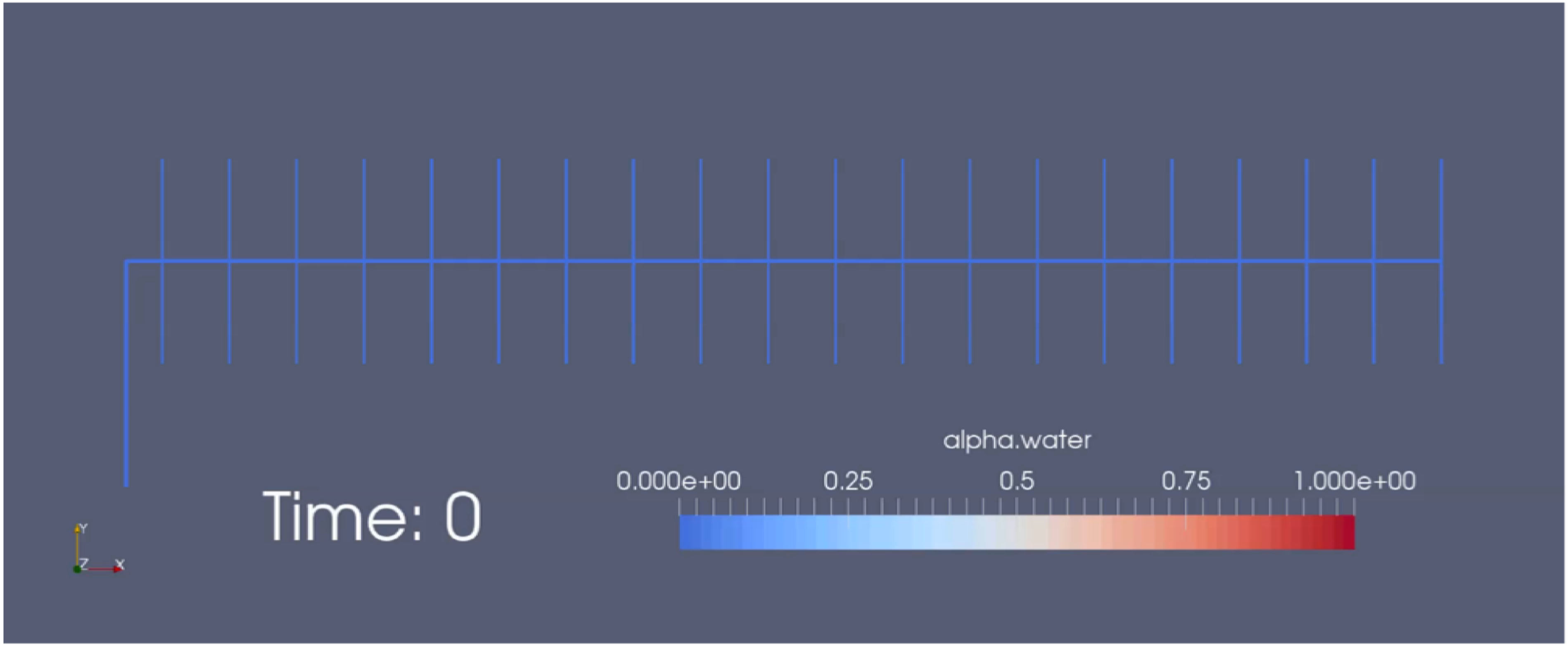
K115 Sprinkler: Water fraction after pump activation



Competition of two phenomena: air compression under moving water front and discharge through open nozzle/sprinkler

Results : Scenario 1 – electronic accelerator

K43 Nozzle: Water fraction after pump activation



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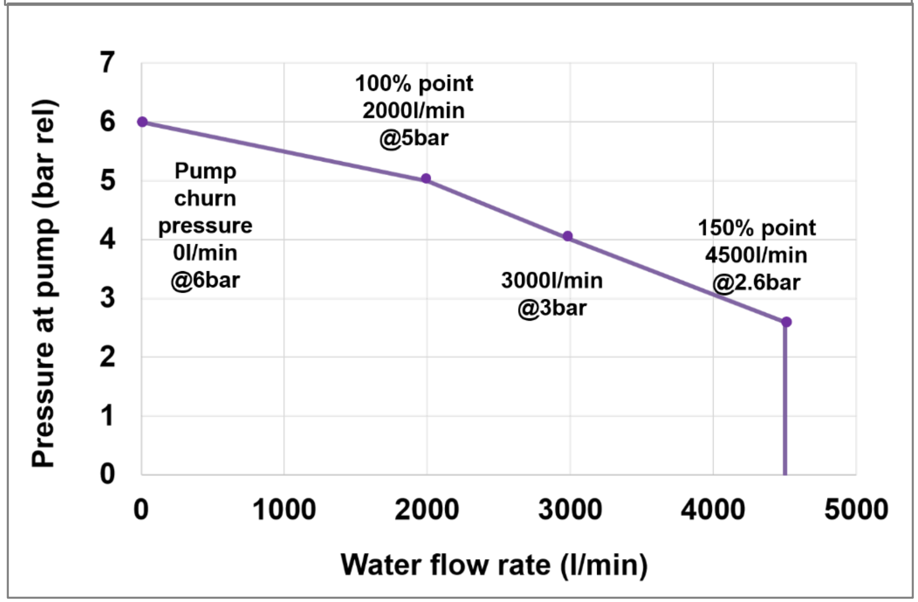
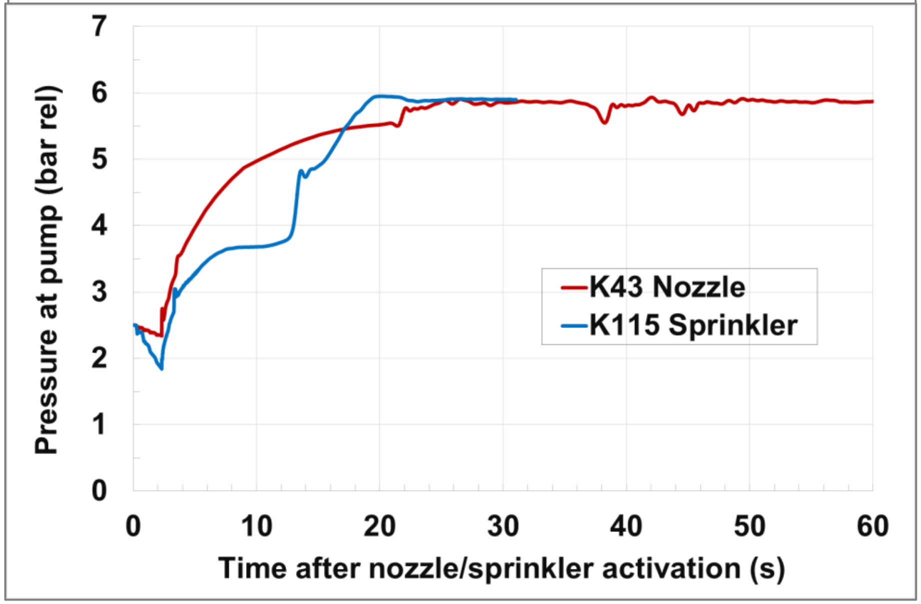
Results : Scenario 1 – electronic accelerator

Pump curve



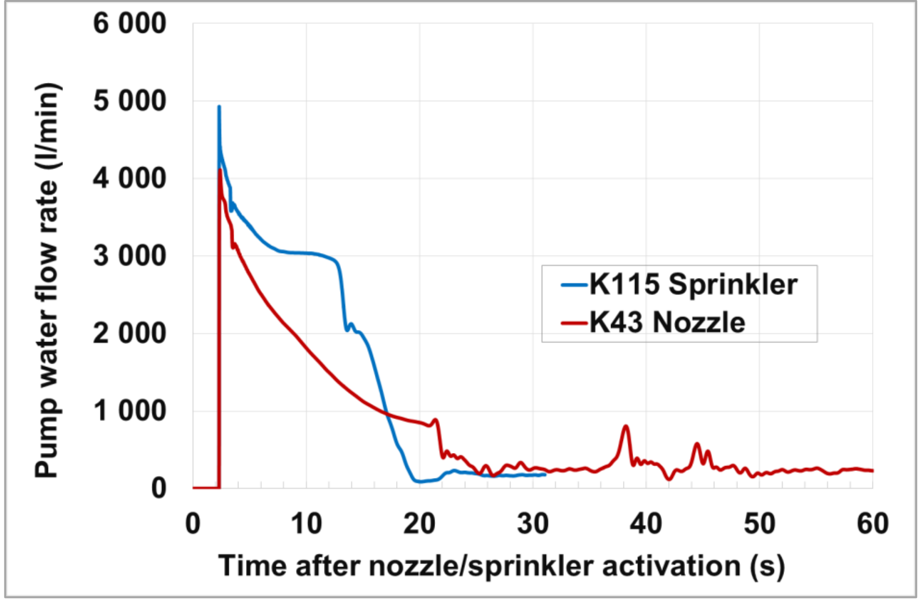
Pressure at pump after valve activation



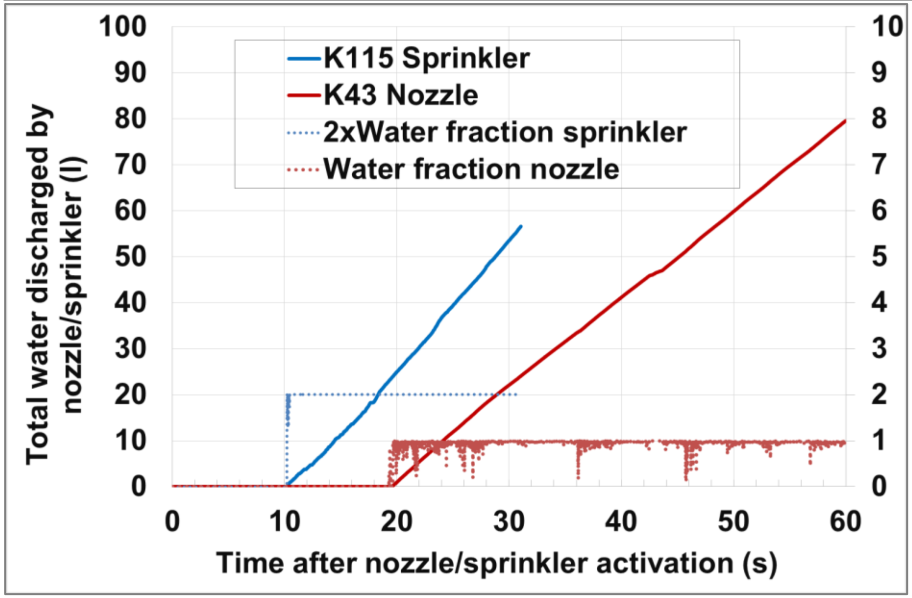
Pump facing a lower initial pressure in system for **sprinkler** than for **water-mist**
➡ Pump working at lower pressure for a longer time = higher water flow rate

Results : Scenario 1 – electronic accelerator

Pump water flow rate



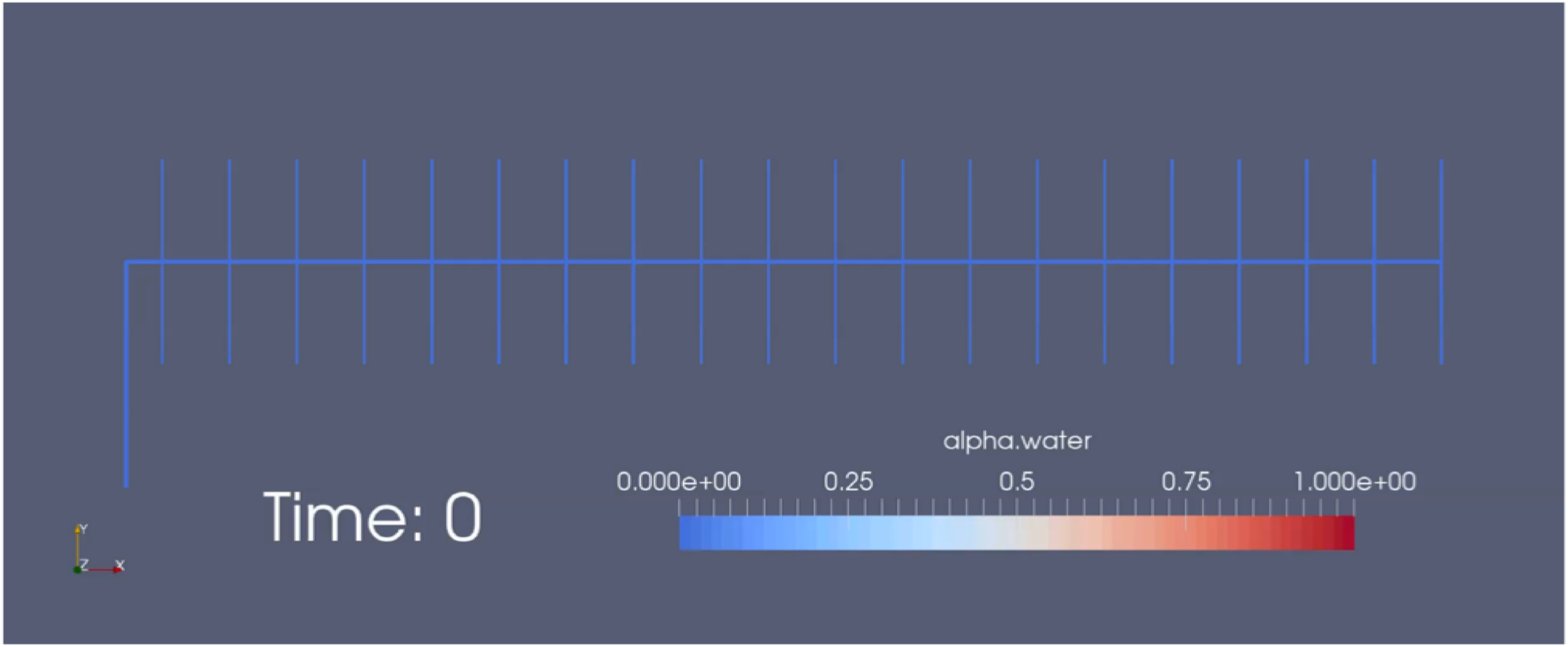
Total water volume discharged by nozzle/sprinkler



- Higher water flow rate: Faster water delivery for sprinkler than for water-mist
- But steady-state reached faster after water delivery for water-mist
- Fewer air bubbles for sprinkler since less air was trapped in the branchlines (lower pressure at activation)

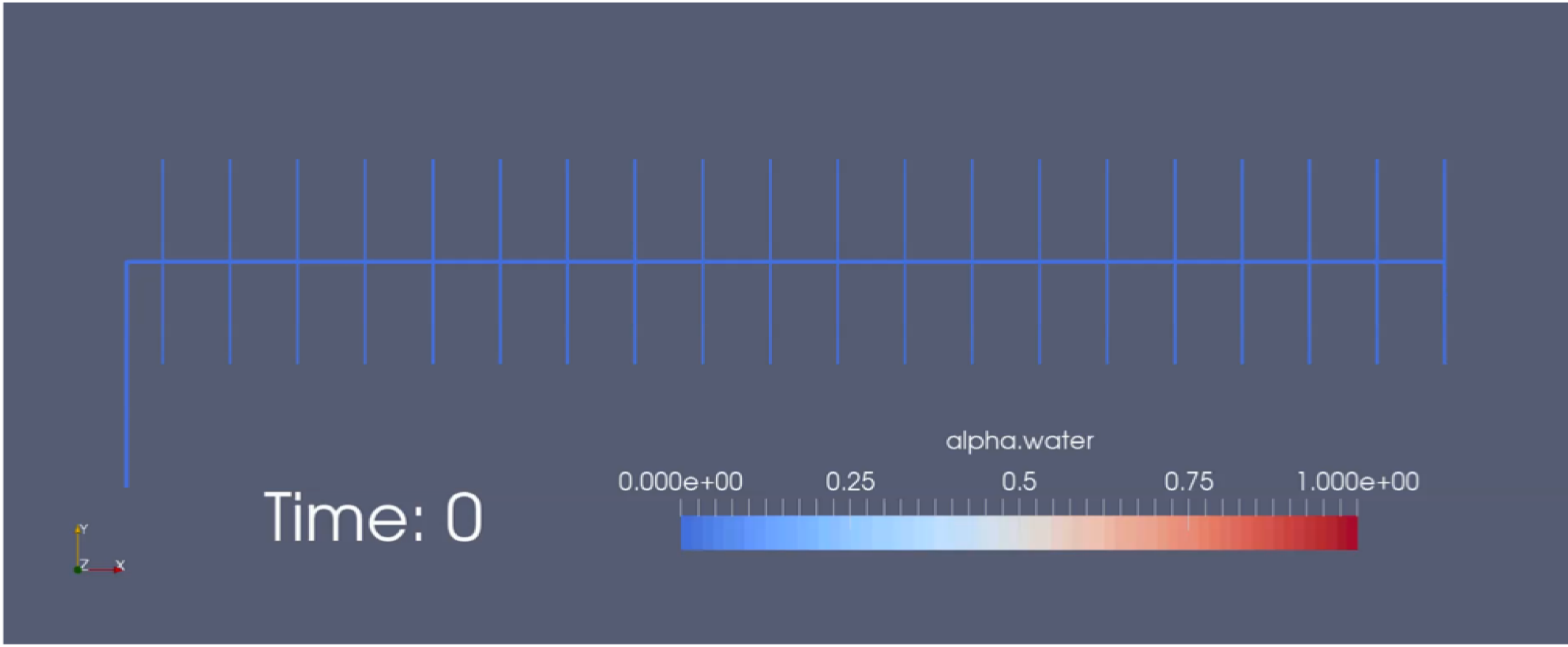
Results : Scenario 2 – mechanical accelerator

K115 Sprinkler: Water fraction after pump activation



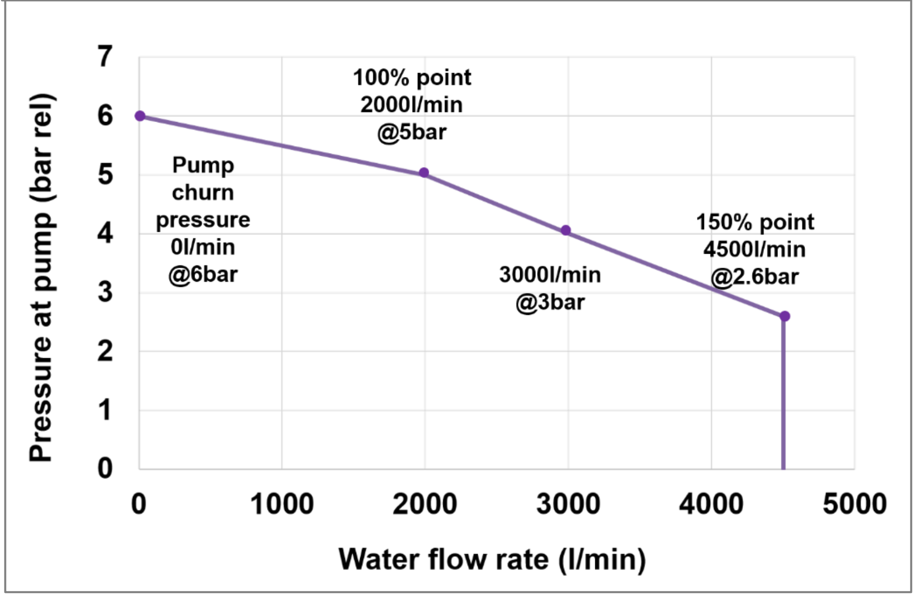
Results : Scenario 2 – mechanical accelerator

K43 Nozzle: Water fraction after pump activation

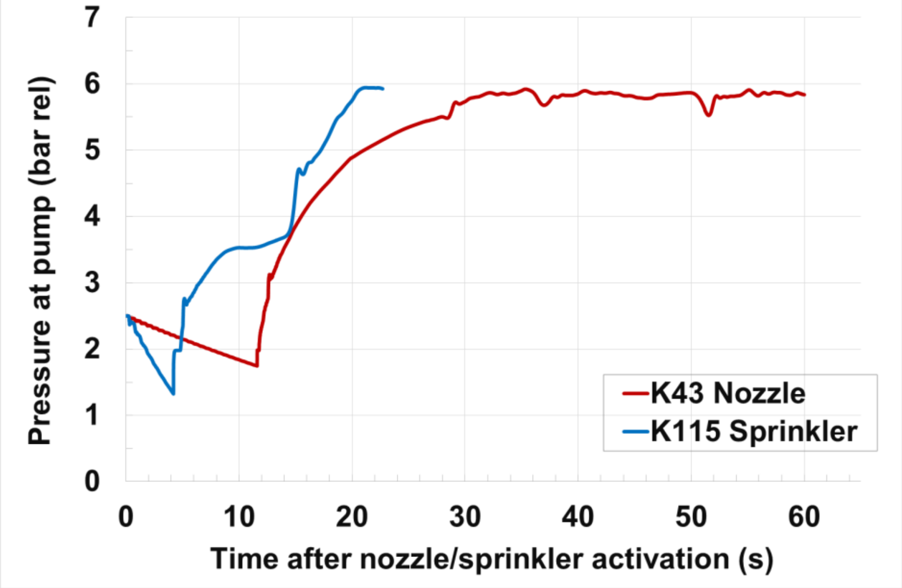


Results : Scenario 2 – mechanical accelerator

Pump curve



Pressure at pump after valve activation



Similarly: pump facing a lower initial pressure in system for **water-mist** than for **sprinkler**

➡ Pump working at lower pressure for a longer time = higher water flow rate

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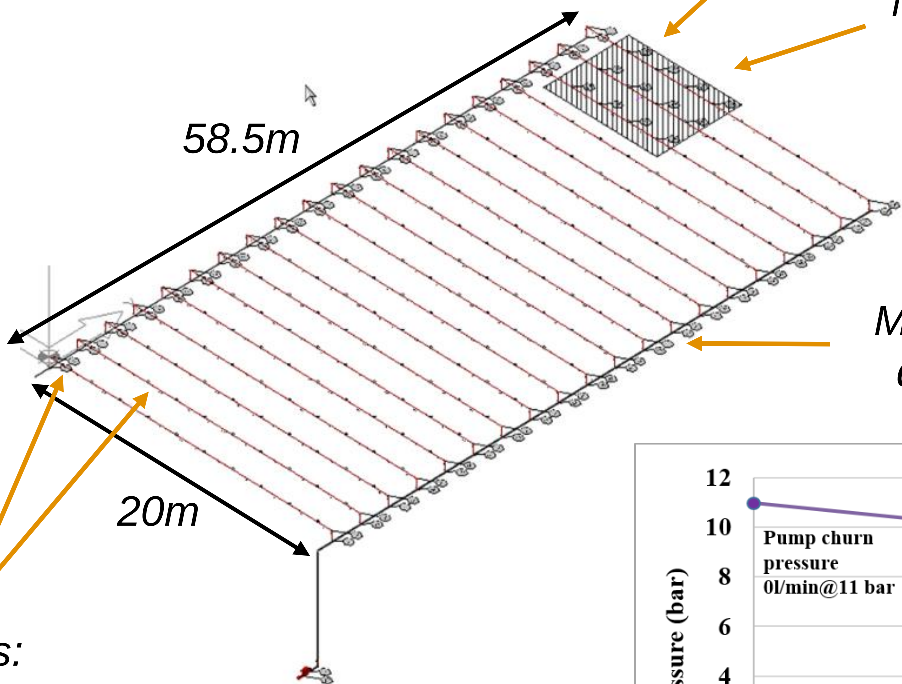
2nd Modelled system

System of gridded typology

Outlet : K80 Sprinkler head/nozzle (80 l/min/bar$^{1/2}$) U=f(p,α)

Most remote area



58.5m

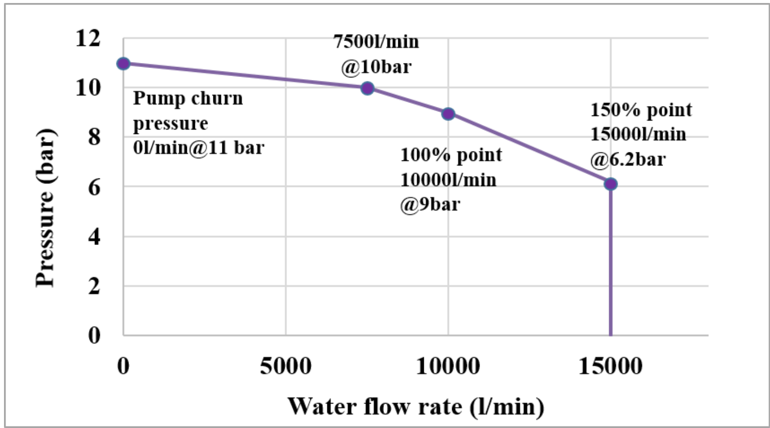
20m

20 branches System volume = 3.642 m^3

Main header: internal diameter = 160mm

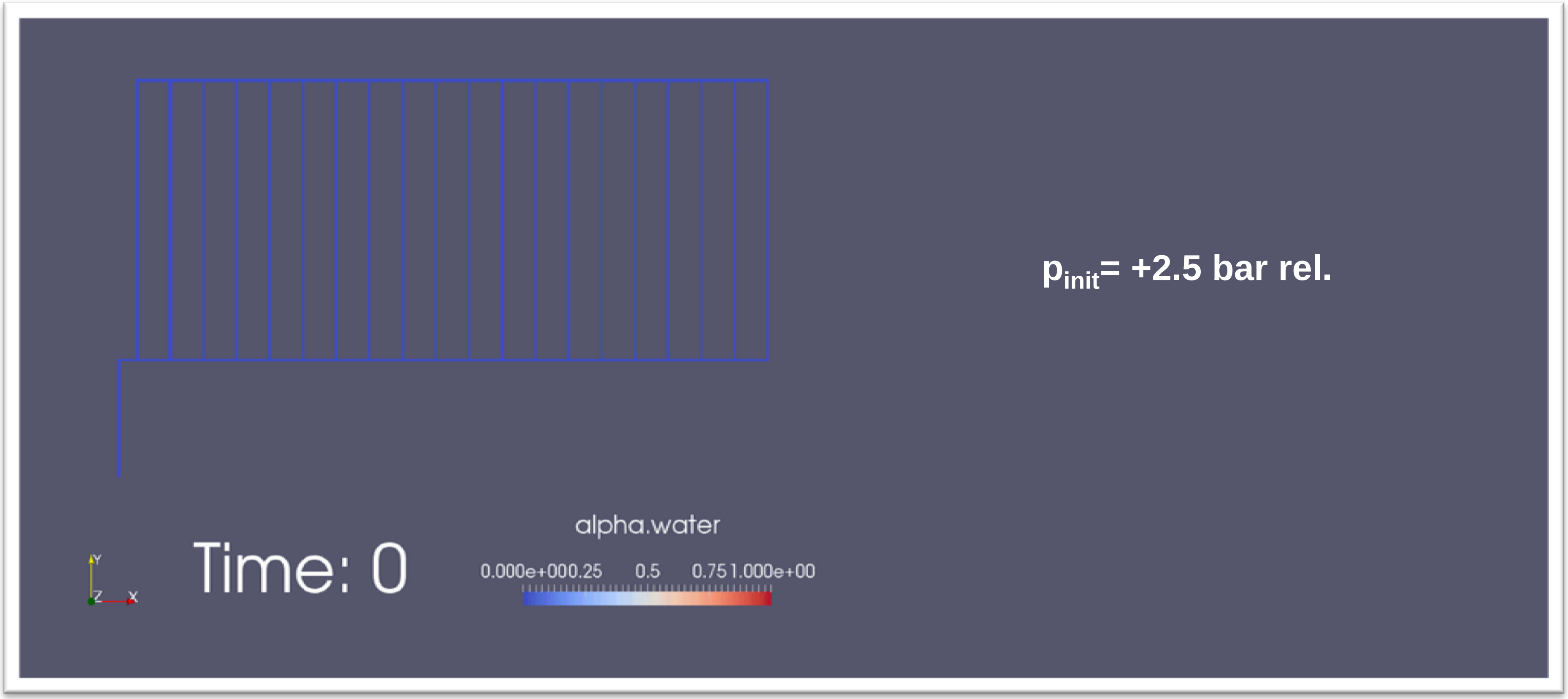
Branches and risers: internal diameter = 55.7mm

Inlet: Main fire pump Ptot=f(Q)



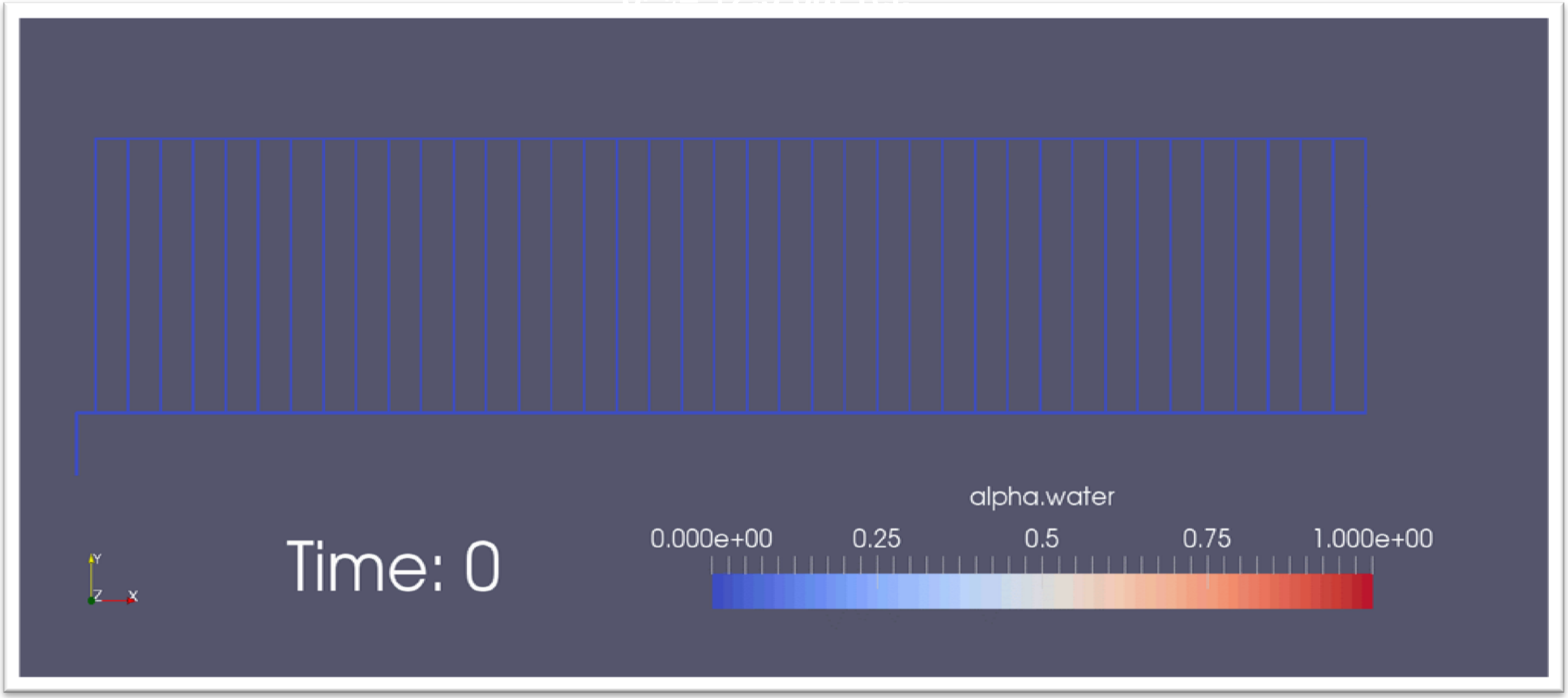
Results : Scenario 3 – test of the model on a gridded system

System volume = 3.642m³ : Water fraction after pump activation
(preaction case: pump activation without nozzle/sprinkler opening)



Results : Scenario 3 – test of the model on a gridded system

System volume = 7.284m^3 : Water fraction after pump activation
(preaction case: pump activation without nozzle/sprinkler opening)



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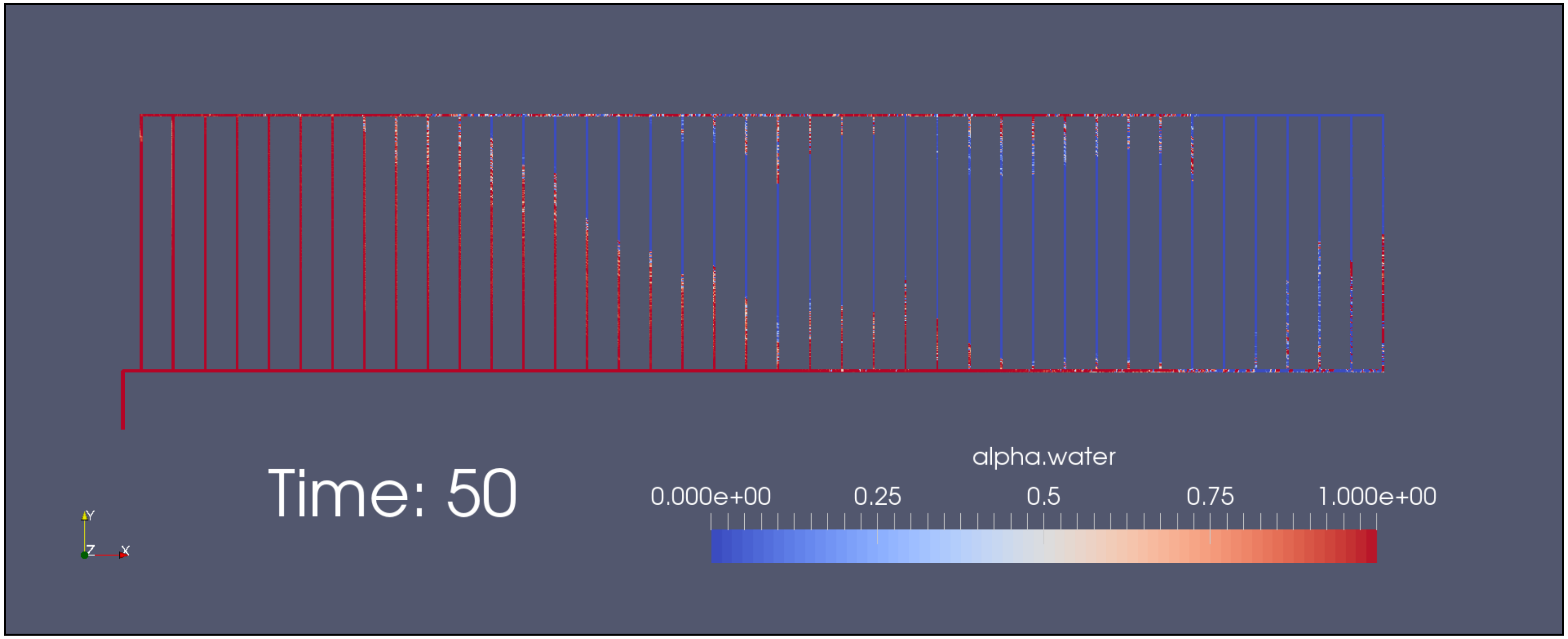
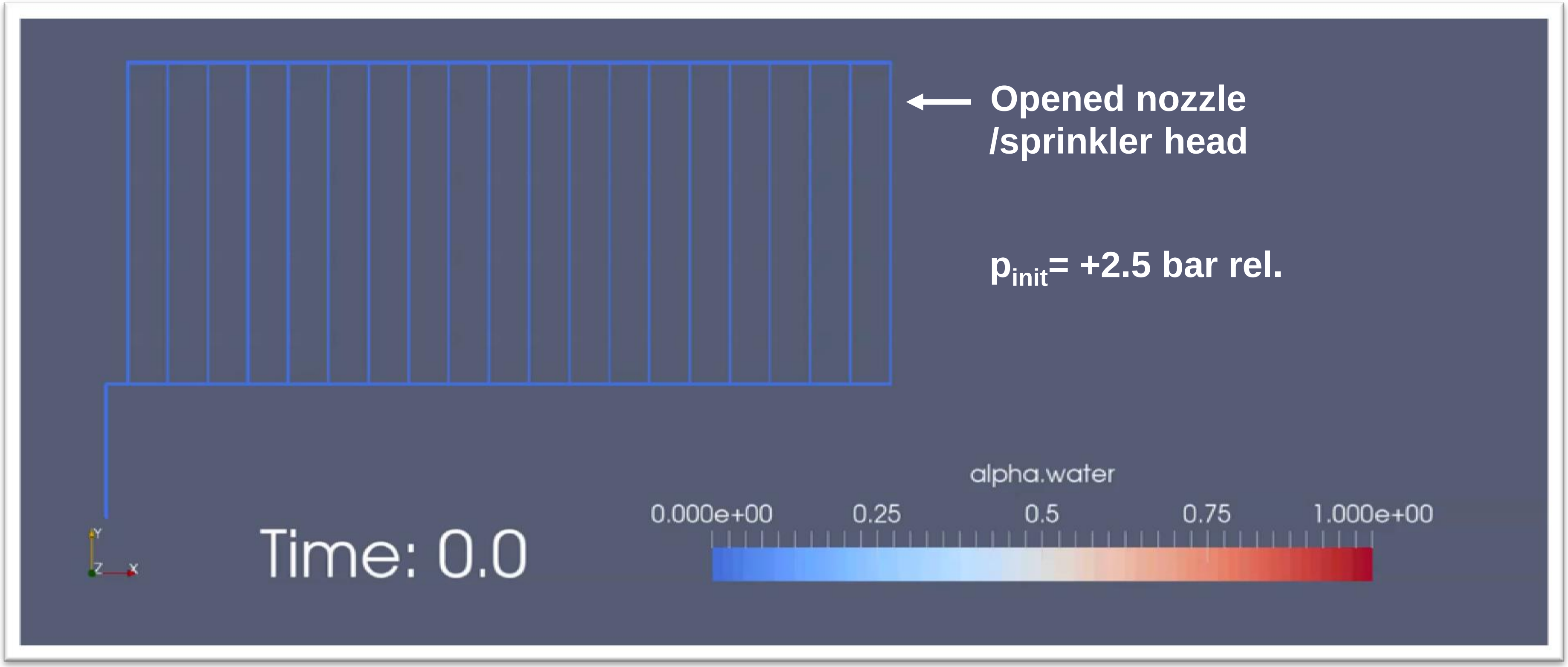


- 64% of system filled with water for at equillibrium for pinit=+2.5bar

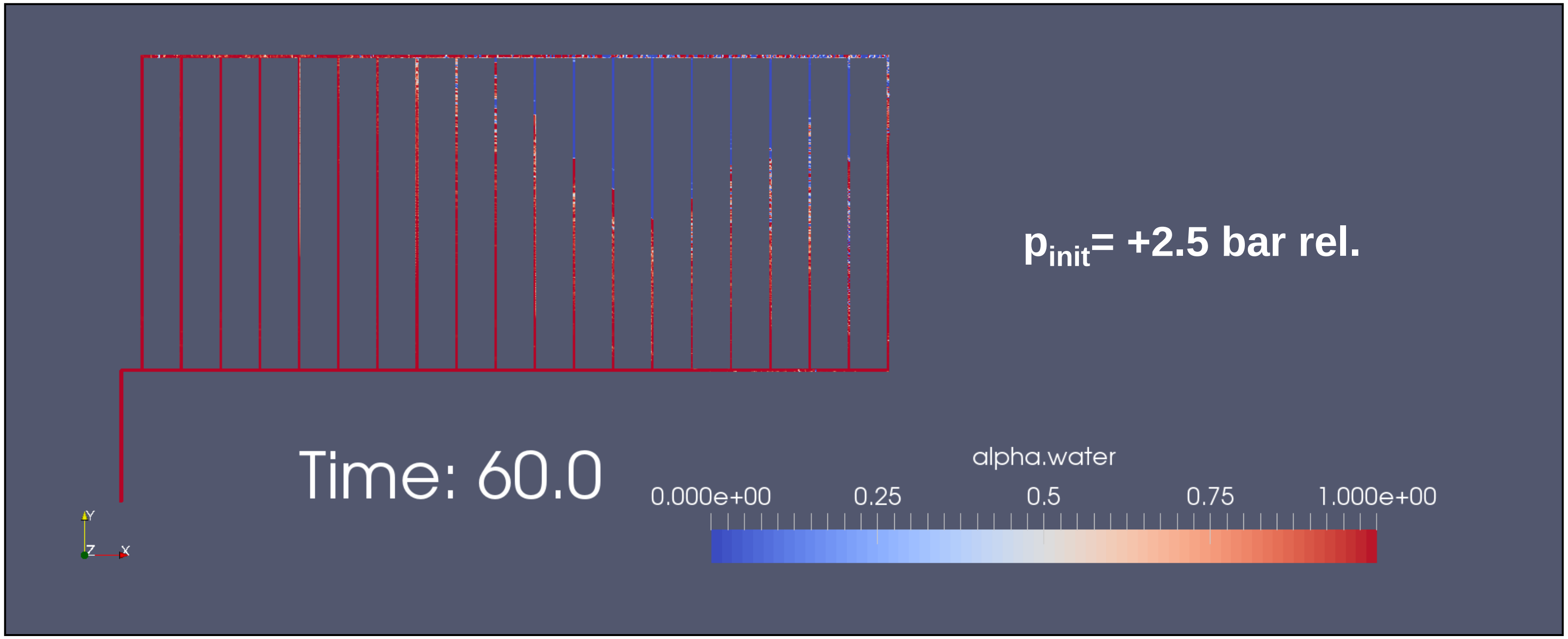
Results : Scenario 3 – test of the model on a gridded system

Water fraction after pump activation (K80 nozzle/sprinkler)



Results : Scenario 3 – test of the model on a gridded system

System volume = 3.642m³ : Water fraction after pump activation (nozzle/sprinkler)

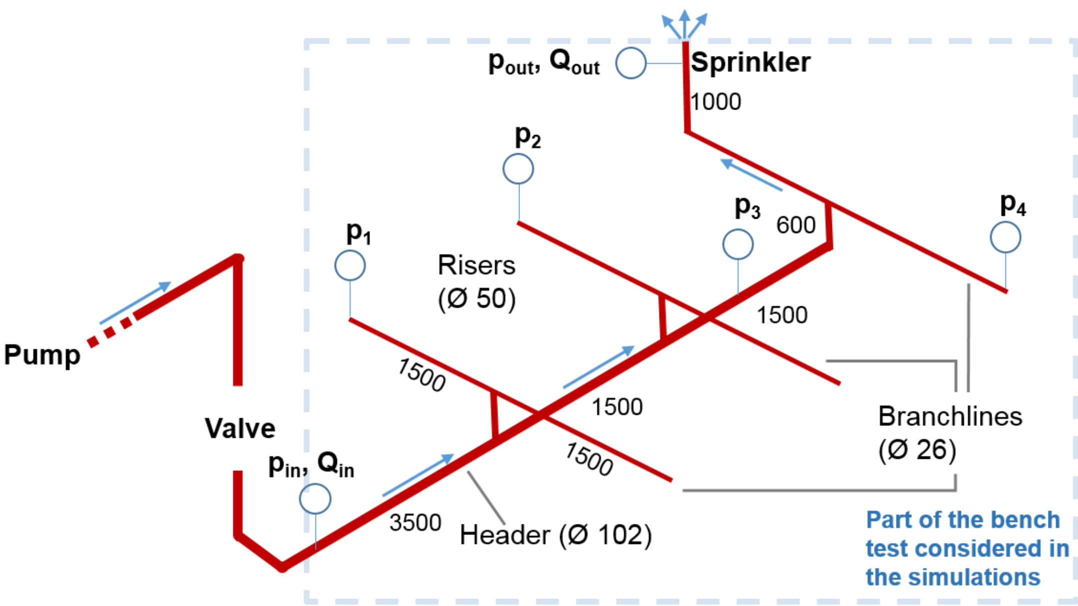


- **P_{init}=+2.5bar :** psystem >> patm at valve activation -> water follows the path of least resistance and air pockets are blocked in the branchlines = potential unstability

Measurements on test bench (scale 1 pipe dimensions)

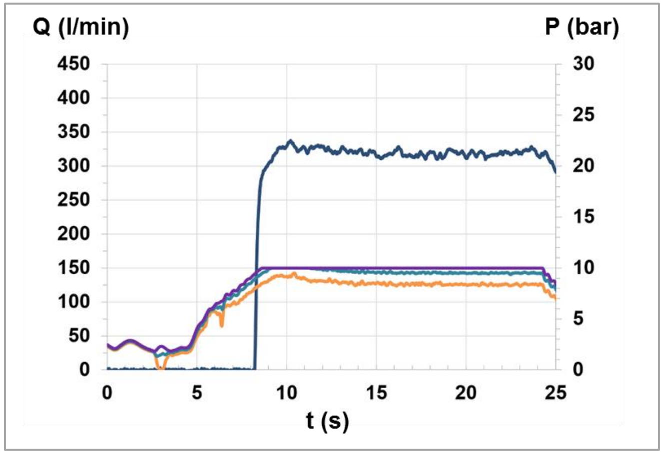
☞ **Objective : validation of the numerical predictions on a 3D configuration**

(work in progress)



Schematic diagram of the test bench

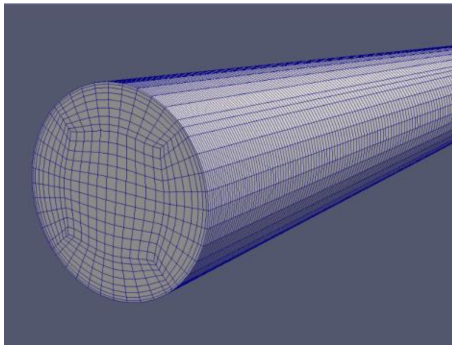
Test bench: Tree typology



Dry-pipe measurements for p_{init} = +2.5bar (K115 sprinkler)

Conclusion and perspectives

- A CFD model was developed, and the flow within dry pipe sprinkler and low pressure water mist systems were assessed on a simplified Tree typology
- The pressure that the pump has to face in the system at activation varies depending on the activation time, technology considered, and orifice diameter
- These parameters impact as well the amount of air trapped in the branches, and the nature of the flow discharged by the nozzle/sprinkler
- 3D CFD simulations will be carried out and compared to the experimental measurements on the test bench with scale 1 pipe dimensions



Mesh of the 3D Case

Thank you for your attention