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Investigation of Water Hammer Overpressure in the Hydraulic Passages of Hydropower Plants Equipped with Francis Turbines

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Abstract. Water hammer shortens hydraulic passage lifespan and may cause sudden failure. The primary goal is to use a hierarchical approach to assess the main parameters associated with water hammer. This will help investigate their influence and assist in decision making. Analytical calculation results and a numerical model are compared against experimental data. Our investigations examine water hammer overpressure loading induced by transient regimes. We used data from experimental campaigns carried out within the Hydro-Québec fleet that cover different types of hydraulic turbines and hydraulic passage configurations as experimental dataset. Guide vane closing rate was the main parameter controlled during the overpressure experiments and a general trend was identified for overpressure. This empirical trend is compared to model estimates in order to validate the hypothesis taken into account for calculations. An in-depth understanding of the water hammer phenomenon helps to select the appropriate theoretical model and recommend the optimal operating parameters to extend lifetime and to avoid catastrophic failures. Our study case suggests that available experimental data can be used along with gradually increasing analysis complexity to identify the optimal methodology for a given configuration.

1. Introduction

In the current energy context, with the advent of different types of renewable energy, Hydraulic Power Generators (HPG) are often used to equilibrate the grid because of a lack of availability and flexibility of new energy sources. HPG are increasingly required to provide flexible operation to regulate and balance the grid, according to March [1]. Dreyer et al. [2] note that it is essential to identify and estimate Hydraulic Passage (HYP) additional loads caused by HPG operation in transient zones. More extreme HPG operating conditions will result in additional water hammer and pressure fluctuations, resulting in premature HYP degradation. Quaranta et al. [3] state that approximately 50% of all hydropower plants (HPP) worldwide were commissioned more than 40 years ago.

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A recent literature review identified the existing methodology and highlighted the increase of model complexity over time to properly capture HYP water hammer loading in [4].

As hydraulics became an applied science, during the 19th century and earlier, scientists were conducting a wide variety of experiments and publishing articles, along with theorists who were developing the general principles of hydrodynamics [5]. Some of them investigated the water hammer phenomenon, including Menabrea [6], Michaud [7], Johannes von Kries [8], Joukowsky [9]. At that time, the analyzed models were generic and direct references to HPG were quite rare [8]. With the occurrence of the first major accidents due to water hammer, concerns about this phenomenon grew in the hydroelectric industry.

In the early 20th century, Bouchayer [10] and De Sparre [11] state some simplistic theories used to design HYP. Allievi [12] takes a structured and scientific approach to the phenomenon, also making recommendations to avoid hazards related to water hammer. Next, the theory is developed by Parmakian [13] from the existing to current classic numerical models and simulations. Selz [14] notes that overpressure is a safety issue regarding compliance with the HYP maximum allowable working pressure (MAWP), which must be updated to the actual degraded status.

Ghidaoui et al. [15] compile a collection of current theories and models with their own limitations and hypotheses. The method of characteristics (MoC) [16] or coupling MoC with Computational Fluid Dynamics (CFD) [17] is commonly used to analyze the HYP design. Bakken and Bjørkvoll [18] propose a mathematical model to consider High Cycle Fatigue (HCF) in operation, as well Low Cycle Fatigue (LCF) in unit start and stop. Furthermore, Gagnon et al. [19] show that cyclical loadings in transient mode have a major impact on equipment reliability. Moreover, according to Trivedi et al. [20], the transients shorten the lifetime of equipment. To account for the turbine, Ramos [21] extended a previous water hammer mathematical model proposing that the runner in overspeed does not represent a constant pressure drop but acts as a dynamic orifice inducing variable pressure loss.

We observe this increase in model complexity to account for more and more phenomena in HYP but are they required for every task? The main objective of this study is to provide an overview of methodologies that can be used if experimental results are available for a given unit or other similar configurations in order to estimate overpressure behaviour. To do so, we compared a simple analytical model and numerical software against the empirical trend observed in experimental data. This will make it possible to identify a validated method to study the global trend in water hammer overpressure and thereby make it possible to use a proper HYP model for units in operation or at the design stage.

Section 2 presents in situ experimental investigations performed to determine the influence of the wicket gates (WG) closing rate (tBAF) on HYP overpressure. The analytical and numerical investigations for a case study are described in Section 3. Then, results obtained with analytical and numerical models are compared with experimental data for validation in Section 4. Finally, some discussion and conclusions are offered.

2. Experimental investigations

Our study analyzes experimental measurements in order to identify factors that contribute to the water hammer phenomenon and establish their influence. Lupa et al. [24] conducted test campaigns on the Hydro-Québec HPP fleet on 24 HPG configurations for different types of runners (Francis, Kaplan, propeller, saxo) and types of HYP (long/short, underground/external, low/high head, concrete/welded, etc.).

The main parameter controlled during the experimental load rejections was the rapid closing rate of the wicket gates. Special attention was paid to the spiral case and penstock MAWP design criteria. The correlation between overpressure and the variation in the rate of wicket gate rapid closure was studied. For load rejections at different WG openings, a third-order polynomial function seems to properly capture the evolution of overpressure maximum values [23].

Figure 1 shows results obtained for overpressures (dP%) as a function of WG opening (%WG) for medium-head Francis turbines (V to Z). In this study, HPP (Y) is considered for our analysis.

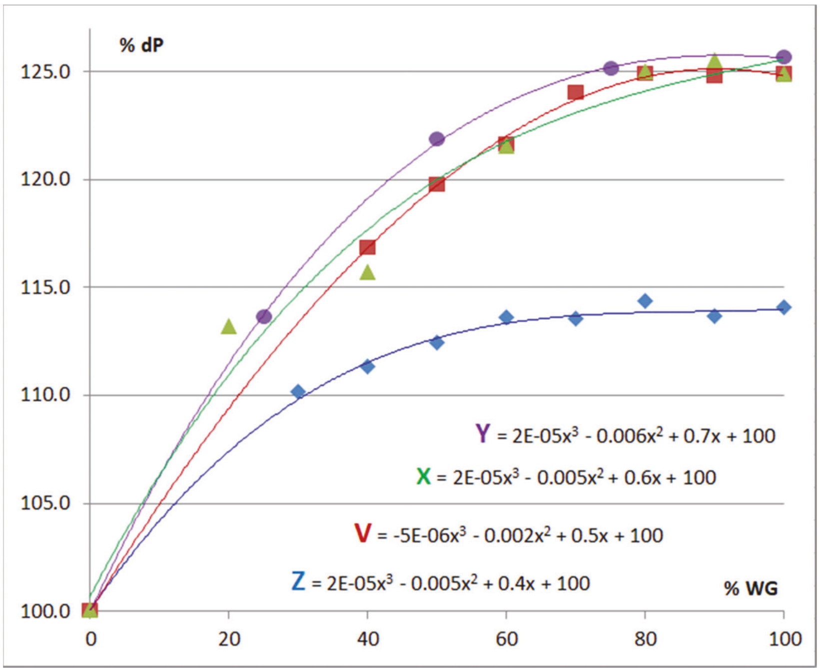

Figure 1. %dP function of %WG, medium-head Francis, HPP (V to Z), 2013 to 2019 [24]

The %dP values were obtained with tBAF adjustment in order to comply with the MAWP, which was 125% of the steady state pressure for considered HPP. Because of the limitation introduced by the intumescence wave of the free water surface at the intake gate, in the case of (Z), the WG closure had to be slower than required by the MAWP, so consequently the %dP obtained for this HPP are lower than for the others.

2.1. Test case setup

Water hammer is a hydraulic shock wave which generates a pressure surge when the flow is forced to stop. In an HPP, water hammer is caused by the HPG (WG closing or other shutoff device) and the HYP will undergo the effects. Figure 2 shows the main HPP elements involved in the phenomenon and identify the measured values listed in table 1.

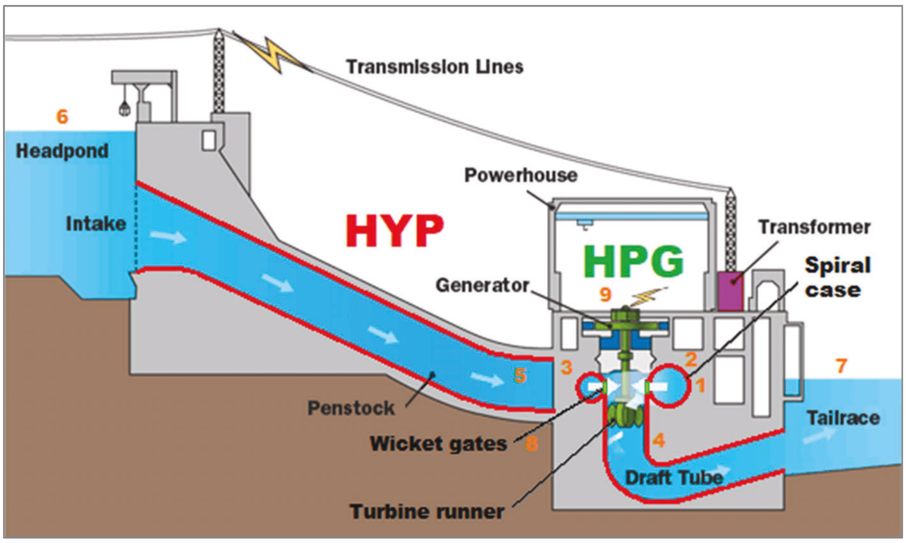

Figure 2. Diagram of a HPP station: HPG in green, HYP in red (original image from [22])

Table 1. Instruments used for testing campaign.

	Instrument location	Measured value
1	Spiral case manhole	Spiral case gauge pressure (dP)
2	Winter Kennedy taps	Spiral case gage pressure (dP)
3	Spiral case inlet section	Spiral case gauge pressure (dP)
4	Draft tube manhole	Draft tube absolute pressure/vacuum
5	Winter Kennedy panel	Turbine flow rate
6	Intake gate	Upstream level
7	Downstream tailrace	Downstream level
8	Servomotor linear position	WG opening
9	Electronic governor	Rotational speed of the unit

2.2. Experimental data
In situ, for each HPP, investigations were carried out to determine operating behaviour during the load rejection procedure at different %WG. Therefore, tests were conducted considering the predetermined settings for each configuration. The tBAF was previously measured in dead water and extrapolated to the complete WG closure to estimate the rapid closing time.

For this study, a test case based on the Francis turbines in HPP (Y) was chosen. For a tBAF = 7.75 seconds, the maximum measured values of the water hammer overpressure (dP) at spiral case inlet section for different WG openings are listed in table 2. These values are shown above in figure 1 and are used in chapter 4 to validate our analytical and numerical models.

Table 2. Maximum water hammer overpressure for different WG openings.

WG opening (%)	Maximum measured pressure (kPa)
100	1808
75	1800
50	1753
25	1558

3. Analytical and numerical investigations
One analytical and one numerical analyses were performed and compared with experimental results for validation. The objective is to find a valid model to orient the investigations for a given unit or similar ones in new projects.

The water hammer phenomenon occurring inside one HYP equipping an HPP was analyzed. In this study, the water hammer equations were adapted for the penstock segment between the intake at the water reservoir and the HPG. To control the amount of water admitted to the turbine, the opening position of the WG, which is adjusted by servo actuators receiving commands from the speed governor or unit protection system, is used. The WG are considered to be the flow shutoff device provoking the water hammer wave.

3.1. Analytical study
As the first analytical validation, Joukowsky's 1D steady equation will allow us to compare the experimental values obtained in situ for water hammer pressure with predicted magnitude of the wave pressure surge [4,15]. In order to simplify the calculation, certain hypotheses and limitations are assumed: 1) the pressure rise is due to uniform WG closure, 2) the damping effect due to headloss is

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neglected, 3) the packing effect due to headloss is neglected, 4) the disturbance by the water column separation/cavitation is not considered, 5) the fluid-pipe structure interaction is not considered, 6) the packing by friction forces and the wall shear stress are neglected, 7) the instantaneous flow acceleration is not considered, 8) the motion and inertia of the pipe are neglected.

This type of simplified approach is appealing because it is quick and easy to use. However, the analytical validation might only work for simple cases if existing empirical values are available for validation. Otherwise, a more sophisticated calculation method combined with a proper Design of Experiment plan (DOE) would be required to validate experimental data.

With these simplifications, the pressure spike ΔP due to the flow absolute velocity change ΔV is calculated with Joukowsky's fundamental water hammer equation [15]:

$$\Delta P = \rho\, a\, \Delta V \tag{1}$$

where a = acoustic water hammer wave speed; ρ = fluid density.

The acoustic water hammer wave speed inside an elastic pipe subject to the axial stress is calculated with Korteweg's general formula [15]:

$$a = \left(\frac{\frac{K_f}{\rho}}{1 + c\,\frac{K_f D}{eE}} \right)^{1/2} \tag{2}$$

where K_f = bulk modulus of elasticity of water; D = pipe diameter; e = pipe wall thickness; E = Young's modulus of elasticity for the pipe material; c = coefficient for pipe anchoring.

For an elastic pipe anchored throughout from axial movement (e.g., a turbine penstock), $c = 1 - \nu_P^2$ [15], with ν_P = pipe material Poisson's ratio (e.g., 0.27 ÷ 0.3 for steel, 0.1 ÷ 0.2 for concrete) and the equation for the acoustic water hammer wave speed becomes:

$$a = \left(\frac{\frac{K_f}{\rho}}{1 + (1-\nu_P^2)\,\frac{K_f D}{eE}} \right)^{1/2} \tag{3}$$

If the pipe is considered rigid ($E \to \infty$), the acoustic water hammer wave speed (celerity) formula becomes:

$$a = \left(\frac{K_f}{\rho} \right)^{1/2} \tag{4}$$

A particular case occurs if the shutoff device closes at a speed much lower than the acoustic water hammer wave speed. To verify this, the closing time of the WG (t_{BAF}) should be compared to the pipeline period T, which is the time required for the water hammer wave to travel from the shutoff device to the boundary condition (reservoir) and back to the point of water hammer wave origin [25]:

$$T = \frac{2\mathrm{L}}{a} \tag{5}$$

where L = penstock length.

If the $t_{BAF} > T$, we are in range of "slow" closures and for this particular case the pressure rise is provided by the Warren M.M. equation [25], which in simplified formula is similar to the Newton second low applied to a rigid water column [13]:

$$\Delta P = \frac{\rho \mathrm{VL}}{t_{BAF}} \tag{6}$$

where V = cross-sectional average velocity of the water column at steady state under study.

For all cases, the maximum pressure occurring in water hammer can be calculated with:

$$P_{MAX} = P_{SS} + \Delta P \tag{7}$$

where P_{SS} = the pressure at steady state before the water hammer. In a first approximation, the P_{SS} is considered equal to piezometrical pressure at the turbine centreline or the reference pressure for tests $P_{REF} = \rho g H$; g = gravitational acceleration; H = piezometrical water head at turbine centreline. Thus, the maximum calculated pressure becomes:

$$P_{MAX} = P_{REF} + \Delta P = \rho\, g\, H + \Delta P \qquad (8)$$

The pressure spike ΔP is calculated by introducing formula (1) for a sudden closure or formula 6 for a "slow" closure, so the previous equation becomes:

$$P_{MAX} = \rho\, g\, H + \rho \frac{\mathrm{L}}{t_{BAF}} V \qquad (9) \text{ for a gradual closure with } t_{BAF} > T$$

$$P_{MAX} = \rho\, g\, H + \rho\, a\, V \qquad (10) \text{ for a sudden closure with } t_{BAF} < T$$

where a is calculated either with formula 3 or 4.

For the validation, the measured pressures in situ shall be compared with the values resulting from formula 8. If the difference between the empirical results and the simplified calculation is acceptable, the model is validated and may be used for similar new projects as a reference point for starting the test series. If the difference is too significant, the new or more sophisticated hypothesis must be considered, and the previous model shall be reconsidered.

3.2. Analytical data results

The simple analytical methodology was applied to power plant (Y) in order to compare the numerical results with the experimental values. The data considered are shown in figure 3.

Using formula 3, the acoustic water hammer wave speed (celerity) for an elastic turbine penstock anchored throughout from axial movement will be:

$$a = 962.94 \text{ m/sec}^2$$

From formula 5, the pipeline period will be:

$T = 0.4$ sec, inferior to t_{BAF} = 7.75 sec: gradual closure case ($t_{BAF} > T$)

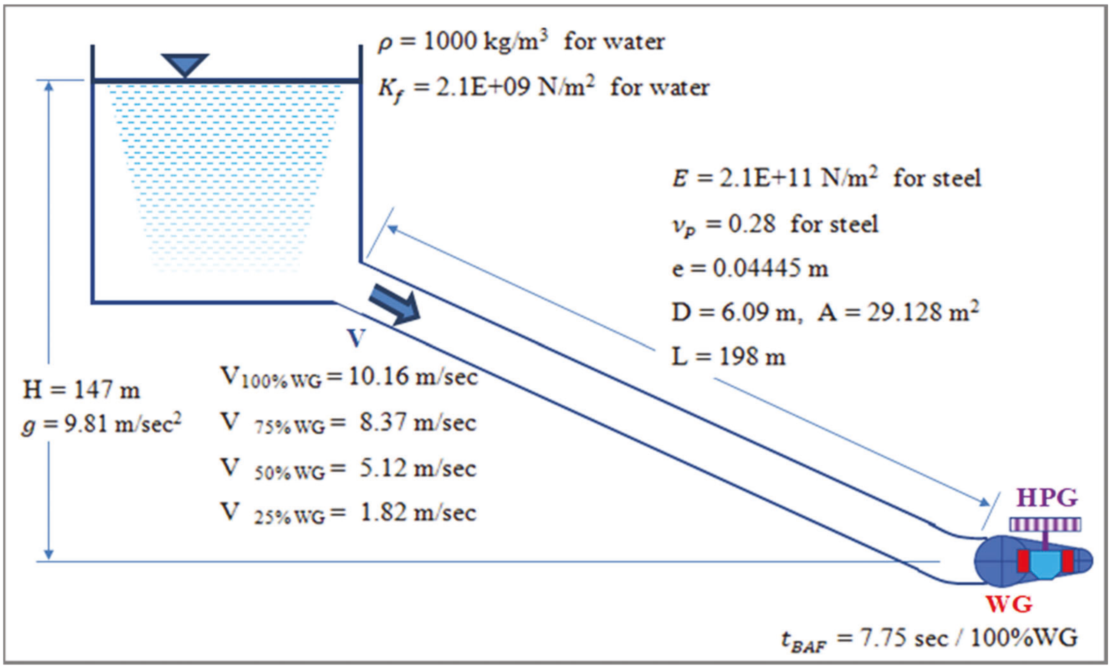

Figure 3. Layout of hydroelectric power plant with data for calculation

Table 3 shows the maximum water hammer pressure values inside the spiral case calculated with formula 9 for different %WG.

Table 3. Maximum analytical water hammer pressure.

WG opening (%)	Effective closing time (sec)	Water speed (sec)	Analytical pressure (kPa)
100	7.75	10.16	1702
75	5.81	8.37	1727
50	3.87	5.12	1703
25	1.94	1.87	1628

3.3. Numerical investigation

The goal of the numerical simulation is to obtain theoretical values to be compared against the experimental data. We use the ALLIEVI software developed by the Polytechnic University of Valencia, Spain for the simulation of steady-state regimes and transients. The transient flow investigation is performed by solving the mass and momentum conservation equations:

$$\frac{dH}{dt} + V\frac{dH}{dx} + \frac{a^2}{g}\frac{dV}{dx} = 0 \tag{11}$$

$$\frac{dV}{dt} + V\frac{dV}{dx} + g\frac{dH}{dx} + f\frac{V|V|}{2D} = 0 \tag{12}$$

where H is the hydraulic head, V is velocity, a is the celerity of the pressure waves, g is acceleration gravity, x is coordinate along the HYP and f is the hydraulic friction losses. The celerity in water is determined based on the following equation:

$$a = \frac{9900}{\left(47{,}6 + C\,\frac{D}{e}\right)^{1/2}} \tag{13}$$

where C is the coefficient depending on the hydraulic passage's material, D and e are the diameter and the thickness of the HYP. ALLIEVI solves the linear algebraic equations for transients in the HYP using the method of characteristics [ALLIEVI User Manual V3, 2018].

Using the software tools, a model was built to reproduce the environment of a hydroelectric unit. The boundary conditions imposed at the end nodes of the hydraulic passage were (1) a tank supplying the water in the hydraulic passage of the hydropower plant, (2) a Francis turbine and (3) a tank receiving the water from the hydraulic passage of the hydropower plant. Tanks with negligible water-free surface-level variation were selected in our investigation in correlation with the test case to ensure reference pressure of 147 metres of water column (mwc) for the turbine. The following particular parameters were selected for the load rejection of the HPP [Y] Francis turbine:

- Water flow = 296 m^3/second
- Maximum power = 351 MW
- Nominal unit rotational speed = 133.3 rpm
- WG closing time t_{BAF} = 7.75 seconds / 100% WG

3.4. Simulation results

For the specific model with the above conditions and parameters, the evolution over time of the pressures was simulated with ALLIEVI for a load rejection from 100% WG opening of HPP (Y). The results for pressures in mwc are depicted in figure 4: in blue at the spiral case inlet and in green inside the draft tube below the runner.

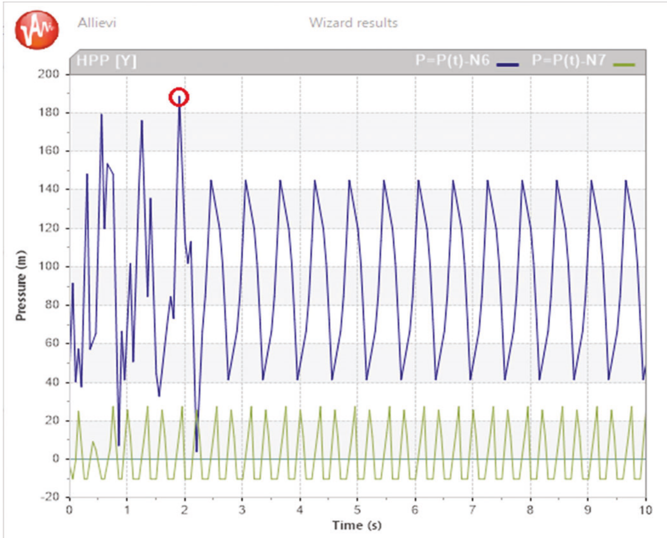

Figure 4. ALLIEVI simulation for temporal pressure surge evolution in HYP of HPP (Y)

As shown in the graph, the maximal absolute value predicted for the water hammer pressure inside the spiral case is 189 mwc (peak circled in red). The simulation program generates pressure oscillation with multiple peaks quasi-similar to the measured values in situ [23]. We note that due to model simplifications and hypotheses, the pressure damping after the WG closure is not effective, which remains subject to improvement.

4. Validation with experimental data

Figure 5 shows on the same graph the experimental data values (dot line in mauve) compared with the analytical calculated rates (dash line in blue) and the numerical validation (red point).

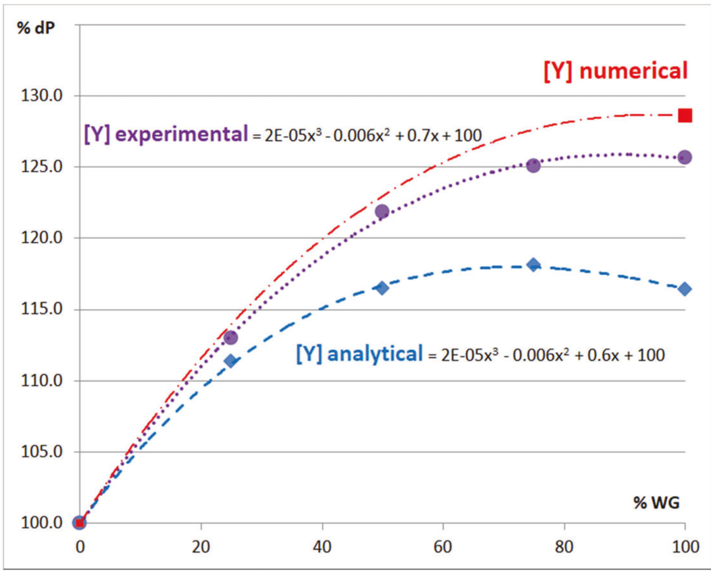

Figure 5. Experimental data, analytical and numerical values for the case study HPP (Y)

For the analytical results (in blue), we observe that the calculated values are inferior to the experimental measurements (in mauve). If the HYP design were based on the analytical values, it is evident that the solicitations will be underestimated, thus the efforts will be greater than considered. The maximal deviation from experimental values is noted for the previous calculated value for the maximum WG opening:

$$\varepsilon_a^{100\%} = \frac{1702 - 1807.7}{1807.7} * 100 = -5.9\ \%$$

This error would decrease the designed HYP capacity by about 6% and is not acceptable. To improve the analytical results, some hypotheses shall be reconsidered, especially those that might increase surge values.

For a load rejection from the maximum WG opening, the numerical simulation (in red) gives 189 mwc (1853 kPa) for the maximal pressure surge, or 128.6% of the reference pressure (147 mwc). The deviation from the experimental value is:

$$\varepsilon_n^{100\%} = \frac{1853 - 1807.7}{1807.7} * 100 = +2.5\ \%$$

This error increases the designed capacity of HYP by about 2.5%. It is obvious that a HYP design based on the numerical simulation overestimate the solicitations, so the equipment will be safer.

Based on the observed results, we conclude that a design based on analytical values may be inaccurate because of hypotheses resulting in the minimization of efforts. However, a numerical simulation might have a better approach, resulting in a safer design.

5. Conclusion

A documented and rigorous understanding of the water hammer phenomenon makes it possible to establish appropriate hypotheses to develop optimal methods to elaborate adapted models for HYP and associated HPG.

The main goal of the study was to investigate the theoretical methods that can be used in conjunction with the experimental results to define water hammer overpressure behaviour. Models of different complexity were validated against empirical trends observed in experimental data. This approach might be useful to compensate for the lack of a priori knowledge on certain configurations.

In the first case, experimental data were compared to a simple atemporal analytical model in order to obtain overpressures and to confirm the considered hypothesis. The calculation results show that due to the simplification in the model, significant error may result. In the same case study, a supplementary analysis was performed using ALLIEVI numerical software, which proved to be within an acceptable margin of error. Hence, this model could be used as reference for similar unit configuration to inform decision making (e.g., accommodate the MAWP of the HYP with the operating mode foreseen for the HPG) or for commissioning (e.g., orient the test campaign according to an appropriate DOE plan).

Correlations and trends observed in experimental data for different configurations, along with future developments in numerical modelling, will help identify the proper level of complexity for a given task. Such information is critical at the design stage of HYP and until commissioning where true values can be observed. Experimental investigations to optimize key parameters during commissioning are always possible but having the proper a priori knowledge from previously validated models on similar configurations will permit the maintenance strategies to be more easily adapted to the age of the equipment [26], while enabling properly defined HPG parameters and mode of operation without requiring expensive DOE.

6. Acknowledgements

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