Investigation of Pressure Relief Valve Performance from 1D Hydraulic Transient Model Calibration to Advanced CFD Analysis

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Abstract. The Swiss hydroelectricity sector faces challenges under Energy Strategy 2050. The HydroLEAP project aim to address these challenges by improving technology and optimizing performance. This paper focuses on the Ernen run-of-river power plant, a demonstrator of the HydroLEAP project. This power plant includes two double-flow horizontal axis Francis turbines of 16 MW operated under a gross head of 270 mWC which are equipped with Pressure-Relief-Valves, PRV. Since this power plant is subject to a future integration of a new Pelton turbine, detailed hydraulic transient calculation is necessary to validate that the capacity increase is compatible with the integrity of the existing penstock. The first step requires validation and calibration of the 1D SIMSEN model of the existing power plant, with particular attention dedicated to the PRV parameters to replicate transient tests measurements performed at site. During the calibration, discrepancies in the PRV discharge characteristic indicated potential functional irregularities, possibly due to cavitation or restricted flow. To validate these hypotheses, 3D CFD simulation was conducted, providing an analysis of the PRV's 3D steady state flow under specific operational conditions. The 3D CFD analysis results closely correlated with the findings from the 1D optimization, revealing critical insights into the physical phenomena affecting PRV performance. The CFD study enabled to identify cavitation zones and flow restrictions as factors contributing to the irregular discharge characteristics, confirming the hypotheses generated during the 1D modeling phase. The findings underscore the importance of integrating multi-dimensional modeling approaches to address challenges in modern hydropower systems.

1. Introduction

The Switzerland hydropower sector plays a central role in the national energy transition outlined in the Energy Strategy 2050, which targets a significant increase in renewable electricity production by 2035 and 2050 [1]. The hydropower must not only continue to provide reliable base-load generation, but also offer greater operational flexibility to support the integration of intermittent sources like wind and solar [2]. This shift imposes new technical and economic challenges on existing infrastructure, including the need to modernize plants, improve grid support services, and ensure mechanical integrity under more dynamic operating conditions [2]-[3]. A key challenge in this process is the safe integration of new generation units or the modernization of existing power plants, especially when complex hydraulic systems are subject to transient phenomena. In order to ensure the smooth operation of hydraulic schemes, understanding their transient functioning is essential during refurbishment, as sudden changes in load, flow rate or valve settings can induce high-pressure fluctuations and water hammer effects, potentially threatening the mechanical integrity of pipelines and hydraulic equipment [4]-[5].

The HydroLEAP project, a national initiative supported by the Swiss Federal Office of Energy, addresses these challenges by combining advanced simulation tools, optimization techniques, and experimental validation to develop robust methodologies for the digital transformation of Swiss hydropower assets. The Ernen power plant, located on the Rhône River, has been selected as a project demonstrator. The plant includes two 16MW horizontal-axis double-flow Francis turbines equipped with Pressure Relief Valves (PRVs), and is currently under study in anticipation of a capacity increase through the addition of a Pelton unit. Since this power plant is subject to a future installed capacity increase, hydraulic transient calculation is necessary to validate that the capacity increase is compatible with the integrity of the existing penstock [4]-[5].

This paper presents a comprehensive methodology that combines 1D hydraulic transient modeling using the SIMSEN simulation tool with 3D Computational Fluid Dynamics (CFD) analysis to assess and validate the hydraulic behavior of the PRV system. The methodology is applied to identify and understand deviations observed during on-site transient tests, particularly related to irregular discharge characteristics of the PRVs. The study highlights the importance of coupling multi-scale simulation approaches for the safe and efficient upgrade of hydropower systems, contributing to the broader objectives of the HydroLEAP project.

2. Ernen power plant demonstrator

The Ernen hydropower plant (HPP) is a run-of-river facility located on the upper part of the Rhône River in the canton of Valais, Switzerland, owned by FMV and operated by Hydro Exploitation. The HPP operates under a gross head of 270 meters and comprises two generating units (see Figure 1), each equipped with a double-flow Francis turbine installed on a horizontal axis. Each turbine has a rated output of 16 MW, contributing to a total installed capacity of 32 MW. The plant is specifically equipped with a Pressure Relief Valve (PRV) system integrated on both units. These PRVs are critical safety components, designed to mitigate the risk of overpressure in the penstock system during rapid load variations or emergency shutdowns and also mitigate the unit overspeed [6].

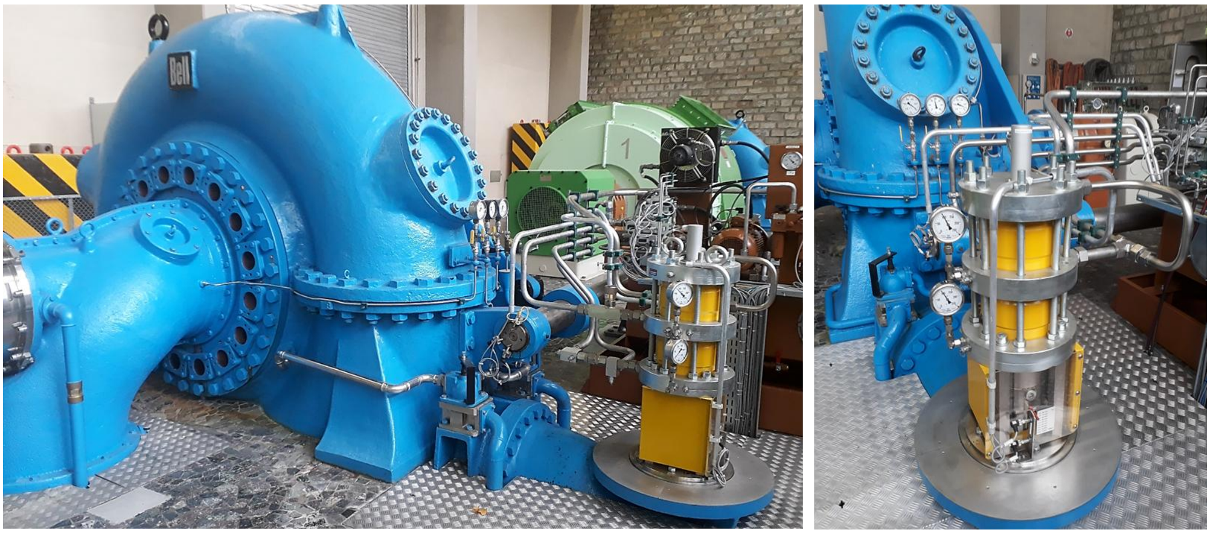

Figure 1: Pictures of the Ernen power unit of 16MW and the PRV system.

3. 1D hydraulic transient analysis

As this power plant is subject to the future integration of a new Pelton turbine, a detailed transient hydraulic calculation is required to validate that the capacity increase is compatible with the integrity of the existing penstock. The first step is to validate and calibrate the 1D model of the existing power plant, paying particular attention to the PRV parameters in order to reproduce the transient test measurements carried out on site. A detailed 1D model of the Ernen HPP was established using the SIMSEN software [7], capturing the hydraulic system's dynamic behavior, including the two double flux Francis turbine units and the PRV system has shown in Figure 2.

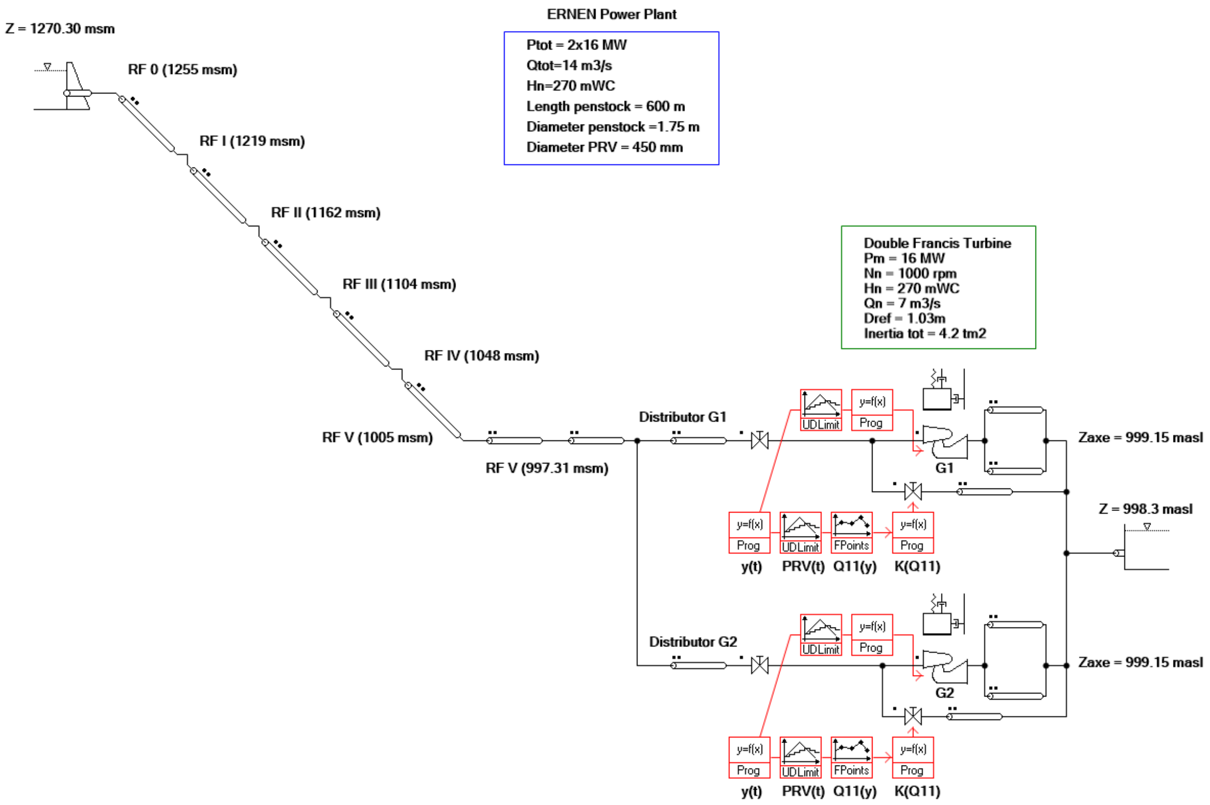

Figure 2: SIMSEN model of the Ernen power plant.

On-site measurement campaign was conducted by Hydro Exploitation to collect high-resolution transient data, including emergency shutdown events at various power levels, which served as reference data for model validation. Once the physical model was implemented using the initial physical parameters, such as the penstock lengths and diameters, the four-quadrant characteristic of the Francis turbine, and the discharge characteristic of the pressure relief valve, a first comparison was carried out. The selected load case is an emergency shutdown (ESD) of a single unit at 16MW. The ESD procedure first disconnects the generator from the grid, causing the turbine to lose load and an overspeed, and then rapidly closes the guide vanes to stop water discharge and bring the unit to a complete stop.

The simulation results were compared to on-site measurements. The pressure variation is measured at the manifolds of the unit upstream of the main inlet valve. Figure 3 shows the turbine behavior with the penstock pressure variations, the transient overspeed and guide vanes opening (GV) from both the measurements and the reference simulation, without any parameter tuning or optimization of the physical model. The results show that while the first pressure peak is accurately reproduced by the 1D model, the second pressure peak is significantly underestimated. This two-peak pressure pattern is a known behavior of Francis turbines equipped with PRV. The model also reproduces overspeed very well, validating the inertia of the turbine unit with the accelerated ramp of the unit and the 4-quadrant characteristic of the Francis turbine.

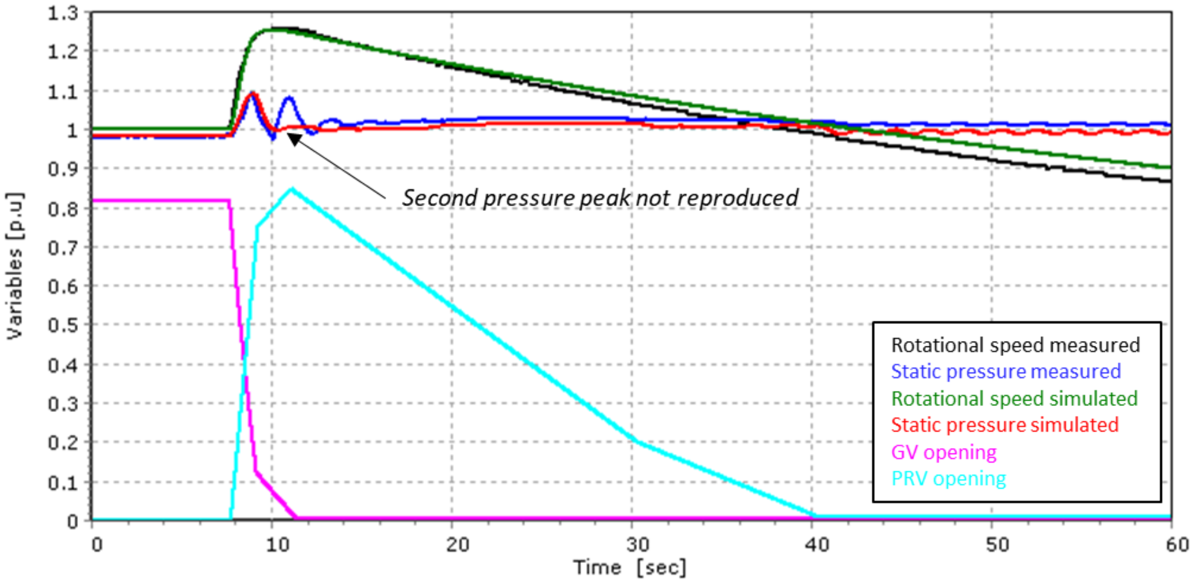

Figure 3: Comparison of measured data with simulation results obtained before parameter optimization with initial reference data characteristics, including penstock pressure, rotational speed, guide vane position, and PRV position.

After identifying the deviation between the measured and simulated pressure signals, and considering that the rest of the model is consistent with the on-site characteristics, the calibration of the model focused on the PRV system, which is known to be a highly sensitive component in hydraulic transient behaviours.

To ensure accurate prediction of the PRV dynamics during transients, a parameter calibration process was conducted on the 1D physical model implemented in SIMSEN. The optimization aimed to minimize the discrepancy between simulated and measured transient pressure in the penstock and the unit's overspeed. The objective function was formulated as weighted sum of several performance indicators, including the mean relative error (MRE) of the pressure signal over time, and the normalized peak error (NPE) computed on both pressure and rotational peaks:

$$\boldsymbol{F(x)} = w_{OS} \cdot MRE_{OverallSignal} + w_P \cdot NPE_{Peak1} + w_P \cdot NPE_{Peak2} + w_{TP} \cdot NPE_{TimePeak1} + w_{TP} \cdot NPE_{TimePeak2} + w_{SP} \cdot NPE_{SpeedPeak}$$

where w_{os}, w_p, w_{tp} and w_{sp} represent the weighting coefficients of the objective function, $MRE_{OverallSignal}$ corresponds the mean relative error of the pressure signal over time, NPE_{Peak}, $NPE_{TimePeak}$ and $NPE_{SpeedPeak}$ refer to the normalized peak error of the pressure peaks, the timing of the pressure peaks and the rotational peak.

The set of parameters optimized in the SIMSEN model included: the diameter of the pressure relief valve, the dead time between the PRV activation and the closing of the guide vanes, as well as 10 discrete values of the PRV's discharge characteristic curve. Constraints and bounds were applied to keep the parameters within physically realistic ranges and help to reduce the size of the search space during optimization process. A gradient-free optimization algorithm was employed to handle the non-linearity of the model response. The optimization process was carried out using MATLAB's Genetic Algorithm [8], a global, derivative-free technique particularly suitable for handling complex, non-linear objective functions arising from transient hydraulic simulations based on detailed physical modelling.

Figure 4 illustrates the comparison between the measured signals (in blue) and the simulation results obtained after the parameter optimization (in red). The optimized set of parameters enables the model to accurately reproduce the overall dynamics, including the timing and the amplitude of the pressure variations. In particular, the second pressure peak, previously underestimated by the model in pre-optimized simulations, is now well reproduced in terms of amplitude. The maximum rotational speed also shows good agreement with the measurement, confirming the improved parameterisation of the model.

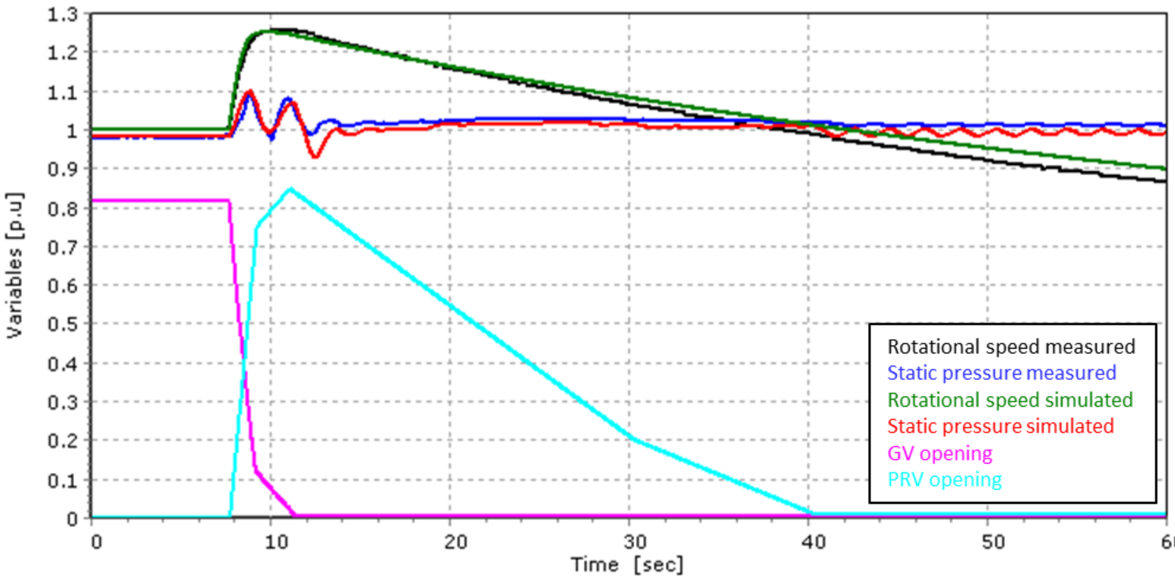

Figure 4: Comparison of measured data with simulation results obtained after parameter optimization, including penstock pressure, rotational speed, guide vane position, and PRV position.

Among the calibrated parameters in the 1D model, the PRV discharge characteristic curve had the most significant impact on the model's ability to replicate the measured pressure dynamics. As shown in Figure 5, the optimized discharge curve differs slightly from the original manufacturer's characteristic up to 80% of the stroke: the flow rate is consistently higher across all opening positions. This adjustment was essential to capture both pressure peaks observed in the measurements, especially the second one.

However, it is worth noting a particular behavior at very high PRV openings. To match the measured pressure in the penstock, the optimized curve suggests a saturation, or even a limitation of the discharge capacity at near-full opening from 80% of the stroke. After a critical opening threshold, the flow rate is controlled by a fixed throttling section (disk area), as the stroke opening no longer contributes to an increase in effective discharge area. This phenomenon, not described by the original characteristic curve, points to a potential physical effect such as flow saturation, cavitation, or partial obstruction of the fluid, which cannot be captured by a 1D model.

Following the 1D model calibration, several hypotheses were formulated to explain the irregular discharge behavior of the PRV, particularly regarding potential flow restrictions and early onset of cavitation. Similar phenomena have been reported in the literature, where cavitation have been observed in the pressure relief valves [9]. To confirm and investigate these assumptions in more detail, a CFD study was initiated, allowing for a more precise analysis of the internal flow dynamics and local pressure conditions within the valve.

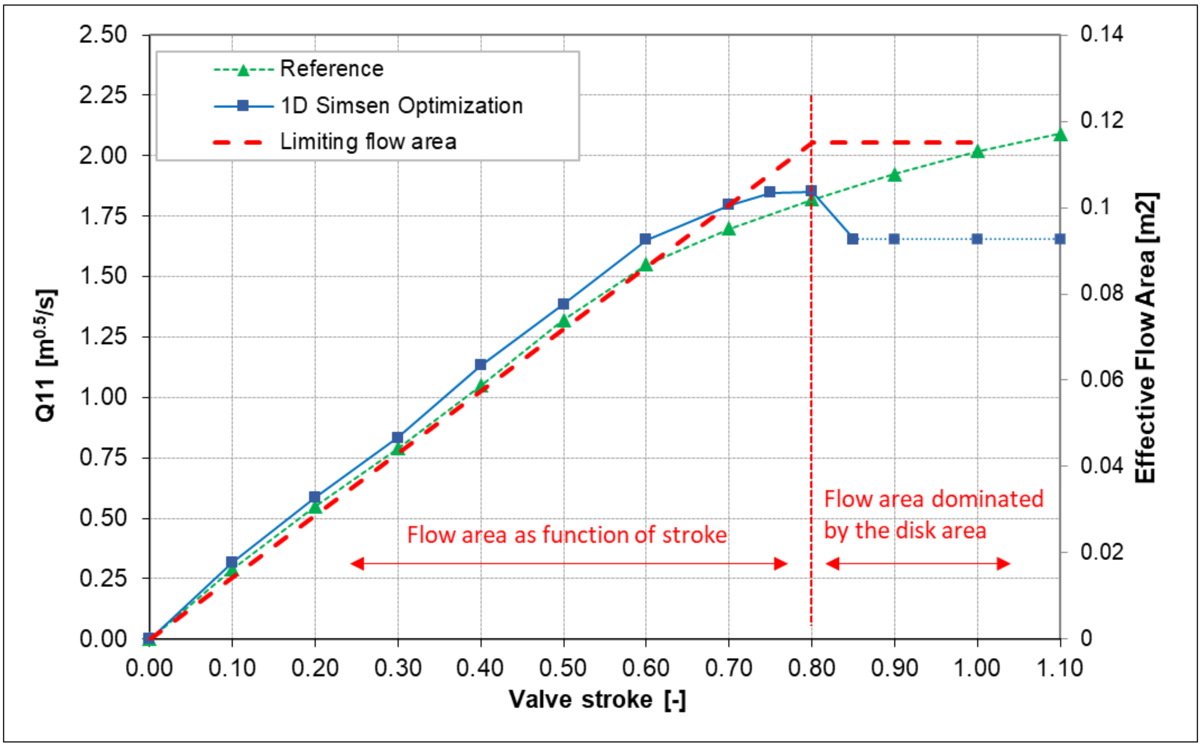

Figure 5: Comparison of the PRV discharge characteristic between the reference (green) and the results obtained by the optimization (blue). The red line is to illustrated the limiting flow area of the PRV.

4. 3D CFD simulation of PRV

To further investigate the hydraulic behavior of the pressure relief valve, particularly the observed flow saturation at high openings, 3D CFD simulations were performed using the OpenFOAM software [10]. Two configurations were studied:

- Steady-state incompressible flow using the *incompressibleFluid* solver.
- Transient multiphase flow with cavitation using the *compressibleVOF* solver.

A mesh sensitivity analysis was conducted to ensure mesh independence and adequate resolution near the walls, targeting appropriate $y+$ values for boundary layer resolution. The selected mesh offers a good compromise between accuracy and computational cost with a total of $7 \cdot 10^5$ cells and also taking advantage of the PRV symmetry, half of the PRV domain was modeled. The mid-plane passing through the valve axis was treated as a symmetry boundary (*symmetryPlane* in OpenFOAM) for velocity, pressure and turbulence variables. This condition enforces zero normal velocity and zero normal gradients of tangential components variables. The assumption is valid since both the geometry and boundary conditions are axisymmetric, and no swirl or lateral loads were imposed. The Figure 6 shows the geometry of the PRV stroke and the mesh generated.

The initial simulations were carried out under incompressible, steady-state conditions without cavitation modeling. These simulations served two purposes: to provide a robust initial flow condition for transient simulations, to evaluate the flow rate at various openings and also the impact of the limiting cross-section of the flow rate under the large valve openings. A fixed head of 254.6 mWC was imposed as boundary condition in order to determine the discharge through the PRV. The key modeling details include the use of the *k-ω SST* turbulence model, the *PIMPLE* algorithm for pressure-velocity coupling, and second-order accurate numerical discretization schemes.

To investigate the potential occurrence of cavitation within the PRV, a transient multiphase simulation was carried out using the *compressibleVOF* solver in OpenFOAM. The flow was modeled as compressible and two-phase, allowing vapor formation to be captured through a volume-of-fluid (VOF) approach. The k–ω SST turbulence model was retained for consistency, and the PIMPLE algorithm was used for robust time-accurate resolution. All numerical schemes were of second-order accuracy, and a CFL condition of 0.3 was enforced to ensure numerical stability during transient resolution.

Several simplifications were necessary in the cavitating flow simulations. The PRV was considered fixed, without accounting for valve motion, and the inlet flow conditions were approximated due to a lack of data. Additionally, the cavitation model could not be calibrated in the absence of experimental measurements. Despite these limitations, the transient simulations qualitatively identified potential cavitation zones and supported the assumptions made during 1D modeling, offering useful insight into the PRV's behavior under extreme conditions.

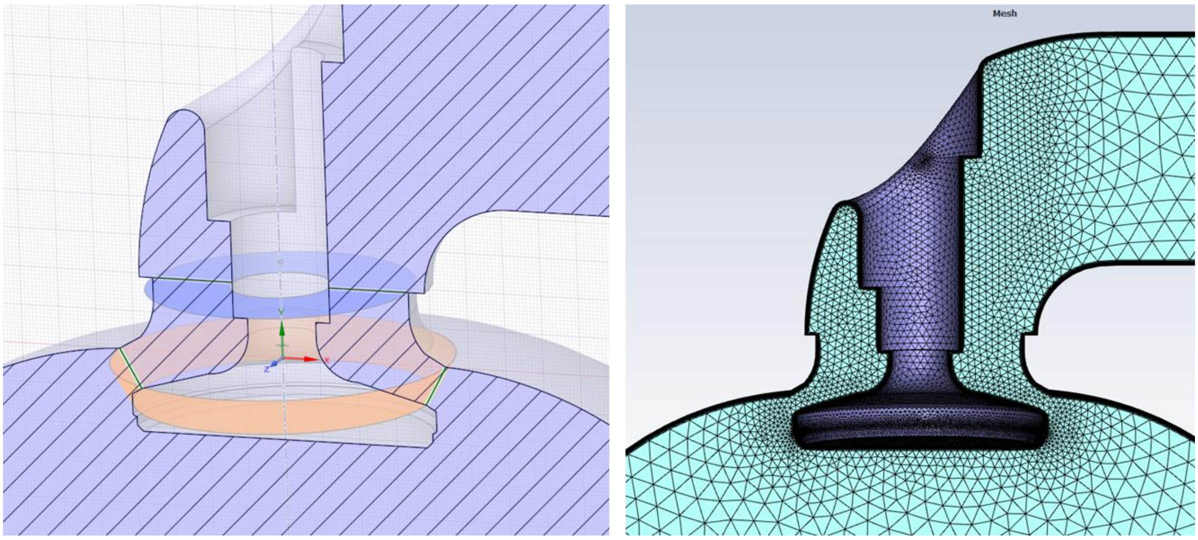

Figure 6: Geometry and meshing of the PRV. The orange ring represents the limiting flow area as function of the stroke and the blue disk the flow area of the throat in the left figure.

The steady-state incompressible simulations show how the flow evolves through the PRV at different openings (10%, 40%, and 100%). As seen in Figure 7, the velocity magnitude increases with the valve opening. All cells with a local pressure below the saturation pressure (Psat = 2300 Pa) were identified. These zones are potential indicators of cavitation inception at 100% of the PRV stroke. They also allowed for an estimation of the flow rate through the PRV as function of the stroke, confirming the validity of the optimized characteristic curve obtained from the 1D model optimization.

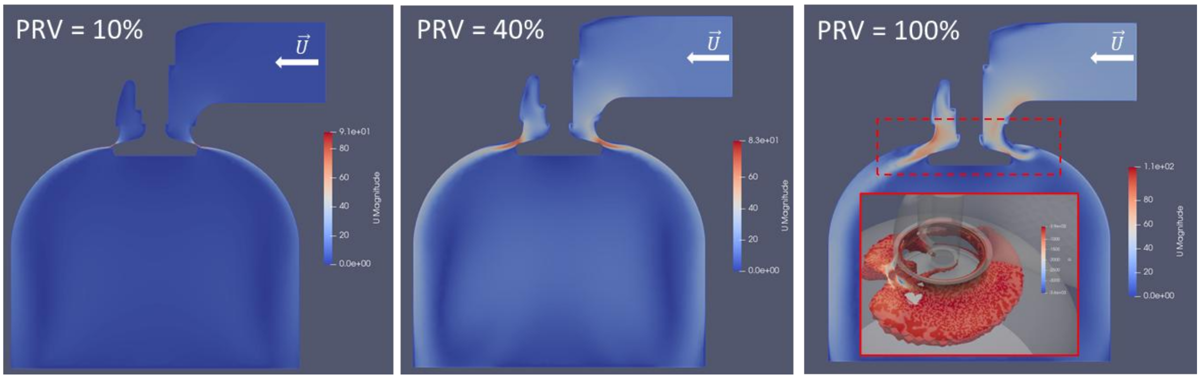

Figure 7: Steady-state incompressible results for the PRV opening of 10%, 40% and 100% showing the velocity magnitude.

The transient two-phase simulation captures the formation of vapor regions during cavitation events. As shown in Figure 8, cavitation mainly occurs near the disk edges, either directly on the disk surface or at the immediate outlet of the valve, where low-pressure zones are observed. The vapor volume fraction varies throughout the opening phase, with peak cavitation developing at large openings where flow acceleration and pressure drops are most significant. The flow oscillations observed during the initial phase are attributed to the dynamic formation of vapor pockets. After approximately 0.04s, the cavitation stabilizes, giving way to more persistent cavitation zones near the valve disk as shown in Figure 8.

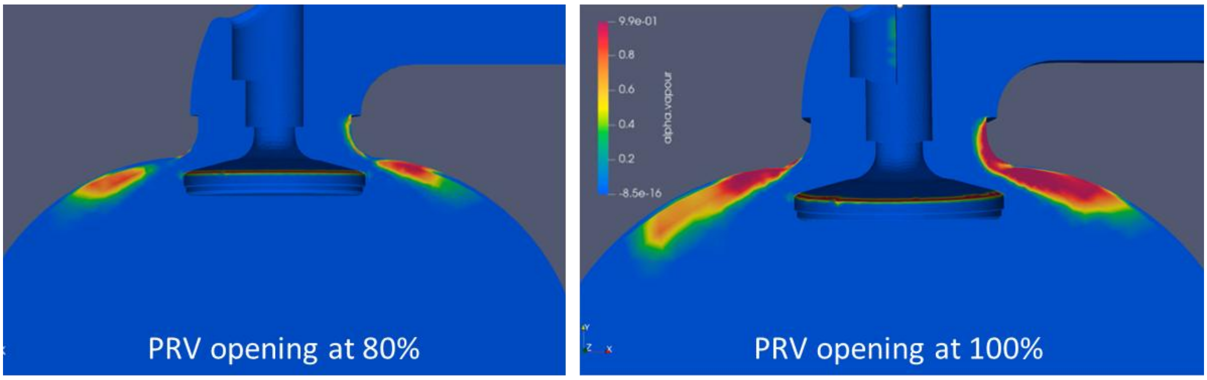

Figure 8: Transient two-phase flow simulation results for the PRV opening of 80% and 100% showing the vapor formation.

The two 3D simulations reveal that the limiting cross-section and the cavitation can probably have significant impact on the PRV discharge behavior. As shown in Figure 9, the PRV flow rate and its saturation due to the limiting cross-section are well reproduced by the incompressible fluid simulation (red), in good agreement with the 1D Simsen optimization results (blue). Moreover, the cavitation model causes a sudden drop in the dimensionless flow rate (Q_{11}), which begins around a relative valve stroke of 0.6, earlier than the expected stroke of 0.8. This premature reduction is likely due to the early onset of cavitation number, which limits the effective discharge area. This behavior confirms that downstream cavitation plays a key role in flow rate saturation at large openings, while a better match with reference data could be achieved by calibrating the cavitation model, particularly the cavitation number. These results support the 1D model's assumption of flow limitation due to vapor formation.

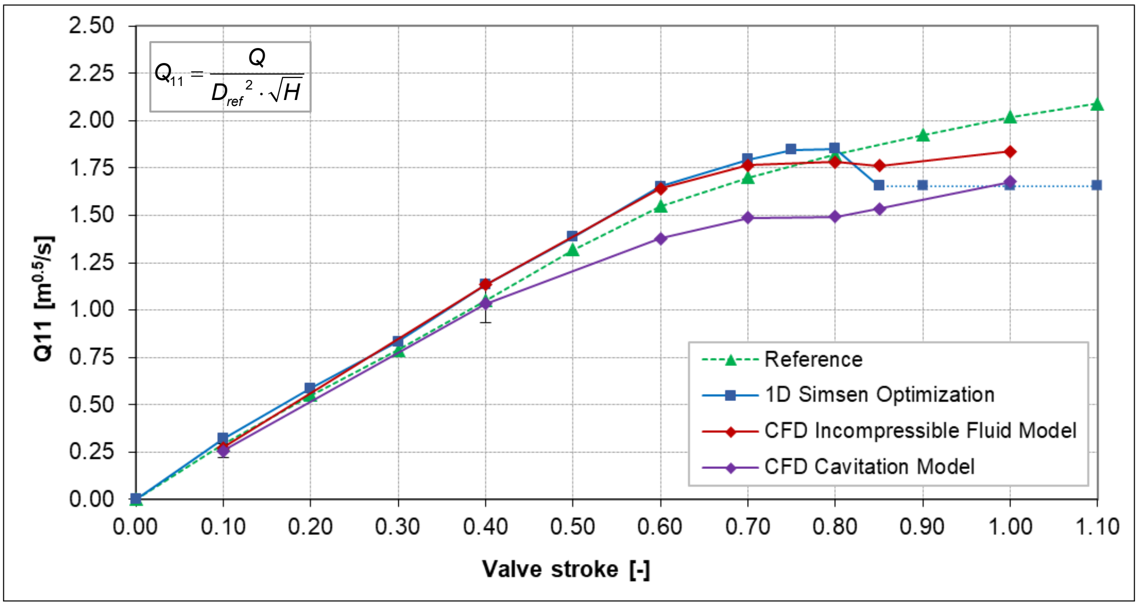

Figure 9: Comparison of the PRV discharge characteristic between the reference (green), 1D model optimization results (blue), steady-state incompressible 3D simulation (red) and transient two-phase flow with cavitation model (purple).

Conclusion

The Swiss hydroelectric sector faces new challenges under the Energy Strategy 2050, requiring performance optimization and infrastructure modernization. This study, part of the HydroLEAP project, focuses on the Ernen run-of-river power plant, a demonstrator featuring two 16 MW double-flow horizontal-axis Francis turbines equipped with Pressure Relief Valves (PRVs). In preparation for the future addition of a Pelton turbine, detailed hydraulic transient analysis is essential to ensure that increased capacity remains compatible with the integrity of the existing penstock.

The calibration of the 1D SIMSEN model revealed discrepancies in the Pressure Relief Valve (PRV) discharge characteristics, suggesting the presence of complex hydraulic phenomena such as cavitation and flow restrictions that could not be fully captured by the 1D approach alone. To investigate these irregularities, detailed 3D CFD simulations were conducted, including steady-state and transient multiphase analyses, which confirmed the occurrence of flow saturation caused by the valve's internal geometry and cavitation effects. The incompressible flow simulation allowed validation of the PRV discharge curve as a function of valve opening and confirmed the presence of a limiting flow section in the valve geometry. These findings validated the adjustments made during the 1D model calibration and provided critical insights into the physical mechanisms influencing PRV performance under transient conditions. The two-phase flow analysis highlighted the potential formation of cavitation within the flow, which could lead to flow blockage, explaining the sudden reduction of flow rate through the PRV at large openings. This study demonstrates the importance of combining 1D and 3D modeling approaches to achieve a deeper understanding and better handling of transient phenomena in modern hydropower plants. These results support the safe and reliable upgrade of the Ernen power plant as part of the HydroLEAP project, contributing to Switzerland's energy transition.

5. Acknowledgements

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References

[1] Swiss Federal Office of Energy (SFOE), Energy Strategy 2050 - Measures and Implementation, 2017.

[2] XFLEX HYDRO – Deliverable D10.3, "Technical White Paper" EPFL, 2024. https://www.xflexhydro.com/knowledge/technical-white-paper

[3] XFLEX HYDRO – Deliverable D10.3, "Recommendations towards industrial deployment of hydropower flexible technologies" IHA, 2024. https://www.xflexhydro.com/knowledge/recommendations-towards-industrial-deployment-of-hydropower-flexibility-technologies

[4] A Bergant, E. Sijamhodzic, Water hammer problems related to refurbishment and upgrating of hydraulic machinery, Proceedings of Hydro 1977, Portoroz, Slovenia.

[5] A Bergant, B Karney, S Pejovic, J Mazij, Treatise on water hammer in hydropower standards and guidelines, Proceedings of IAHR 2014, Montreal, Canada.

[6] J Gale, P Brejc, J Mazij, A Bergant, Turbine by-pass with energy dissipation system for transient control, Proceedings of Hydro 2014, Como, Italy.

[7] C Nicolet 2007, Hydroacoustic modelling and numerical simulation of unsteady operation of hydroelectric systems, EPFL, Thesis n° 3751.

[8] The MathWorks I. Global Optimization Toolbox. Natick, Massachusetts, United State; 2019. Available from: https://www.mathworks.com/help/gads/

[9] F Flemming, et al., Design and Safety Considerations for Pressure Relief Valves, Proceedings of Hydrovision, 2011. DOI: 10.13140/2.1.2020.4801

[10] OpenFOAM Foundation (2025). OpenFOAM – The Open Source CFD Toolbox, version 24.06.