HSLU Lucerne University of Applied Sciences and Arts

Engineering and Architecture
B.Sc.. Energy and Environmental Systems Engineering
Bachelor-Thesis

Parametric and free form Optimization of a Pelton Turbine Needle

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1. Introduction, Goals and Research Questions

Relevance and Problem Hydropower provides around 60% of Switzerland's domestic electricity production, generating roughly 37 TWh annually (SFOE, 2025). Because these plants operate many hours per year, even small efficiency gains have a relevant energetic and economic impact. In the Pelton turbine, the injector needle directly influences the jet velocity profile and overall turbine efficiency (Zhang, 2016, pp. 2–3, 29).

Research Gap Existing studies are limited to comparing discrete needle configurations rather than exploring the design space continuously. The link between intentional needle profile changes and the resulting jet quality is therefore not well quantified.

Aim and Objectives This thesis develops a fully automated CAD-to-CFD optimization workflow which adapts the needle geometry to optimize quantities of interest such as to reduce total pressure loss and maximize jet impulse across three needle positions (MP06, MP50, and MP94)

2. Method Overview and Materials

The optimization workflow is fully automated and orchestrated by optiSLang (optimization software), which proposes geometric parameters that are passed through a Python-based workflow (Figure 1): geometry generation, meshing in Pointwise, CFD simulation in ANSYS Fluent and post-processing. The extracted results are returned to optiSLang which then closes the loop.

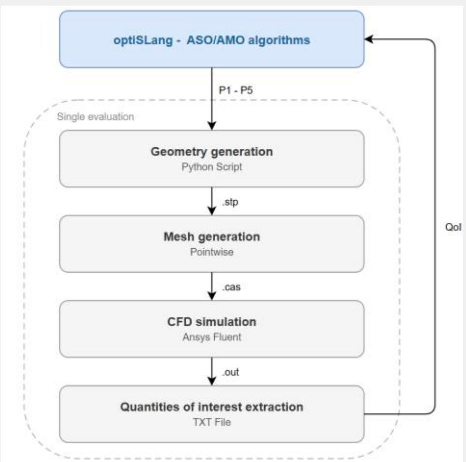

Figure 1: Visualization of the workflow with OptiSlang as the orchestrator.

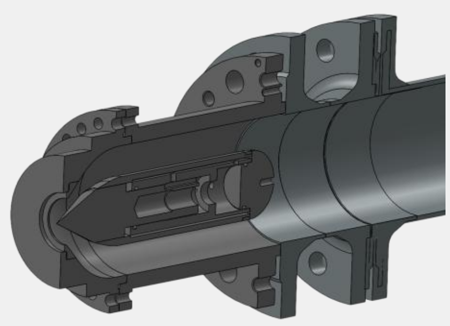

Figure 2: Visualization of the Pelton Injector with the needle in the center.

As shown in figure 2, the needle sits axially inside the converging nozzle, forming an annular flow passage that shapes the free jet. Five optimizable radial offsets control the needle contour, and the structured mesh adapts automatically for each new geometry. The CFD simulation uses a steady-state VOF model with the SST k-ω turbulence model. Two objectives are optimized simultaneously: minimizing total pressure loss Δp and maximizing jet impulse I. The ASO (adaptive single objective) algorithm validates the workflow and is compared against an adjoint free-form optimization. The main study uses the AMO (adaptive multiple objectives) algorithm, producing a Pareto front across 201 designs at MP50. The selected design is then evaluated at MP06, MP50, and MP94 to assess off-design performance. Results are analyzed through pressure development, radial velocity profiles, axial impulse development, and the jet uniformity index γ.

Industry Partner: HSLU

3. Results and Discussion

The baseline needle shows a clear trend: pressure loss increases and jet impulse decreases as the needle closes from MP06 to MP94, while jet quality remains high with γ above 0.984. The single-objective ASO and adjoint optimization both achieved ~69% pressure drop reduction at the cost of ~28% impulse loss. As impulse directly determines the force on the runner buckets and the power output, minimizing Δp alone is insufficient. The multi-objective AMO optimization resolves this conflict. Run 163, selected from the Pareto front (Figure 4), achieves 13.3% lower Δp at only 3.5% impulse reduction at MP50, directly increasing the kinetic energy available to the runner. Jet uniformity γ stays consistently at or above the baseline across all positions, with Δp reductions of 10.8% at MP06 and 10.6% at MP94 at impulse reductions of 5.1% and 1.4%.

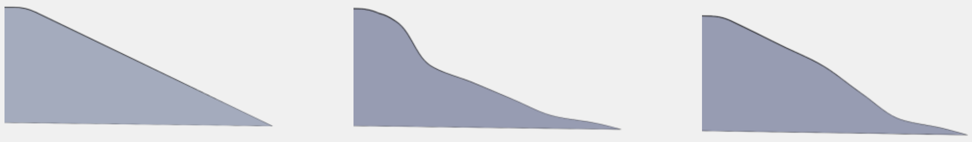

Figure 3: Base needle profile (left), ASO optimized needle profile (middle), AMO optimized needle profile (right).

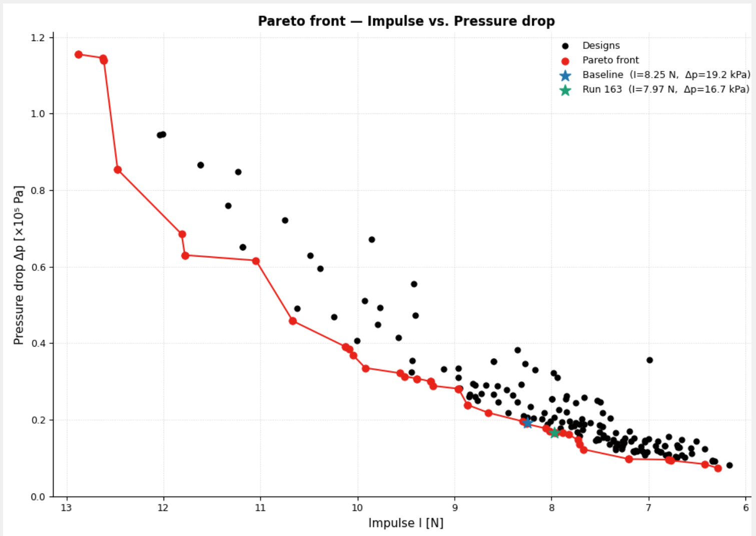

Figure 4: Pareto front showing the trade-off between jet impulse and pressure drop.

4. Conclusion and Recommendations

This study showed that an automated multi-objective optimization of the Pelton injector needle delivers meaningful gains with a favorable trade-off. Pressure drop reduces by 13.3% while jet impulse decreases by only 3.5% at MP50 and the improvement transfers consistently across all three needle positions. Jet uniformity stays at or above the baseline throughout, confirming the geometry change introduces no new sources of non-uniformity. Future work should extend the optimization to multiple needle positions simultaneously and couple the injector with a runner model to assess the shaft power directly.

References

Swiss Federal Office of Energy. (2025). *Hydropower*. Federal Administration. https://www.bfe.admin.ch/bfe/en/home/supply/renewable-energy/hydropower.html

Zhang, Z. (2016). *Pelton Turbines*. Springer Verlag.

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