(REVIEW ARTICLE)

Effect of control needle tip and contraction section on the efficiency of Pelton turbine nozzles

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Abstract

This study investigates the influence of nozzle geometry on the efficiency and performance of Pelton turbine micro-hydropower plants. Geometric modeling was carried out for different nozzle configurations, specifically varying the control needle tip angles (55°/130° and 75°/130°), and compared with the original Techydro design (60°/130°). Hydraulic analyses and numerical simulations were conducted to evaluate water flow velocity, energy losses, and nozzle efficiency. Minor truncations of the control needle tip had negligible impact on efficiency, whereas larger truncations increased energy losses and caused deviations in flow direction. Optimization of the nozzle contraction section based on the Wiedosinski curve enhanced efficiency by 5.64% and extended service life by 43.2%. Detailed analysis of nozzle losses along the flow provided critical insights for targeted design improvements. These findings highlight the importance of nozzle design in minimizing hydraulic losses and improving turbine performance, offering valuable guidance for the design and optimization of high-performance micro-hydropower plants.

Keywords: Pelton Turbine; Micro-Hydropower; Nozzle Geometry; Wiedosinski Curve; Hydraulic Efficiency; Energy Losses

1. Introduction

Hydropower is currently the third largest source of electricity generation worldwide, after coal and natural gas. In 2024, it generated approximately 4,500 terawatt-hours of electricity, accounting for 14% of total global electricity production. By the end of the next decade, more than 150 gigawatts of new hydropower capacity are planned to be commissioned, particularly in developing countries [1].

Uzbekistan is taking a structured approach to green energy, actively implementing projects with support from international financial institutions. According to the "Uzbekistan 2030" strategy, by the start of the next decade, renewable energy sources are expected to account for 40% of electricity generation, or 25 GW of installed capacity. By 2024, the installed capacity of renewable energy in Uzbekistan reached 4.5 GW, supplying 16% of the country's electricity. This helped save nearly 1 billion cubic meters of natural gas and prevent 1.4 million tonnes of greenhouse gas emissions. To date, six new hydropower plants 183 MW have been launched in Andijan, Samarkand, Surkhandarya, and Tashkent regions [2].

According to the decree of the Government of the Republic of Uzbekistan, strategic objectives have been set for the development of the national micro hydropower plant (micro HPP) network in 2025–2026. A total of 2,983 micro hydropower plants are planned to be constructed, with a cumulative installed capacity of 164 MW. These facilities are

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expected to generate approximately 500 million kWh of environmentally sustainable electricity annually, significantly contributing to the diversification of the country's energy mix and the reduction of dependence on fossil fuels [3].

Taking the above into account, improving the efficiency of designed micro hydropower plants is a pressing issue at present. One of the key technical factors aimed at increasing the efficiency of micro hydropower plants is the improvement of the structural and hydraulic characteristics of the nozzle device, which ensures the formation and direction of the water jet, since the nozzle directly influences the flow velocity, energy losses, and the overall efficiency of the turbine.

Figure 1 illustrates the scientific research conducted by Chinese researchers led by Chun Zhang on "The influence of the tip shape of the regulating needle in a Pelton-type turbine nozzle on water flow." In this study, the jet flow formed by the nozzle was analyzed using numerical simulations for four different cutting (truncation) configurations of the regulating needle tip. The results showed that when the truncation was up to $0.1\,d_0$, the reduction in efficiency was very small (approximately 0.02%). However, when the truncation reached $0.3\,d_0$, energy losses increased to 0.41%, which is about 3.7 times higher. In addition, truncation of the needle tip was found to have no significant effect on the flow rate or on the forces generated by the water flow. The water–air interface of the jet remained almost unchanged within the truncation range of 0–$0.1\,d_0$; however, for truncations greater than $0.2\,d_0$, air bubbles appeared in the flow, the low-velocity zone expanded, and deviation from the central flow direction was observed [4].
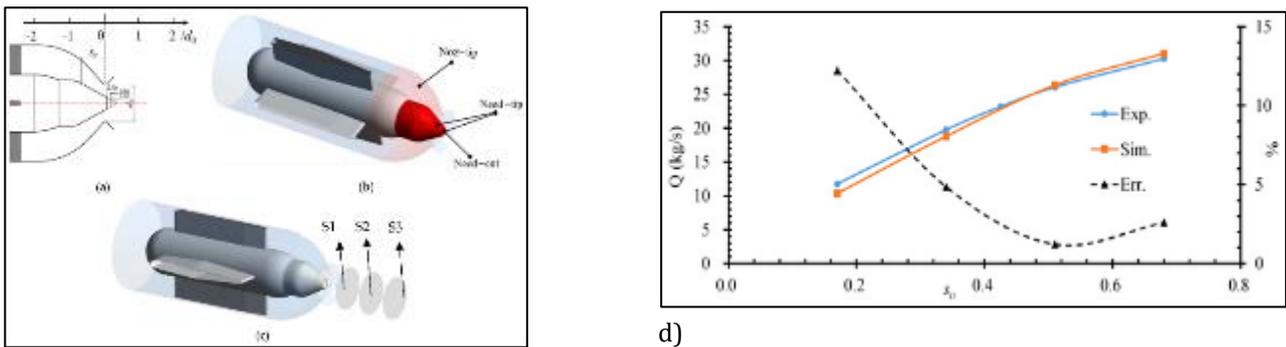

Figure 1 Schematic diagrams of the (a) injector, (b) diagram of the needle tip cutoff, (c) model and the name of the nozzle and needle walls schematic of the monitoring jet sections (d) the experimental and predicted injector discharge with error at different nozzle openings

Figure 2 illustrates research on improving the efficiency of a suspension abrasive water-jet nozzle. The nozzle section geometry was optimized using hydrodynamics, enumeration, and multi-parameter orthogonal optimization methods. The results indicate that a contraction section with a Wiedosinski curve, an inlet diameter coefficient of 0.333, and an axial length coefficient of 2.857 increases the nozzle efficiency by 5.64% and extends its service life by 43.2%. Minor truncation of the needle tip has no significant effect on the flow or the forces generated; however, for truncations greater than $0.2\,d_0$, air bubbles appear in the flow, the low-velocity zone expands, and deviation from the central flow direction is observed [5].
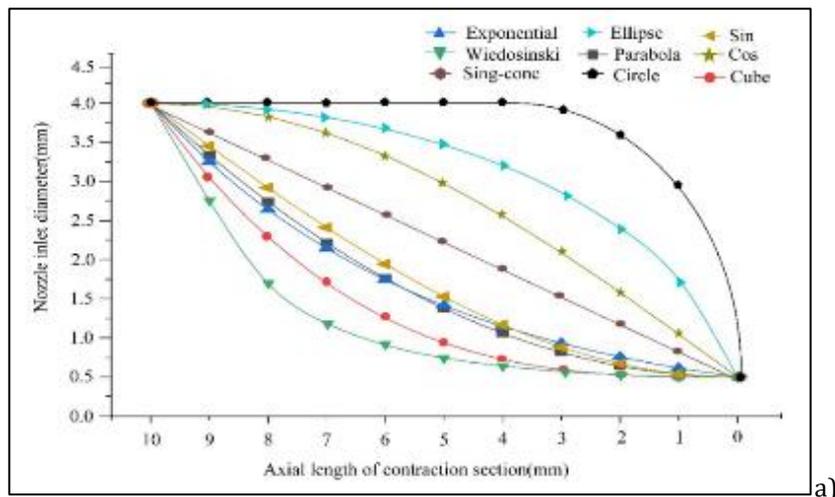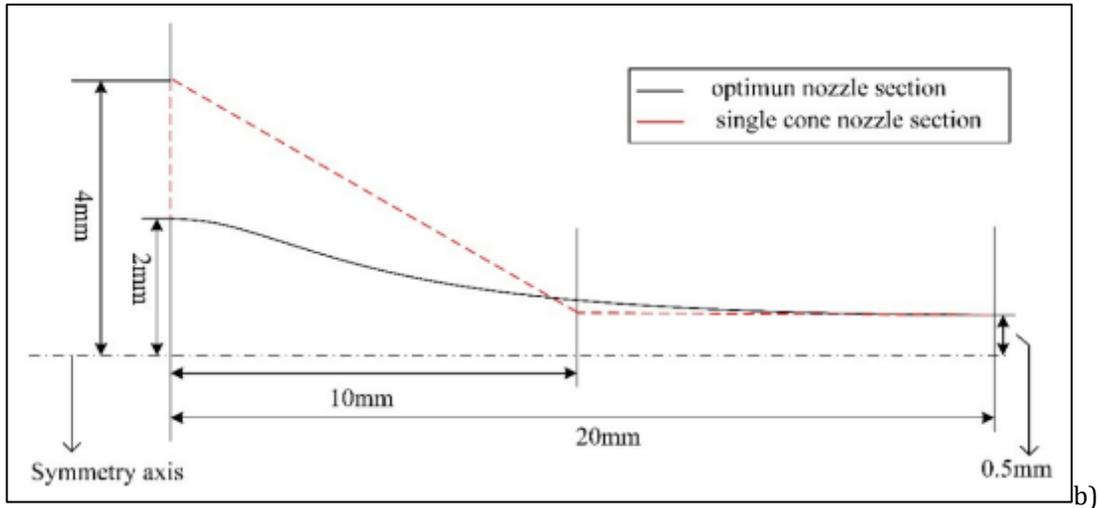
Figure 2 Diagram of (a) the nozzle contraction section curve and (b) Comparison of the geometry of optimal and commercial nozzles

The efficiency of the nozzle in Pelton-turbine micro hydropower plants is directly related to the profile of the contraction section, namely the regulating needle, the stability of the flow direction, and the flow exit angle. Although previous studies have provided important results in reducing flow losses and improving jet quality, the complex interactions of hydraulic processes within the nozzle, particularly the optimal relationship between the profile shape and the exit angle, have not been sufficiently investigated. The objective of this study is to propose a new nozzle profile modified based on the Wiedosinski curve and to determine its effects on flow direction, deviation from the central axis, and the quality of the jet at the outlet.

2. Material and methods

Geometric modeling was performed for two types of nozzles, and the tip angles of the regulating needle were set to 55°/130° and 75°/130°, respectively. The initial model was provided by the Techydro brand, in which the needle tip angle was assumed to be 60°/130°. The shape and dimensional parameters of the nozzle are determined through the following steps [5]:

Determination of effective head:

$$H_{Ef} = H_{um} - H_y \tag{1}$$

where: H_{um} – is the total head from the water source to the turbine wheel, in meters; H_y – represents the losses in the pipe and nozzle, in meters.

Calculation of hydraulic power:

$$P_h = Q\rho g H_f \tag{2}$$

Here, Q – is the flow rate, ρ – is the water density, g – is the acceleration due to gravity.

Flow velocity at the nozzle outlet:

$$V_j = c_v\sqrt{2gH_n} \tag{3}$$

here, c_v – is the velocity coefficient (typically in the range of 0.97–0.99).

The process of determining the nozzle diameters is carried out through the following main steps [6]:

$$d_0 = \sqrt{\frac{4Q}{\pi c_v \sqrt{2gH_{um}}}} \qquad (4)$$

$$d_1 = \sqrt{\frac{4Q \sin \alpha}{\pi \mu 0.75 C_v \sqrt{2gH_f}}} \qquad (5)$$

here, d_0 — is the nozzle orifice diameter, mm; d_1 — is the actual nozzle outlet diameter, mm; α — is the regulating needle angle; μ — is the flow viscosity. According to empirical relationships: $d_1 = (1.2 \sim 1.25)d_0$ – the actual nozzle diameter is usually 20–25% larger than the ideally calculated diameter.

The losses occurring through the nozzle can be calculated using the following equation [7].

$$P = \int_A \left(p + \frac{\rho u^2}{2}\right) u\, dA = \sum_{i=1}^{n} \left(p_i + \frac{\rho_i u_i^2}{2}\right) u_i A_i \qquad (6)$$

here, P — is the fluid power, p_i — is the static pressure, ρ_i — is the fluid density, u_i — is the flow velocity in each individual computational mesh cell, A_i — is the area of an element at the cross-section and n is the number of mesh cells at the cross-section.

Using Equation (6), the magnitude of power at any reference cross-section plane can be determined. Accordingly, the accumulated losses in the region between the inlet plane and the reference outlet plane can be calculated using Equation (7).

$$L_{ref} = \left(1 - \frac{P_{out}}{P_{in}}\right) \cdot 100\% \qquad (7)$$

where, L_{ref} — is the losses in the reference region, P_{in} — is the power at the inlet reference plane and P_{out} — is the power at the outlet reference plane, Figure 3.
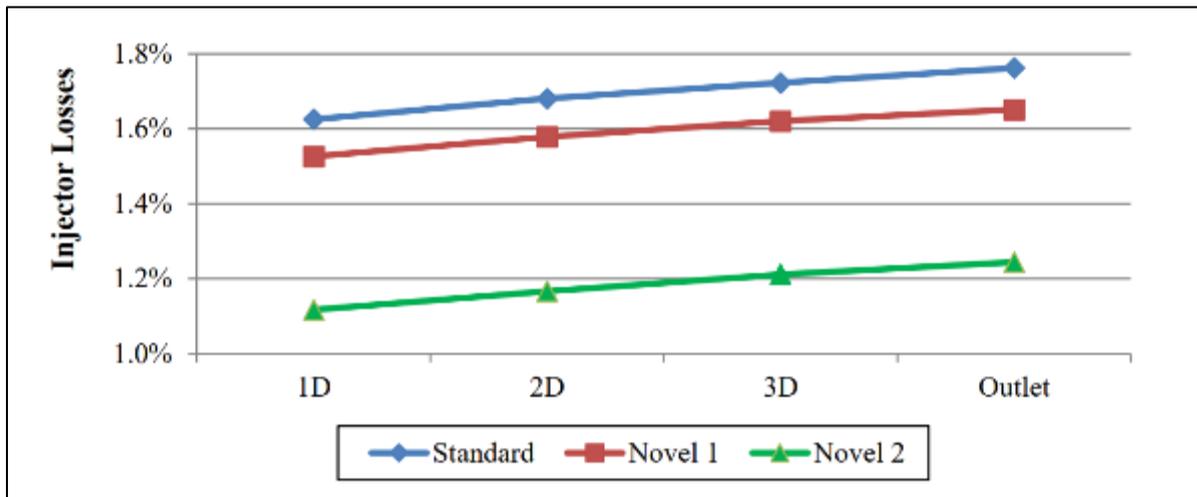

Figure 3 Nozzle losses at different planes along the pressurized water flow

3. Result and Discussion

The efficiency of micro-hydropower plants, particularly those employing Pelton turbines, is strongly dependent on the design of the nozzle, which governs both the formation and direction of the water jet. Enhancing the structural and hydraulic characteristics of the nozzle is crucial, as it directly influences flow velocity, energy losses, and overall turbine performance.

Previous research, including the studies by Chun Zhang et al., has demonstrated that minor modifications to the control needle tip, such as truncations up to 0.1 d_0, have a negligible effect on efficiency (~0.02%). In contrast, larger truncations, such as 0.3 d_0, can increase energy losses by approximately 0.41%, nearly four times higher. Excessive truncation (>0.2 d_0) leads to the entrainment of air bubbles, the expansion of low-velocity zones, and deviations from the central flow path, whereas small truncations do not significantly affect flow forces or volumetric rates.

Optimization of nozzle geometry through hydrodynamic analysis, parametric enumeration, and multi-parameter orthogonal methods has indicated that a contraction section following the Wiedosinski curve, with an inlet diameter coefficient of 0.333 and an axial length coefficient of 2.857, can enhance nozzle efficiency by 5.64% and extend service life by 43.2%. These findings underscore the critical role of contraction profile, flow stability, and exit angle in determining nozzle performance.

Geometric modeling of two nozzle configurations with control needle tip angles of 55°/130° and 75°/130° enabled comparison with the original Techydro design (60°/130°). The modeling process involved determining the effective head, calculating hydraulic power, evaluating jet velocity, and estimating nozzle diameters based on flow parameters and empirical adjustments.

Moreover, analyzing nozzle losses at various cross-sectional planes along the pressurized water flow provides insights into the spatial distribution of energy dissipation within the nozzle. Using integral formulations, the power at any reference plane can be calculated, and cumulative losses between the inlet and outlet can be quantified. This detailed assessment facilitates targeted design improvements and enhances the overall efficiency of micro-hydropower plants.

4. Conclusion

This study demonstrates that the efficiency and reliability of Pelton-type micro-hydropower plants are directly dependent on nozzle design. While minor modifications to the control needle tip have negligible effects on efficiency, larger truncations can significantly increase energy losses and disrupt the flow. Optimizing nozzle geometry by implementing a contraction section based on the Wiedosinski curve can enhance efficiency and substantially extend service life. Geometric modeling and analysis of different nozzle configurations highlighted the critical importance of the contraction profile, exit angle, and flow stability in minimizing hydraulic losses. Detailed analysis of energy dissipation along the nozzle facilitates targeted design improvements, thereby improving turbine performance and the overall efficiency of micro-hydropower plants. These findings underscore the significance of nozzle construction in Pelton turbine systems and provide valuable guidance for the design and optimization of high-performance micro-hydropower installations.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Renewable electricity capacity growth by technology segment, main case, 2013-2030 https://www.iea.org/energy-system/renewables/hydroelectricity

[2] Kazakhstan and Uzbekistan drive green energy progress in Central Asia https://qazaqgreen.com/en/news/central-asia/2842/

[3] Uzbekistan plans to build 3,000 micro hydropower plants by 2026. Retrieved from https://www.kun.uz/en/news/2025/04/04/uzbekistan-plans-to-build-3000-micro-hydropower-plants-by-2026

[4] Chun Zhang, Chao Wang, Qianhe Tian, Quanwei Liang, Yilin Zhu, Yexiang Xiao, Yong Bai, Zhaoning Wang, Hengte Zhou and Xianwu Luo "Effect of Injector Needle Tip Shape on Jet Flow for Pelton Turbine", Energies 2025. https://doi.org/10.3390/en18010102

[5] Daniel G. Taborda, Jorge Sierra-Del Rio "CFD analysis of the needle tip angle in Pelton injector on jet quality for the power generation" Physics and Engineering, 45-59, 2021.

[6] Than Zaw O, Nyi, Cho Khaing "Design Calculation of Pelton Turbine for 220 kW" International Journal of Scientific and Research Publications, vol. 9, 218-224, 2019. http://dx.doi.org/10.29322/IJSRP.9.07.2019.p9131

[7] S Petley, A Panagiotopoulos, D S Benzon, A Židonis, G A Aggidis, J S Anagnostopoulos and D E Papantonis "Investigating the influence of the jet from three nozzle and spear design configurations on Pelton runner performance by numerical simulation", Earth and Environmental Science, 2019