CFD ASSESSMENT OF AN INDALMA PICO-HYDRO TURBINE UNDER ELEVATED HEAD CONDITIONS

Marjam R. Jodiwongso[1], Rudi H. van Els[2], Erick O. do Nascimento[3]

[1]Vanguard Foundation, Research Institute Vanguard, Energy and Fluid Dynamics Laboratory, Surinamestraat 54, Suriname (marjamjodi@gmail.com)
[2]Universidade de Brasília, Brasília, Brazil
[3]Technische Universiteit Vanguard (TUV), Research Institute Vanguard, Energy and Fluid Dynamics Laboratory, Surinamestraat 54, Suriname

Abstract: This study used Computational Fluid Dynamics (CFD) to evaluate an Indalma pico-hydropower turbine under higher water heads (10–20 m) compared with the 5.5 m reference case. Higher heads increased water pressure, flow speed, and power output while maintaining stable flow inside the turbine. At 20 m head, the turbine produced about 3.4 kW, demonstrating its potential for higher-head hydropower applications, although structural evaluation is still recommended.

Keywords: Hydraulic turbine; Indalma turbine; Elevated Head; CFD

INTRODUCTION

Small-scale hydropower systems play an important role in supplying electricity for isolated and decentralized communities, especially in regions where grid expansion is technically difficult or economically unfeasible. Pico hydraulic turbines, operating typically below 5 kW, have received growing attention because they can be installed in low-cost schemes using existing water infrastructure and modest heads while still providing reliable power for basic household and community needs. Within this class, the Indalma turbine has been providing electricity to remote communities in the Amazon region. The Indalma turbine, presented in Figure 1, was empirically developed by Indalma Industries in Santarém, Pará, Brazil (Els et al., 2010).

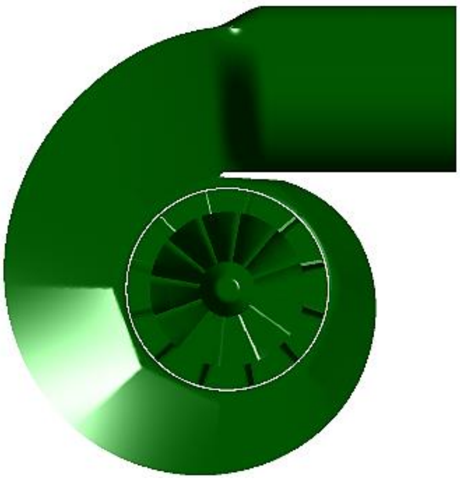


Figure 1. Indalma turbine flow outlet side.

Mac Donald and Sloot (2014) demonstrated through experimental and numerical analyses that the Indalma turbine operates as a Francis-type turbine, achieving a maximum shaft power of approximately 530 W at 1050 rpm with an efficiency of around 64%. This relatively low efficiency was mainly attributed to simplified and cost-effective design choices, which resulted in flow separation and inefficient drag-dominated energy transfer. Expanding on this work, Nascimento et al. (2020) confirmed the earlier findings and showed that hydraulic efficiencies above 80% are attainable near the design operating condition. Their study also provided further insight into the flow mechanisms responsible for performance losses, highlighting the occurrence of vortex formation near the blade tips under off-design flow conditions.

Latest study on the Indalma pico-hydro turbine was that of Jodiwongso et al. (2025) who experimentally investigated the transient behavior of the turbine. The authors analyzed rotor speed fluctuations, torque variations, pressure response, and power output using an upgraded ESP32-based data acquisition system integrated with ScadaBR. A transfer function for the rotational speed was identified in MATLAB, and the second-order model showed better agreement with the experimental response than the first-order model, with fits of 88.09% and 74.77%, respectively. The results indicated a natural frequency of 16.14 rad/s, a damping ratio of 0.73, and an experimental overshoot of 0.078, suggesting that the Indalma turbine exhibits self-regulating behavior associated with transient flow phenomena, thereby indicating its potential suitability for electricity generation in remote communities.

Many rural and peri-urban sites present elevated head possibilities, for instance at drops in irrigation canals, small weirs, or existing water supply systems, where the hydraulic potential is higher than in the original pico applications. However, as of now, no Indalma turbine installation with a head greater than 10 m has been reported (Els et al., 2010). Operating an Indalma turbine at heads above 10 m may significantly alter flow structures, load patterns, and energy conversion efficiency, and therefore requires careful comparative assessment before broader adoption.

In this context, Sudsuansee et al. (2025) numerically and experimentally analyzed a low-head propeller hydro turbine operating under different water head conditions, ranging from 3 to 11 m. The study evaluated the influence of head variation on the turbine's hydrodynamic performance, considering parameters such as runner blade angle, guide vane angle, rotational speed, and flow conditions. The CFD simulations were performed using the SST κ-ω turbulence model and Poly-Hexcore mesh. The authors observed that increasing the water head increased the generated power while maintaining high efficiency levels. The maximum efficiencies obtained were 76.40% at 3 m, 77.34% at 7 m, and 78.03% at 11 m, while the highest power output, 81.09 kW, was achieved at 11 m and 800 rpm. These results indicate that the water head has a direct influence on hydraulic energy conversion and on the turbine's ability to operate efficiently under different hydraulic conditions.

Ruiz et al. (2025) experimentally investigated a variable-speed contra-rotating pump-turbine for low-head pumped hydro energy storage systems, with emphasis on its operation under low and variable head conditions. The study is directly related to the influence of head because low-head systems are designed for flat regions where conventional high-head pumped hydro storage is not feasible. Using a model-scale test rig with two open water surface tanks to generate the hydraulic head, the authors evaluated the performance of the machine in both pump and turbine modes. The results showed that the contra-rotating pump-turbine maintained high hydraulic efficiency over a wide range of operating conditions, reaching peak efficiencies of 86.1% in pump mode and 88.4% in turbine mode. These findings indicate that efficient operation under variable low-head conditions is possible, making the technology suitable for pumped hydro energy storage applications in regions with limited height difference.

Hoffstaedt et al. (2025) experimentally and numerically investigated a low-head pumped hydro storage system using a novel reversible pump-turbine with two contra-rotating runners and independent drivetrains. The study is related to the influence of head because low-head systems operate with larger relative head variations than conventional high-head systems, which affects both steady-state performance and transient behavior. A 50-kW experimental setup with a 1:22 scale pump-turbine model was designed and tested in both turbine and pump modes under different runner speed ratios. The results showed maximum efficiencies of 89% in turbine mode and 92% in pump mode. The authors also compared the experimental data with CFD-based numerical models and obtained good agreement, especially in turbine mode, with correlation coefficients between 0.90 and 0.97. The transient analysis showed that the numerical model accurately predicted changes in flow rate and rotational speed, and the shutdown simulation indicated no risk of dangerous pressure transients during runner deceleration and valve closure.

Salehi and Nilsson (2022) numerically investigated the validation of CFD results for the high-head Francis-99 turbine model during a transient shutdown sequence. Although the study does not focus directly on variations in water head, it is related to turbine operation under high-head conditions and to the safe expansion of hydraulic turbine operating ranges. The authors analyzed how uncertainties in the positioning of the experimental PIV measurement plane affect the comparison between CFD and experimental velocity fields. Using polynomial chaos expansion for uncertainty quantification and Sobol' indices for sensitivity analysis, they showed that the horizontal velocity component was most sensitive to the plane-normal positioning of the PIV plane. The results indicated that the differences between numerical and experimental data could be explained within the range of measurement uncertainties, supporting the reliability of CFD validation for transient operation in high-head hydraulic turbines.

Chaulagain et al. (2024) experimentally investigated an ultra-low-head vertical-shaft hydro turbine designed for power generation from the head-drop section of an open canal. The study is directly related to the influence of head because the turbine was designed to operate with only 0.5 m of hydraulic head and a discharge of 0.088 m^3/s. The authors analyzed how outlet flow control, varied from 0.0 to 0.5 m, affected the runner condition, ranging from free to submerged operation. The experiments were conducted at a constant flow rate of 0.088 m^3/s and a constant rotational speed of 115 rpm. The results showed a maximum overall efficiency of 53.8% when the flow rate was 10% above the design flow, with a measurement uncertainty of ±1.85%. The authors concluded that outlet flow control is necessary to improve turbine efficiency at a specific head, and that further performance improvements could be achieved through blade profile optimization.

Suehara et al. (2012) conducted a technical assessment of a micro hydroelectric power plant, which uses a single-runner Pelton turbine under a gross head of about 20 m and a measured flow rate of 0.101 m³/s. The turbine operates at 450 rpm and currently produces about 1.2 kW of electrical power, corresponding to 1.5 kVA of apparent power, although the site is estimated to have a generation potential of up to 20 kVA after the proposed improvements. The authors analyzed how hydraulic losses, flow conditions, and mechanical performance affect the plant's efficiency. They identified major energy losses linked to reservoir deficiencies, leakage in the penstock, excessive turbine vibration, and inadequate electrical installations, and they proposed practical measures to improve overall performance.

Several recent studies have investigated the performance of hydraulic turbines and pump-turbines operating under low-head, ultra-low-head, and variable-head conditions. These works show that the available water head is a key parameter influencing hydraulic efficiency, power output, flow behavior, and transient response. Table 1 summarizes selected studies related to the influence of head on turbine performance, highlighting the operating conditions, numerical or experimental approaches, and main results reported by the authors.

Table 1 - Summary of studies on the influence of water head on hydraulic turbine performance.

Study	Head condition	Main findings
Sudsuansee et al. (2025)	3–11 m	Low-head propeller turbine. Efficiency increased from 76.40% at 3 m to 78.03% at 11 m. Maximum power was 81.09 kW at 11 m.
Ruiz et al. (2025)	Variable low head	Contra-rotating pump-turbine for low-head pumped hydro storage. Peak efficiencies were 86.1% in pump mode and 88.4% in turbine mode.
Hoffstaedt et al. (2025)	Low-head PHS	Reversible pump-turbine with contra-rotating runners. Maximum efficiencies of 89% in turbine mode and 92% in pump mode were obtained.
Salehi and Nilsson (2022)	High head	CFD validation of the Francis-99 turbine during shutdown. The study focused on PIV-plane uncertainty rather than head variation.
Chaulagain et al. (2024)	0.5 m	Ultra-low-head vertical-shaft turbine for open canals. Maximum efficiency was 53.8%. Outlet flow control improved turbine performance.
Suehara et al. (2012)	± 20 m	Single-runner Pelton turbine. Current output is 1.5 kVA. Suggested improvements could lead to an estimated generation potential of 20 kVA.

In this context, the present study aims to perform a comparative evaluation of an Indalma pico-hydraulic turbine under conditions of high head of 10 m, 15 m, and 20 m, using the Ansys CFX software. Specifically, the study evaluates how the increase in head influences the hydraulic behavior of the turbine. Furthermore, the results were compared with literature data obtained for a head of 5.5 m.

MATERIAL AND METHOD

The present study builds on the study of Mac Donald and Sloot (2014) and Nascimento et al. (2020), who characterized an Indalma pico-hydro turbine experimentally and numerically, respectively, and their 5.5 m head case is used here as the reference operating point. From that reference condition, the corresponding experimental values are extended to higher heads to estimate the inlet pressure, rotor angular velocity, and mass flow rate used in this study.

Experimental basis

The experimental work of Mac Donald and Sloot (2014) provided measured turbine performance at different operating heads and delivered the baseline data needed to define the comparison conditions for the elevated-head assessment. In the present work, the 5.5 m head measurements from that study, presented in Table 2 are treated as the nominal case, and the values for higher head are derived from the 5.5 m head experimental values.

Table 2 - Measurements at 5.5 m head with submerged draft tube.

Parameter	Value
Head	5.5 m
Inlet mass flow rate	15.15 kg/s
Rotation	930 rpm
Outlet pressure	101325 Pa
Power	379.00 W
Efficiency	46.10 %

These measurements were then used as the starting point for the elevated-head comparison, so the new conditions are not arbitrary but are anchored in the original 5.5 m experimental operating point. For this reason, the present work uses the original experimental values as the basis for estimating the inlet pressure, angular velocity, and mass flow rate at the higher-head cases.

Numerical approach

The numerical analysis was performed under steady-state conditions and assuming incompressible flow. The flow was modeled with a Reynolds-averaged Navier–Stokes, or RANS, formulation. To close the system, the SST κ-ω turbulence model was used because it combines the near-wall accuracy of the κ-ω model with the freer-stream robustness of the κ-ε, making it well suited to separated and rotating internal flows (Moeljoredjo et al., 2025).

The governing equations solved in the simulation were the conservation of mass and momentum. For incompressible flow, the continuity equation can be written as:

$$\nabla \cdot \mathbf{u} = 0 \qquad (1)$$

which enforces mass conservation by requiring the velocity field to remain divergence-free. The momentum equation is the averaged Navier–Stokes equation, written in the RANS form as

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}\right) = -\nabla p + \nabla \cdot \tau + F \qquad (2)$$

where ρ is the fluid density, **u** is the velocity vector, t is the time, p is the static pressure, τ is the viscous stress tensor, and F is the body force term (Xu & Guo, 2025).

Computational domain and boundary conditions

The computational domain consisted of the main hydraulic passages of the Indalma turbine: inlet section, volute, runner region, and draft tube. The volute and draft tube were defined as stationary domains, while the runner region was defined as a rotating domain. The interface between the stationary and rotating domains was used to transfer the flow variables between the volute, runner, and draft tube.

The simulations were performed in steady state, considering water as an incompressible Newtonian fluid. The flow was modeled using the RANS formulation with the SST κ-ω turbulence model, as described in the previous section. No-slip boundary conditions were imposed on all solid walls (do Nascimento et al., 2020).

The inlet condition was defined from the hydraulic head considered in each case. The 5.5 m case was used as the reference condition, based on the experimental data reported by Mac Donald and Sloot (2014). For this reference case, the inlet mass flow rate was 15.15 kg/s and the rotational speed was 930 rpm. The cases of 10, 15, and 20 m were obtained from the reference condition using hydraulic similarity relations for rotational speed and mass flow rate. The outlet boundary condition was imposed at the end of the draft tube as a static pressure condition (Nascimento, et al., 2020). Table 3 summarizes the boundary conditions used in the numerical simulations.

Table 3 - Boundary conditions adopted in the numerical simulations.

Head (m)	Mass flow rate (kg/s)	Rotational speed (rpm)
5.5	15.15	930
10	20.43	1254
15	25.02	1536
20	28.89	1773

The same computational domain, turbulence model, wall treatment, and convergence criteria were maintained for all cases. Thus, the differences observed in pressure field, velocity field, torque, and power output are associated only with the variation in hydraulic head and the corresponding scaled operating conditions.

Data reduction

The experimental and derived variables were obtained from standard hydraulic relations. For the new-head conditions, the rotor speed (*N*) was estimated from the head ratio relation

$$\left(\frac{N_2}{N_1}\right)^2 = \frac{H_2}{H_1} \qquad (3)$$

which was used to scale the rotational speed from the reference condition to the elevated-head cases. The same type of proportionality was applied to the mass flow rate (*Q*) using

$$\left(\frac{Q_2}{Q_1}\right)^2 = \frac{H_2}{H_1} \qquad (4)$$

allowing the inlet mass flow rate to be adjusted consistently with the change in head.

Power was calculated from the torque acquired through CFD analysis and the calculated rotational speed obtained from Eq. (3). To obtain the shaft power (*P*) the following equation was used:

$$P = \frac{\tau \times 2\pi \times N}{60} \qquad (5)$$

which converts rotational speed (*N*) in revolutions per minute into angular velocity and multiplies it by torque (τ) to obtain the shaft power. In practical terms, these formulas transform the measured experimental baseline at 5.5 m head into a complete set of expected operating variables for the higher-head cases, ensuring that the comparison between experiment and simulation is based on consistent hydraulic scaling.

This approach also keeps the data reduction physically interpretable, because pressure, speed, flow, and power remain linked through the same energy balance used in hydro-turbine analysis (Dixon & Hall, 2010).

RESULTS AND DISCUSSION

Pressure field analysis

Figure 2a-d shows the local pressure contours in the volute and draft tube of the Indalma pico-hydraulic turbine for heads of 5.5, 10, 15, and 20 m. As expected, increasing the head raises the overall pressure level inside the turbine while preserving the same general distribution pattern.

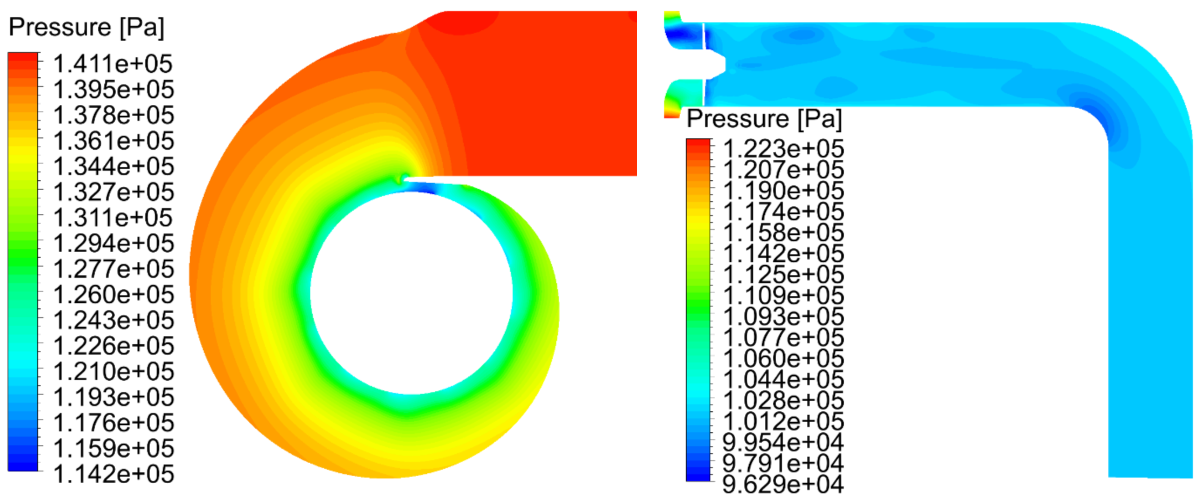
In the volute, pressure decreases gradually from the inlet toward the runner for all cases, which is typical of reaction turbines where pressure head is progressively transformed into kinetic energy. When the head increases from 5.5 m to 20 m, the maximum volute pressure rises from about $1.41 \cdot 10^5$ Pa to $2.46 \cdot 10^5$ Pa, an increase of roughly 75%. Localized high-pressure zones appear near the inlet and volute end region, where the flow decelerates and changes direction, but their location and extent remain similar over the whole head range. In the draft tube, pressures are lower than in the volute, reflecting the energy extracted by the runner. The contours show a smooth pressure recovery along the tube, confirming its diffuser role. With increasing head, the pressure gradients become steeper, yet the overall pattern is still consistent; lower-pressure regions concentrate near the curved section, likely due to local acceleration and secondary flows.

The pressure contours also show that the increase in head mainly affects the pressure magnitude, without changing the main pressure-field topology. For all operating conditions, the highest-pressure region remains associated with the inlet and outer volute wall, while the lowest pressure region is located near the runner entrance. This indicates that the volute maintains a similar hydraulic behavior over the analyzed head range (Xu et al., 2023).

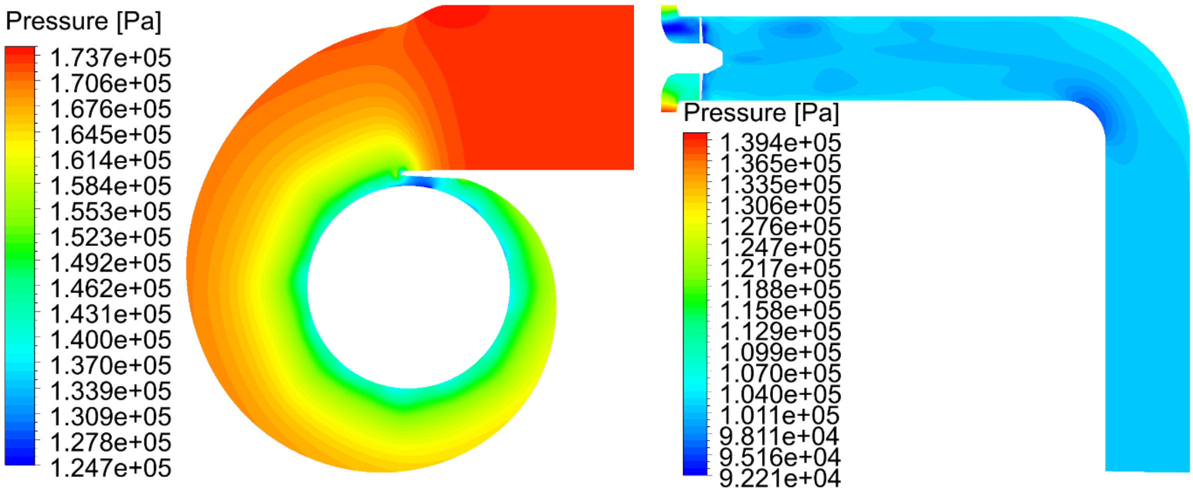
At higher heads, the pressure difference between the inlet region and the runner entrance becomes more pronounced. This stronger pressure gradient may increase the hydraulic loading on the runner blades and on the volute casing. Therefore, although the pressure distribution remains stable from a flow perspective, the 15 m and 20 m cases require further mechanical evaluation (Mao et al., 2021).

In the draft tube, the pressure field indicates progressive pressure recovery downstream of the runner. However, the lower-pressure region near the curved section becomes more relevant as the head increases. This region should be considered in future analyses because it may be associated with secondary flows, local separation, and possible cavitation susceptibility under elevated-head operation.

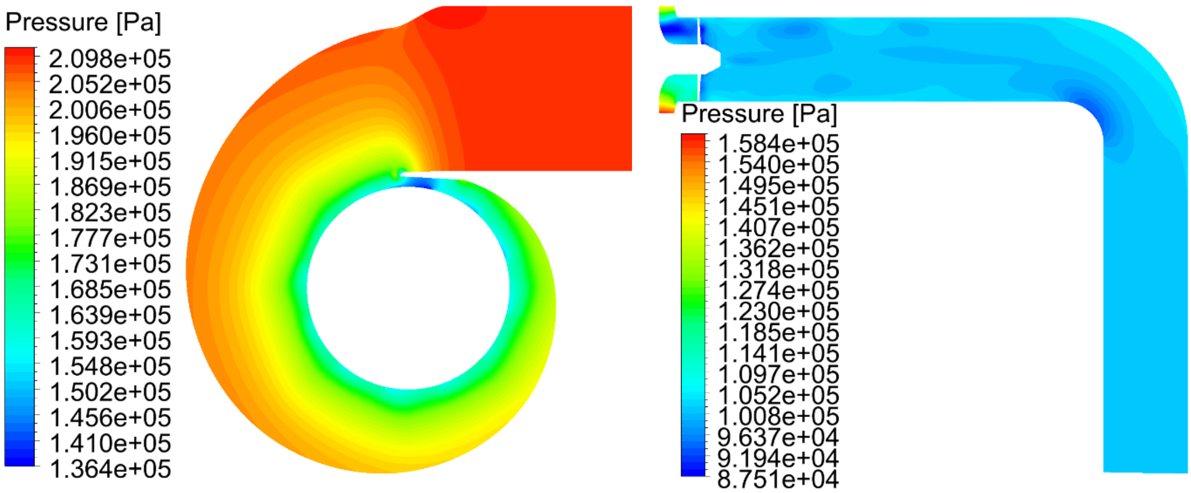
a) 5.5 m



b) 10 m



c) 15 m



d) 20 m

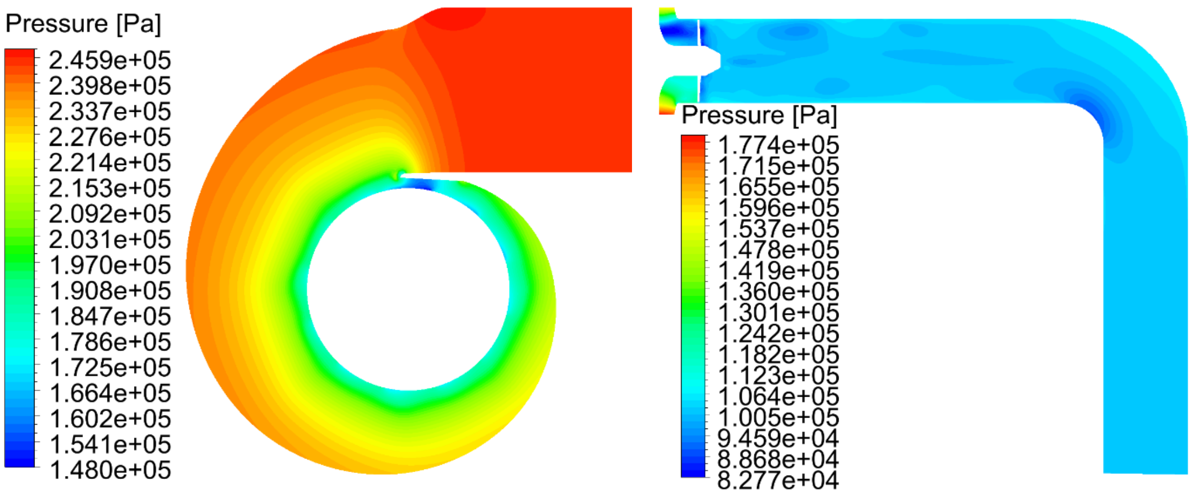
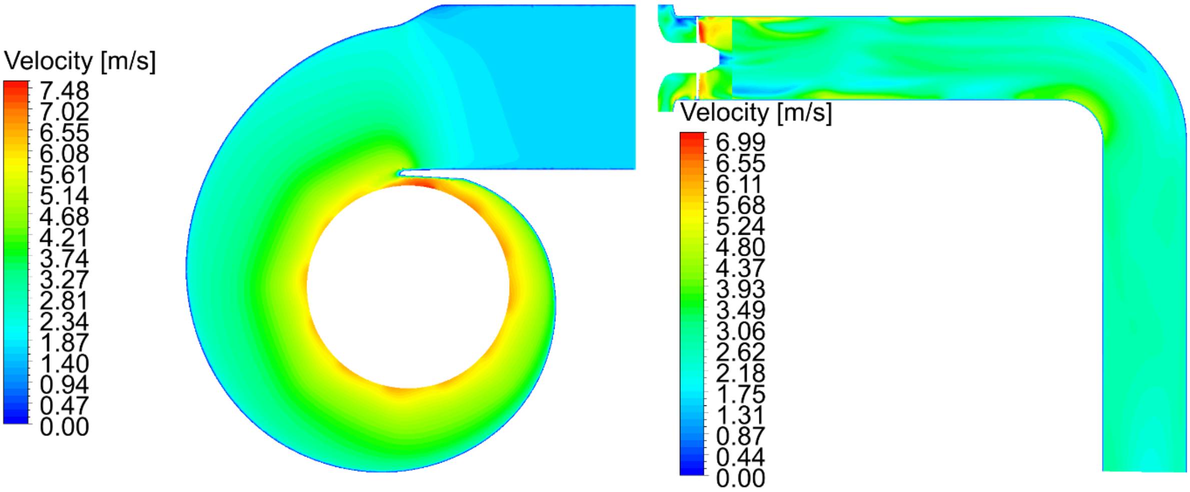
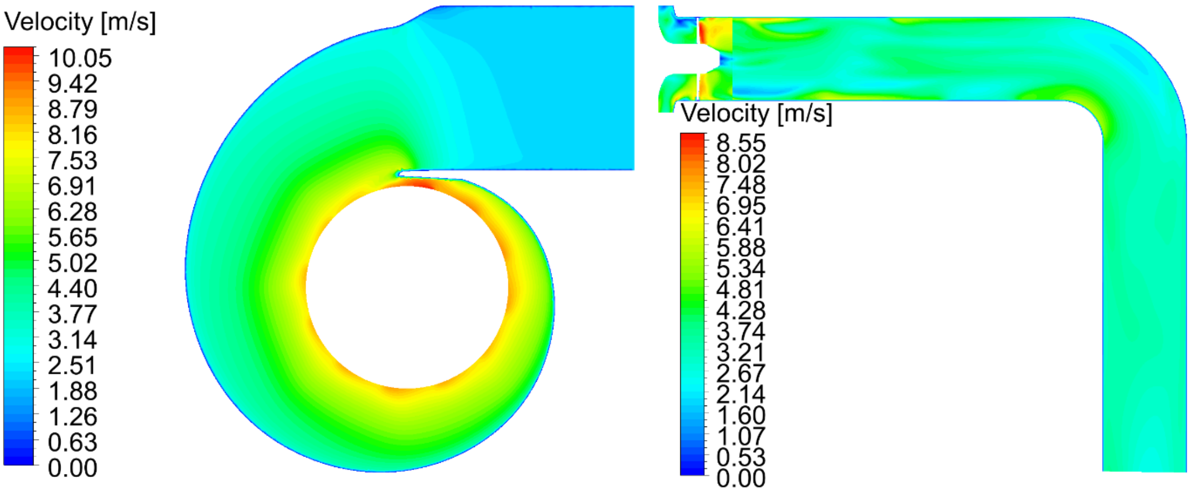


Figure 2. Pressure contours of the volute (left) and draft tube (right) for various elevated heads: a) 5.5 m, b) 10 m, c) 15 m, and d) 20 m.

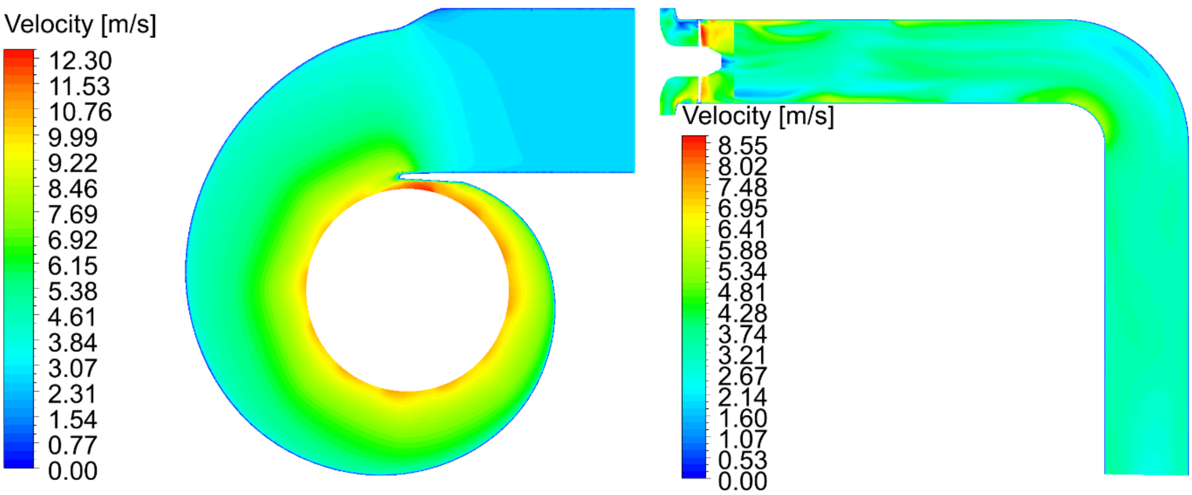
a) 5.5 m



b) 10 m



c) 15 m



d) 20 m

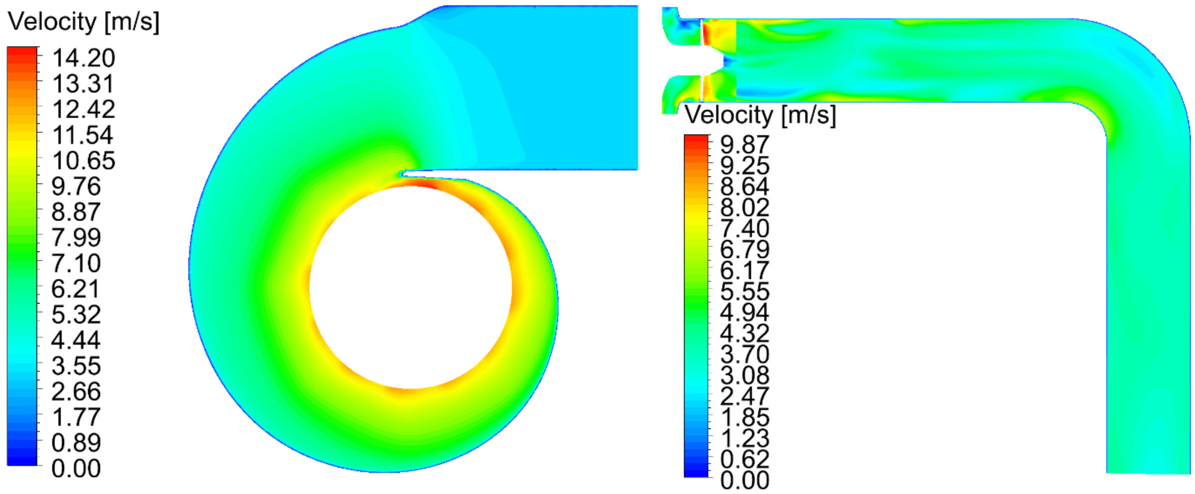


Figure 3. Velocity contours of the volute (left) and draft tube (right) for various elevated heads: a) 5.5 m, b) 10 m, c) 15 m, and d) 20 m.

Velocity field analysis

Figure 3a-d presents the corresponding velocity contours for the same operating heads. In the volute, velocity increases steadily as the flow approaches the runner entrance, with peak values near the volute end region and runner inlet where the cross-sectional area narrows. As the head rises from 5.5 m to 20 m, the maximum volute velocity grows from about 7.48 m/s to 14.20 m/s, which is an increase of approximately 90%.

Despite this strong increase in magnitude, the main flow paths and recirculation features remain essentially unchanged, indicating that the volute geometry continues to guide and distribute the flow effectively over the entire head range. In the draft tube, relatively high velocities are observed just downstream of the runner, followed by a gradual deceleration along the diffuser, consistent with kinetic energy recovery. The maximum draft-tube velocity increases from roughly 5.19 m/s at 5.5 m to 9.87 m/s at 20 m, again close to a 90% rise. Local high-velocity zones appear near the inlet and along the bend, reflecting curvature-induced acceleration and secondary flow structures, but no qualitative change in the overall flow topology is observed.

The velocity contours also show that the increase in head mainly affects the velocity magnitude, while the global flow pattern remains similar for all operating conditions. In the volute, the highest velocity region remains concentrated near the runner entrance, where the flow is accelerated before entering the rotating domain. This indicates that the volute preserves its flow-guiding function even under elevated-head operation (Lazarevikj & Markov, 2022).

As the head increases, the velocity gradients become more pronounced near the inner region of the volute and close to the runner inlet. These regions are important because they directly influence the flow incidence on the runner blades. Therefore, higher heads may increase local non-uniformity at the runner entrance, even though the overall velocity distribution remains stable (Chitrakar et al., 2018).

In the draft tube, the highest velocities are observed immediately downstream of the runner and near the draft tube inlet. Along the diffuser section, the velocity decreases progressively, indicating kinetic energy recovery after the runner. This behavior is consistent with the pressure recovery observed in the pressure contours (Chakrabarty et al., 2016).

For the 15 m and 20 m cases, the higher velocity levels may intensify secondary flows in the curved section of the draft tube. This can increase local hydraulic losses and may contribute to flow separation under more severe operating conditions. Thus, future studies should evaluate velocity profiles, turbulence intensity, and possible unsteady effects in the draft tube for elevated-head operation.

Figure 4 shows a clear relationship between turbine output power and available hydraulic head. As the head increases from 0 to 20 m, the power output rises continuously, from approximately 480 W at 5.5 m to about 1.2 kW at 10 m, 2.2 kW at 15 m, and nearly 3.4 kW at 20 m. This behavior indicates that the turbine responds strongly to increasing hydraulic potential, as expected from hydropower theory, in which power is proportional to the product of head, discharge, density, gravity, and efficiency.

The trend is nonlinear, with a more rapid increase in power at higher heads. This suggests that, in addition to the direct effect of head, the turbine may also be experiencing an increase in discharge and/or efficiency as operating conditions become more favorable, leading to a more-than-linear gain in output. Such behavior is consistent with the fundamental hydropower relation, where both head and flow rate contribute to the available power. The steeper rise beyond 10 m indicates that the turbine can effectively convert the additional hydraulic energy into mechanical work over the investigated range.

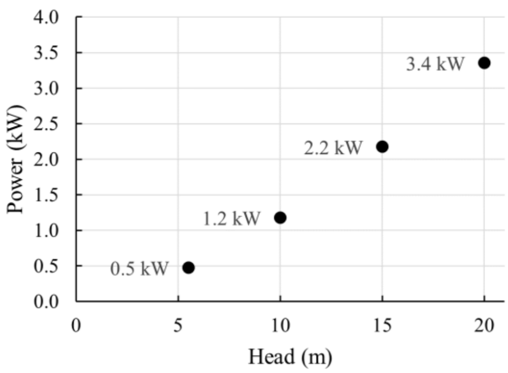


Figure 4. Relationship between the hydraulic head and the turbine output power.

Mechanical implications of elevated-head operation

The increase in hydraulic head also has mechanical implications for the turbine components. Higher heads produce higher pressure levels, higher flow velocities, and higher rotational speeds. As a result, the runner, shaft, bearings, and volute casing may be subjected to larger hydraulic and centrifugal loads (Xue et al., 2024).

The runner is the most critical component under elevated-head operation. Since the rotational speed increases with head, the centrifugal forces acting on the blades also increase. In addition, the stronger pressure gradients near the runner inlet may produce non-uniform hydraulic loading on the blades. This effect can contribute to vibration, fatigue, and local stress concentration during long-term operation (Huang et al., 2024).

The draft tube and volute should also be considered in the mechanical assessment. The higher-pressure levels in the volute may increase the loading on the casing, while the higher velocities in the draft tube may intensify secondary flows and unsteady forces. These effects are more relevant for the 15 m and 20 m cases.

Therefore, although the CFD results indicate stable hydraulic behavior, elevated-head operation should be complemented by structural and vibration analyses. Future work should include stress analysis of the runner, shaft verification, bearing load estimation, and modal analysis to evaluate the mechanical safety of the turbine under higher-head conditions (Song et al., 2025).

Comparison Indalma turbine and Pelton turbine

The elevated-head operating conditions investigated in the present study allow a qualitative comparison with the Pelton turbine evaluated by Suehara et al., (2012), which operates at a head of approximately 20 m. As presented in Table 4, the Pelton turbine operates with a measured discharge of approximately 0.101 m³/s and produces about 1.2 kW of electrical power under its current installation. The CFD results indicate that the Indalma turbine is capable of producing a higher shaft power and rotational speed at the same hydraulic head, reaching approximately 3.4 kW and 1773 rpm, respectively, at 20 m under the scaled operating conditions adopted in this study.

Table 4 – Comparison Indalma turbine and Pelton turbine at 20 m head.

Parameter	Indalma	Pelton
Head (m)	20	20
Volumetric Flow (m^3/s)	0.029	0.101
Rotational Speed (rpm)	1773	450
Power (kW)	3.4	1.2

An important distinction between both turbines is their hydraulic operating principle. The Pelton turbine is an impulse turbine, where the discharge is primarily controlled by the injector nozzle and generally remains nearly constant for a fixed nozzle opening and available head. In contrast, the Indalma turbine behaves as a reaction turbine (Mac Donald & Sloot, 2014; Nascimento et al., 2020), in which the discharge depends on both the available head and the runner operating condition. Previous experimental investigations by Jodiwongso et al. (2025) showed that, under low electrical loading and high rotational speeds, the Indalma turbine exhibits self-regulating behavior, resulting in a reduction in flow rate. Consequently, unlike a Pelton turbine, the Indalma turbine does not necessarily consume a constant amount of water throughout its operating range.

This characteristic may provide an operational advantage in water-limited installations. At elevated heads, an Indalma turbine operating under reduced loading may require less discharge than a Pelton turbine supplied through the same intake system, while still maintaining stable operation. Although the present CFD model employs hydraulically scaled flow rates and therefore cannot directly quantify this potential reduction in water consumption, the observed self-regulating behavior suggests that the relationship between discharge and rotational speed deserves further investigation. Future work should therefore compare both turbine types under identical head, intake geometry, and available discharge to determine their relative hydraulic efficiency, water consumption, and energy production.

CONCLUSION

This study numerically evaluated the hydraulic performance of an Indalma pico-hydro turbine under elevated operating heads of 10, 15, and 20 m using ANSYS CFX, with the experimentally validated 5.5 m condition as the reference case. The CFD results show that increasing the available head raises the pressure levels, flow velocities, rotational speed, and shaft power while preserving the overall pressure and velocity distributions within the volute and draft tube. These results indicate that the turbine maintains stable hydraulic behavior over the investigated operating range. The highest performance was obtained at 20 m head, where the simulated shaft power reached approximately 3.4 kW at 1773 rpm, highlighting the considerable increase in energy conversion potential compared with the reference condition.

Although the hydraulic performance remained stable, the higher operating heads also resulted in increased hydraulic loading and rotational speeds, which are expected to increase stresses on the runner, shaft, bearings, and casing. Therefore, before practical implementation at elevated heads, comprehensive structural verification is required. Future work should include fluid–structure interaction analyses, stress and vibration assessments, cavitation evaluation, and experimental validation to confirm the long-term safety and reliability of the turbine under high-head operating conditions.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Technische Universiteit Vanguard, the Research Institute Vanguard, the Energy and Fluid Dynamics Laboratory, the Vanguard Foundation, and the University of Brasília (UnB) for their support of this work.

REFERENCES

Chakrabarty, S.; Bikash Kr. Sarkar; Subhendu Maity. CFD Analysis of The Hydraulic Turbine Draft Tube to Improve System Efficiency. MATEC web of conferences, v. 40, p. 02003–02003, 2016.

Chaulagain, R. K.; Poudel, L.; Maharjan, S. Design and experimental analysis of a new vertical ultra-low-head hydro turbine with the variation of outlet flow level on the head drop section of an open canal. Results in Engineering, v. 22, p. 102240, 2024.

Chitrakar, S.; Dahlhaug, O. G.; Neopane, H. P. Numerical investigation of the effect of leakage flow through erosion-induced clearance gaps of guide vanes on the performance of Francis turbines. Engineering Applications of Computational Fluid Mechanics, v. 12, n. 1, p. 662–678, 2018.

Dixon, S. L., Dixon, S. L., & Hall, C. A. Fluid Mechanics and Thermodynamics of Turbomachinery. Butterworth-Heinemann, 2010.

Nascimento, E. O. D., De Freitas, E. A., Lins, E. F., & Vaz, J. R. P. Performance assessment of an Indalma hydro-turbine. SN Applied Sciences, v. 2, n. 12, 2020.

Els, R., Diniz, J., Souza, J. & Brasil Junior, A. Eletrificação rural em Santarém: Contribuição das micro centrais hidrelétricas. Revista Brasileira de Energia, Volume 16, pp. 35-46, 2010.

Hoffstaedt, J., Laguna, A. J., Ruiz, R. A., Schürenkamp, D., Goseberg, N., Truijen, D., De Kooning, J., Stockman, K., Fahlbeck, J., & Nilsson, H. Analysis of a contra-rotating pump–turbine for low-head applications: An experimental study and numerical comparison. Energy Conversion and Management, v. 341, p. 119950, 2025.

Huang, X., Ou, H., Huang, H., Wang, Z., & Wang, G. Flow-Induced Stress Analysis of a Large Francis Turbine Under Different Loads in a Wide Operation Range. Applied Sciences, v. 14, n. 24, p. 11782, 2024.

Jodiwongso, M., Moeljoredjo, P., Bhaggan, Y., Prawesh, S., Prevez, H. B., Van Els, R., Mendes, R. C. F., Noleto, L. G., & Nascimento, E. O. D. A Study on the dynamic behavior of a Indalma Pico Hydraulic Turbine. Proceedings of the 28th International Congress of Mechanical Engineering, 2025.

Lazarevikj, M.; Markov, Z. Automated hydraulic design procedure for a Francis turbine spiral casing. IOP Conference Series: Earth and Environmental Science, v. 1079, n. 1, p. 012009, 2022.

Mac Donald, R. & Sloot, N. Experimental and Numerical Study of the Performance Characteristics of a Pico Hydro Turbine Manufactured by Indalma Industries Inc.. Rio de Janeiro, Brazil, p. 8, 2014.

Mao, Z., Tao, R., Chen, F., Bi, H., Cao, J., Luo, Y., Fan, H., & Wang, Z. Investigation of the Starting-Up Axial Hydraulic Force and Structure Characteristics of Pump Turbine in Pump Mode. Journal of Marine Science and Engineering, v. 9, n. 2, p. 158–158, 2021.

Moeljoredjo, P., Van Els, R., Mendes, R. C. F., Noleto, L. G., & Nascimento, E. O. D. Repowering through virtualization of the Afobaka hydro powerplant in Suriname. Proceedings of the 28th International Congress of Mechanical Engineering, 2025.

Ruiz, R. A., Schürenkamp, D., Truijen, D. P., Hoffstaedt, J. P., Laguna, A. J., Fahlbeck, J., Nilsson, H., Joseph, M., Zangeneh, M., De Kooning, J. D., Oldeweme, J., Schwarz, H., & Goseberg, N. Performance evaluation of a variable-speed contra-rotating pump-turbine for low-head pumped hydro energy storage: An experimental study. Energy Conversion and Management X, v. 26, p. 101009–101009, 2025.

Salehi, S.; Nilsson, H. Effects of uncertainties in positioning of PIV plane on validation of CFD results of a high-head Francis turbine model. Renewable Energy, v. 193, p. 57–75, 2022.

Song, H., Xie, W., Han, W., Qiu, H., Guan, Z., Wang, S., & Huang, X. Pressure Pulsation Characteristics and Flow-induced Vibration Optimization in a Turbine Runner under Low Flow Conditions. Journal of Applied Fluid Mechanics, v. 19, n. 1, 2025.

Sudsuansee, T., Phitaksurachai, S., Pan-Aram, R., Sritrakul, N., & Tiaple, Y. Design and Hydrodynamic Performance of Low Head Propeller Hydro Turbine for Wide Range High Efficiency Operation. International Journal of Thermofluids, p. 101228–101228, 2025.

Suehara, B. B., Pereira, W. M., Baracho, G. M. M. O., Gonçalves, J. S., van Els, R., Castro, V. Estudo técnico da turbina hidrelétrica da Chapada Imperial. VII Congresso Nacional de Engenharia Mecânica, São Luís, Maranhão, Brasil, 2012.

Xu, T., Cheng, Q., Lin, C., Yu, Q., & Hu, X. Study on Flow Characteristics of Francis Turbine Based on Large-Eddy Simulation. Water, v. 15, n. 19, p. 3372, 2023.

Xu, L.; Guo, T. Analysis of hydraulic stability of a Francis turbine under partial load conditions based on Liutex method and entropy production theory. Energy, v. 328, p. 136528, 2025.

Xue, S., Tian, H., Cheng, Y., Hou, X., Guan, Z., Yang, W., Wang, Z., Wang, Z., & He, Q. Mechanism analysis of the abnormal head-cover vibration of an ultra-high-head pump-turbine operating in pump mode by CFD and FEM. Engineering Applications of Computational Fluid Mechanics, v. 18, n. 1, 2024.