Available *online* at : http://jnte.ft.unand.ac.id/

Jurnal Nasional Teknik Elektro

| ISSN (Print) 2302-2949 | ISSN (Online) 2407-7267 |

Power and Efficiency Investigation of Compressors as Turbines (CATs) for Pico-Hydropower Plants

Yul Hizhar, Uyung Gatot Syafrawi Dinata, Dendi Adi Saputra*

Universitas Andalas, Kampus Limau Manis, Padang, 25163, Indonesia

ARTICLE INFORMATION

Received: June 23, 2026
Revised: July 13, 2026
Accepted: July 13, 2026
Available online: July 31, 2026

KEYWORDS

Compressor as turbine (CAT), turbocharger, pico-hydropower application, output power, turbine efficiency

CORRESPONDENCE

E-mail: uyunggsdinata@eng.unand.ac.id

A B S T R A C T

This study investigates the power and efficiency performance of compressor as turbine (CAT) units for pico-hydropower applications using laboratory experiments under varying head conditions. Motivated by the increasing demand for low-cost, pico-scale hydropower (<5 kW) units and the limited availability of conventional turbines for remote areas, this work evaluates six nearly similar Garrett turbocharger compressors as turbines using different models with different sizes from a single compressor PC family (PC78US-6, PC130-7, PC200-6, PC300-6, PC400, and PC500) due to their geometric similarity to Francis-type turbines. The experiments were conducted using a pump-circulated test rig commonly used for assessing pico-hydroturbine-generator characteristics, with measurements of output power and efficiency at head levels of 6, 8, 10, and 12 m. The tests show that all CAT units exhibit a parabolic efficiency–rotational-speed relationship for a reaction turbine, with head-constant best-efficiency points (BEPs) ranging from 52% to 70%, occurring at a rotational speed range of 1750–2100 rpm and a discharge range of 0.004515–0.009442 m^3/s. At a head level of 12 m, the smaller units (PC78, PC130, and PC200) reach turbine-individual maximum powers of 373–486 Watt with peak efficiencies of 60–65%, while the larger units (PC300-6, PC400, and PC500) achieve performances of 508–774 Watt with 67–70%. The results clearly suggest that the CAT characteristics are significantly influenced by runner size and hydraulic head. The resulting test graphs can serve as a practical guideline for selecting a PC-family compressor model for pico-hydropower sites based on the available water head and discharge, as well as on the specific rotational speed. Based on this study, low-cost, mass-produced turbocharger compressors used as turbine alternatives instead of a specially designed turbine have favorable prospects for inexpensive pico-hydropower systems.

INTRODUCTION

Energy is crucial for global social and economic growth. Energy demand is rapidly increasing due to the growth of human activities, and producing alternatives is not fast enough because of the slow pace of renewable energy expansion. Today, access to affordable, reliable, sustainable, and modern energy that is in line with SDG 7 is the key requirement for providing electricity for socio-economic development, especially in rural regions [1]. Electric energy plays a crucial role as a secondary energy form, which is converted from nuclear, fossil, and renewable primary energy sources [2]. Global electricity production has been supplied with more than 80% from fossil fuels [3]. Due to limited fossil fuel resources and their impacts on the environment, the energy transition has been motivated by renewable energy. Hydropower schemes contribute to global renewable power, supplying global electricity at a percentage of about 14.3% [4]. Electrification for rural and remote areas often relies on off-grid micro-hydropower systems ranging from 5–100 kW and pico-hydropower systems up to 5 kW. Both systems use a run-of-the-river hydropower application with the diversion of irrigation and small river flows to drive a small-scale turbine [5], [6].

The main components of a small-scale hydropower system consist of infrastructure construction, electromechanical devices, and electrical distribution lines [7], [8], with the turbine-generator functioning as the primary device [9], [10]. Generally, the system has low operating expenses but high initial costs, which could be solved by providing small, lightweight, and efficient turbine designs [9], [11]. It is an ultimate task to develop and acquire highly efficient pico-hydroturbines to support the feasibility of small-scale hydropower systems [8], [10], [12].

To provide a low-cost hydraulic turbine, a pump as a turbine (PAT) is used, whereas a standard pump is employed as a substitute for a regular turbine [13–20]. The PAT applications have shown reliability for years and have now been adopted in various countries. Such a technology has many advantages because mass-produced pumps are available on the market in various sizes, which makes it easy to find suitable PATs for specific head and discharge requirements [15–17]. Moreover, PAT technology provides quick delivery, a long equipment life, relatively easy

https://doi.org/10.25077/jnte.v15n2.1605.2026

installation, and easily accessible replacement for its mechanical parts [17–20]. A PAT efficiency reported in pico-hydro experiments was 38%, with an output of 235 Watt [20].

The use of a blower as a turbine (BAT) is another category of turbomachinery repurposing, especially for pico-hydropower schemes, due to its low cost and widespread availability. In BAT systems, a centrifugal blower, which is originally designed to add energy to air, employs reverse operation, enabling water flow to drive its impeller as a turbine runner and generate a power output. Bachtiar et al. [21] have shown that a blower tested could work as a pico-scale hydroturbine with an output power of 583.02 Watt and an efficiency of 50.9%. The BAT performance was strongly influenced by parameters such as impeller geometry, head variation, and discharge, with efficiency trends comparable to those of other small-scale turbines [21], [22]. In addition, BAT units offer advantages such as simple construction, ease of maintenance, and suitability for low-head conditions. Dinata et al. proposed a BAT for a portable generator turbine product as a compact water genset and then analyzed its market potential [23].

Furthermore, a compressor that is coupled to and driven by a turbocharger, which is powered by exhaust gas thermal energy, has potential as a small-scale hydraulic turbine [24], [25]. The compressor, when repurposed as a hydroturbine, is expected to generate output power with higher efficiency due to its precise design. The compressor as a turbine (CAT) is chosen based on its low cost and ease of obtaining it on the market, compared with more expensive conventional turbines. Previous studies by Bachtiar et al. had demonstrated that a single turbocharger compressor could operate as a pico-hydroturbine, studied at a constant head in a field test, reaching an efficiency of 52.7% with an output power of 342 Watt [24], while Hizhar et al. have recently conducted laboratory tests of a single CAT with head variations, resulting in a best efficiency of 70% [25].

In general, the previous investigations of pumps, blowers, and compressors used as turbines have focused only on single hydropower units [12-25]. Practically, power and efficiency performance data are still limited for selecting different compressors for CAT units, which are strongly influenced by runner and casing sizes, blade design, head, discharge, and rotational speed. The comparative operating behavior and head-dependent power-efficiency characteristics were insufficiently studied for several nearly identical turbomachineries from a single product family. To date, no studies have examined the characteristics of some nearly similar centrifugal compressors for hydroturbines. Hence, this research focuses on such compressors from the same family of a given brand to become CATs.

The novelty of the current study lies in its comparative approach to several nearly similar PC-family turbocharger compressors used as turbines, to provide performance maps for pico-hydropower schemes. Hence, the aim of this original study is to experimentally investigate the power and efficiency performance of six models of CATs originating from low-cost Garrett PC-family turbocharger compressors with geometrically similar six-blade impellers inside a spiral casing under different head levels of 6, 8, 10, and 12 m. Moreover, this research exclusively involves specific four-parameter graphs for best performance analysis using head, discharge, rotational speed, output power, and efficiency. The performance maps would be practically useful for selecting an appropriate pico-hydroturbine using site-specific head and discharge that provide the best efficiency at an optimal rotational speed for generating high output power.

METHODS

Materials

This study was started by selecting commercially available, low-cost turbocharger compressors, measuring devices, and other supporting instruments. Subsequently, each compressor was dismantled and repurposed as a CAT. This was followed by its setup on the pico-hydroturbine-generator test rig, testing, and then data analysis. The turbocharger components that were separated and used included a compressor impeller, which was repurposed as a hydroturbine runner, its shaft, and its spiral casing/volute. In the CAT schemes, the outlet side of the compressor acts as the inlet side for the water inflow, while the compressor inlet side serves as the outlet side for the water outflow. The components were located on a structural support with a pulley installed on the shaft for torque measurement [25].

The basic concept of using a compressor as a turbine is based on the nearly identical geometry of the centrifugal compressor and a Francis-type radial turbine, as shown in Figure 1 for the runner and Figure 2 for the spiral casing. The CAT principle involves the reversal of the volute inlet and outlet functions, along with the use of its impeller as the runner in the reverse rotational direction. The runner dimensions on the CAT, as indicated in Figure 1, consist of the inducer diameter denoted as A, the exducer diameter B, and the blade height C. Furthermore, the essential dimensions for the spiral casing involve the inlet diameter D and the outlet diameter E, as shown in Figure 2.

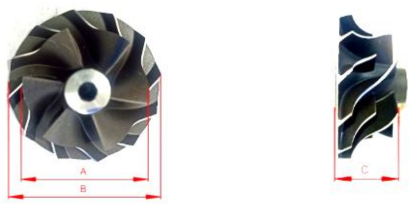

Figure 1. Runner: front view (left) and side view (right)

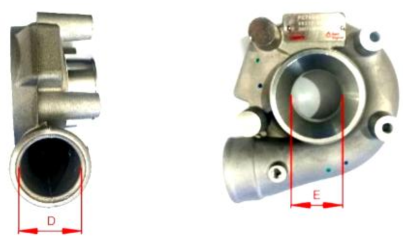

Figure 2. Spiral casing: inlet view (left) and outlet view (right)

All turbochargers used in this study carry the same Garrett brand, with six types from the PC family: PC78US-6, PC130-7, PC200-6, PC300-6, PC400, and PC500. The detailed dimensions of the turbocharger compressors tested as turbines in this study are presented in Table 1. The compressors were chosen from a low-cost turbocharger compressor family that guarantees strong geometric similarity, especially for the runner, as depicted in Table 2. This table presents partial pictures of the turbocharger compressors used as CAT in this study. The six compressor types

https://doi.org/10.25077/jnte.v15n2.1605.2026

in the PCxxx family were recorded to compare their main hydraulic-flow components.

For each CAT type, the runner photos were taken from the front and side views to check the similar blade number, blade curvature, inducer–exducer geometry, and overall impeller profile, while the spiral-case ones were documented to identify almost the same casing shape, inlet geometry, flow passage, and outlet configuration. The runners had different diameters but showed strong similarity mainly in the blade geometry. The inlet section of each compressor was also documented to evaluate the intake geometry and connection arrangement for the CAT test rig. This documentation was intended to ensure that all CAT units tested were clearly identified, geometrically compared, and consistently installed in the experimental setup under reverse-flow test conditions.

Table 1. Dimensions of Garrett PCxxx Family Turbocharger Compressors Used as CATs

Type	Dimension (mm)				
	A	B	C	D	E
PC78US-6	35.5	49	19.5	37.5	35.5
PC130-7	35.5	49	19.5	38.5	66
PC200-6	46.5	60	22	34.5	52
PC300-6	52.5	76	26	44.4	62
PC400	57	76	25.5	51.5	92
PC500	60.5	84	32	58.5	77

Table 2. Runner and Spiral Casing of Garrett PCxxx Family Turbocharger Compressors Used as CATs

Part / Type	Runner, Front View	Runner, Side View	Spiral Casing/Volute and Outlet Side	Inlet Side
PC78-US-6				
PC130-7				
PC200-6				
PC300-6				
PC400				
PC500				

Figure 3. (a) Pico-hydroturbine-generator test rig unit with reservoirs, pump, pressure gage; (b) control valve, inlet pipe, CAT, dynamometer pulley, draft tube, upper reservoir, weir meter, bypass pipe; and (c) scales and brake dynamometer [20]

Experiments and Analysis

This research used an experimental method with control parameters, namely the six different CAT types (Table 1 and Table 2) and the hydraulic head (H) with variations of 6, 8, 10, and 12 m. The latter was the maximum head of the test rig. The independent variables were the input parameters, namely the water discharge (Q) using gate-valve openings, and the rotational speed (n) using pulley braking. The dependent variables were the CAT system variables, namely the water input power (P_w), shaft torque (T), output power (P_t), and efficiency (η) [21], [22], [25].

The experimental testing was conducted at the Laboratory of Fluid Dynamics in the Mechanical Engineering Department at Universitas Andalas. As seen in the top view in Figures 3(a) and 3(b), the pico-hydroturbine-generator test rig enables water circulation with a lower reservoir, a pressurizing and circulating pump, a main pipe, a control gate valve, a bypass pipe for safety, and a CAT. Water in the lower reservoir is pumped and enters the CAT connected to a Prony braking system for measuring the shaft torque (Figure 3(c)). Water then exits the CAT through its draft tube into the upper reservoir, equipped with a weir meter for measuring the water discharge. Water flows back to the lower reservoir and is subsequently recirculated during the testing.

The main instruments include: 1) a digital tachometer with a magnetic sensor to measure the shaft rotational speed (n); 2) two hanging scales to measure the turbine braking load (F) by using a brake mechanism on a pulley with a radius (r) for determining the shaft torque (T); 3) a pressure gage for recording the water pressure in the turbine inlet pipe (p_i) to measure the water head; 4) a weir meter with a 90° V-notch; and 5) a steel ruler for measuring the water level at the weir. The last two instruments are used to determine the discharge based on a calibration equation ($Q = 1.3921 \cdot h^{2.5536}$, where h is the water level).

The testing of the performance of the six CAT types was conducted at four varying head levels. The water head level was determined from the water pressure on the pressure gage located at the turbine inlet pipe, as depicted in Figure 3(a) and (b). The constant head level was achieved by setting the control and bypass valves to the desired pressure. The input water power (P_w) is a function of Q, H, and the water's specific weight (γ_w). The output power (P_t) is the multiplication of the parameter T and the angular speed (ω) of the shaft's rotational speed. Moreover, the efficiency (η) is the ratio of P_t to P_w [22], [25]. The electrical output should consider the efficiency of a generator used.

To ensure the accuracy of the presented CAT performance data, measurement uncertainty and error analysis were conducted. The assessment took measurement repeatability and instrument accuracy into account. Head level, discharge rate, rotational speed, and shaft torque were measured for calculating input water power, output shaft power, and hydropower efficiency. The mean results of the five repetitions of the measurements under the same head, discharge, and rotational speed settings at each operating condition were used for performance analysis.

Furthermore, the standard deviation of repeated measurements was used to assess data dispersion, and the pressure gauge, water level meter, tachometer, and torque measuring system parameters were used to determine equipment uncertainty. To ensure that performance variations between CAT models represented real operating characteristics rather than chance measurement errors, the combined uncertainty was used to evaluate turbine output power and efficiency.

RESULTS AND DISCUSSION

The CAT performance testing involved six turbocharger compressor types without modification. The types had different dimensional details, especially the runner inducer-exducer diameters, as shown in Table 1. The experiment was carried out at various head levels to investigate output power and efficiency in relation to the effects of discharge and rotational speed.

To assess the reproducibility of the experimental data, statistical validation was carried out using the mean value and standard deviation of repeated measurements. As demonstrated by the coefficient of variation values below the recognized repeatability limit for comparative experimental measurements, the output power and turbine efficiency data for each CAT model and each working head showed low dispersion. This demonstrates that the observed variations in power and efficiency among the CAT units were not primarily caused by random fluctuation and that the repeated measurements were sufficiently consistent. As a result, the study's comparative performance trends can be used to evaluate how compressor size, operating head level, discharge rate, and rotational speed affect CAT performance.

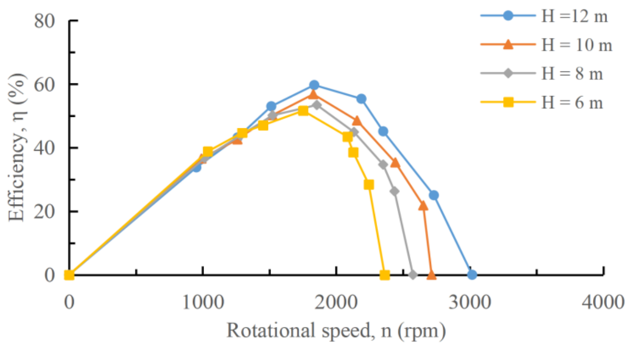

Figure 4. Efficiency of PC78US-6 CAT versus rotational speed

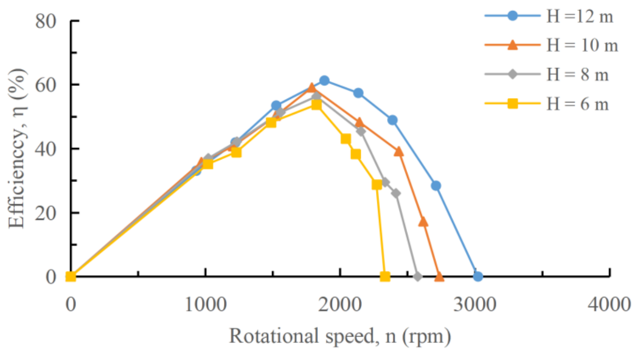

Figure 5. Efficiency of PC130-7 CAT versus rotational speed

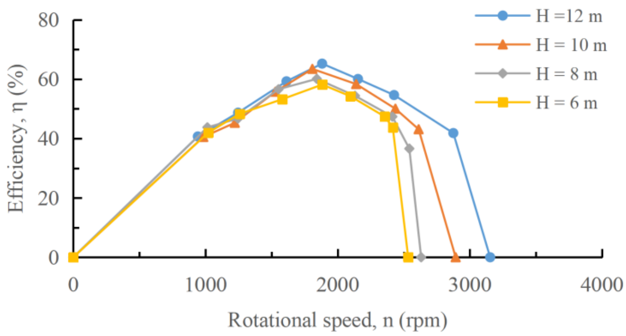

Figure 6. Efficiency of PC200-6 CAT versus rotational speed

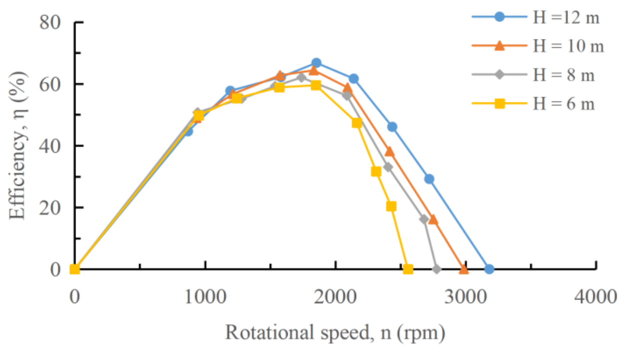

Figure 7. Efficiency of PC300-6 CAT versus rotational speed

https://doi.org/10.25077/jnte.v15n2.1605.2026

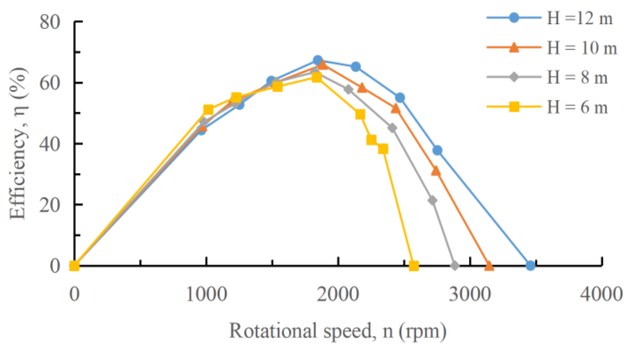

Figure 8. Efficiency of PC400 CAT versus rotational speed

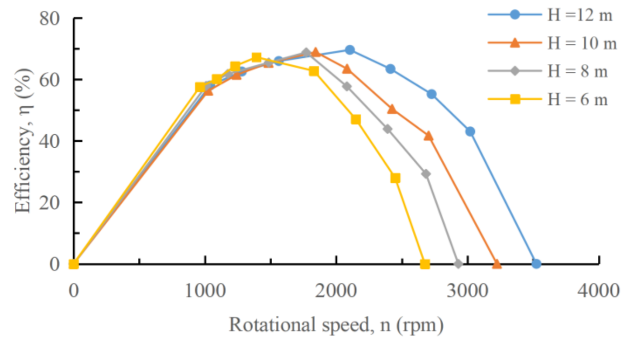

Figure 9. Efficiency of PC500 CAT versus rotational speed

Figures 4–9 show the curve trends of the turbine efficiency of all Garrett PC-type CATs (PC78US-6, PC130-7, PC200-6, PC300-6, PC400, and PC500) at four operating head levels of 6, 8, 10, and 12 m. The graphics show nearly parabolic curves that are close to a quadratic equation, as shown also in [24], indicating that as the rotational speed changes, efficiency adjusts to maintain a perfect balance, likely due to higher volumetric losses at lower speeds and higher hydraulic losses at higher speeds. Across the four head levels, the efficiency–rotational-speed characteristic curves consistently display the typical pattern of common reaction turbine operation: an initial rise in turbine efficiency with increasing rotational speed, reaching a distinct (local) best efficiency point (BEP), and a subsequent gradual decline that ends in a clear drop at a terminal speed limit at a runaway speed without load. In the low-speed regime ($n < 1000$ rpm), the efficiency trend may appear to increase almost linearly. Each local best efficiency value occurs nearly in the middle of the rotational speed range. The charts show that the efficiency values are nearly zero over the ranges of n = 2360–2675 rpm at H = 6 m, n = 2575–2930 rpm at H = 8 m, n = 2710–3220 rpm at H = 10 m, and n = 3020–3525 rpm at H = 12 m.

With an increase in the head level, each individual CAT unit clearly indicates increasing local maximum rotational speeds, growing local peak efficiencies, and broadening local rotational speed ranges for a high-efficiency span. These results may be due to increasing optimal discharges rotating the runner inside the volute. Generally, the highest achieved global performance of the CATs consists of an output of 774 Watt, an efficiency of about 70%, a rotational speed of 3525 rpm, a head of 12 m, and a discharge of 0.009613 m^3/s, as in line with [25]. The local BEPs occur within a narrow speed window of 1750–2100 rpm, where the peak efficiencies of all local curves range from 52% to 70%. This could lead to CAT applications in pico-hydropower systems.

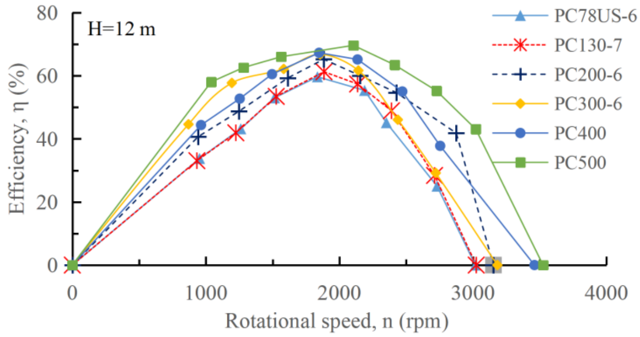

Figure 10. Individual maximum efficiency curves of six CAT types versus rotational speed at a head of 12 m

Figure 10 compares the individual maximum efficiency curves of six examined CAT types as a function of rotational speed at a tested maximum head of 12 m. The curves suggest a quadratic representation following Francis turbine theory, and all models conform to a characteristic parabolic efficiency response shaped by their intrinsic runner hydraulics. Larger units, namely PC300-6, PC400, and PC500, consistently reach higher individual maximum efficiencies in the range of 67–70%, while smaller units (PC78US-6, PC130-7, and PC200-6) achieve slightly lower individual peak values of roughly 60–67%. Across all units, the individual BEP values at a head of 12 m occur within a narrow rotational speed range of around 1835–2100 rpm. This result indicates that the CAT units can deliver quite high-efficiency energy conversion (60–70%) within their optimal operating speed range due to more precise design. Hence, they exceed the previously reported CAT efficiency of 52.7% [24], as well as the BAT efficiency of 50.9% [21] and the PAT efficiency of 38% [20]. At excessive rotational speeds, particularly around 3000–3500 rpm, the efficiency levels decrease sharply, indicating increased turbulence and hydraulic losses. Overall, the figure shows that larger CAT units deliver better efficiency and a wider efficient operating span for pico-hydropower schemes.

In addition, the PC500 shows both the highest global BEP at approximately 70% and the widest high-efficiency operating band ($\eta > 60\%$) at about 1100–2500 rpm, indicating robust performance across varying speeds, whereas smaller CATs display sharper efficiency deterioration at high rpm due to their greater sensitivity to hydraulic conditions. Overall, the chart confirms that CAT performance is essentially affected by size, particularly by runner diameters.

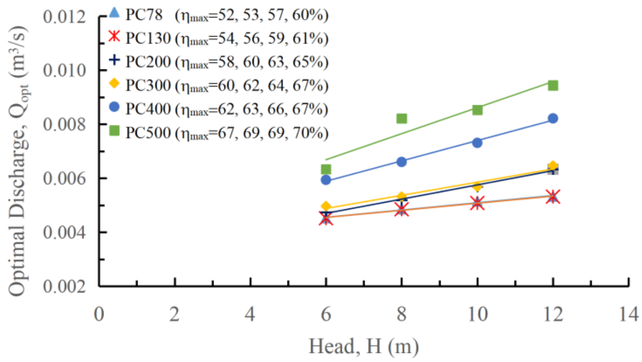

Figure 11. Local optimum discharges versus head levels for six PC-family CATs across the spans of the local peak efficiencies

Figure 11 illustrates specifically the optimum discharge–head relationship for six PC-family CATs, along with their corresponding head–local peak efficiency spans. The discharge–head characteristics indicate that each CAT type operates within a specific discharge window as the head increases from 6 to 12 m for best efficiency. The smaller CAT units (PC78 and PC130) operate optimally at relatively low discharges of 0.004515–0.005316 m³/s, with efficiency spans of 52–61%. Medium-sized units (PC200 and PC300) require slightly higher discharges (0.004736–0.006465 m³/s) and achieve improved efficiencies of 58–67%. Larger units (PC400 and PC500) operate at much higher discharges, reaching 0.005938–0.009442 m³/s, and they provide the highest efficiency span of 62–70%.

The results show that the optimal discharge increases with higher head and larger CAT size, as follows from hydroturbine theory. This indicates that higher hydraulic input is required to achieve a better corresponding operating condition, and that the runner and spiral-case sizes determine the suitable discharge range. In general, each CAT has a specific operating range for the best pico-hydropower applications; thus, proper matching among the head, discharge, CAT size, and the rotational speed plays an important role in achieving the highest power and efficiency.

The previously unreported four-parameter performance graph can serve as a practical guide for selecting a suitable CAT for pico-hydropower schemes when site head and discharge data are available, along with the achievable peak efficiency, to obtain its maximum output power. The best performance parameters would be achieved at its appropriate rotational speed. If the rotational speed is set to a value other than the optimum, the efficiency, which is a crucial hydropower parameter, will drop. This instrument is, of course, precisely applicable only to the Garrett PCxxx family turbocharger compressors as hydroturbines. In practice, for other compressor families, or even for other manufacturers' products, the application is not as straightforward. Hence, special evaluation is required to confirm that the compressor's design specifications are compatible with the best-performance demands of hydroturbine service.

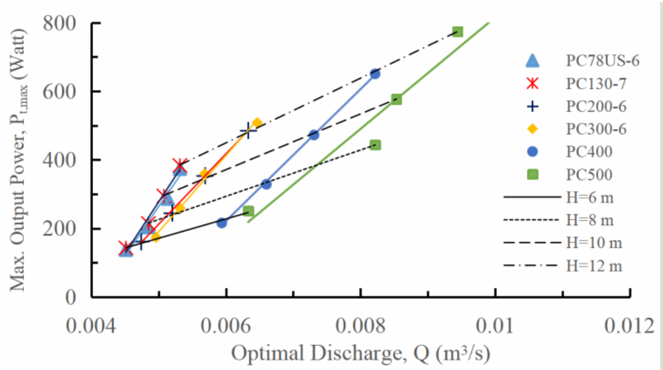

Figure 12. Local maximum output powers of six CAT types versus local optimal discharge at four different head levels.

Figure 12 illustrates the local maximum output powers of each CAT as a function of the optimal discharge for six different CAT types tested under various head levels of 6, 8, 10, and 12 m. The increasing head delivers increasing available hydraulic energy and discharge to each CAT. Based on the test data, each maximum output power value was achieved simultaneously with the highest efficiency. The colored lines in the chart represent the linear trend lines of output power versus discharge data for the same CAT at four different head levels, while the black linear lines represent that relationship for the six different CATs used at the same head level. This result indicates that, with a constant head, increasing the hydraulic discharge rate by opening the control gate valve leads to linearly increasing output power levels for larger CATs. Moreover, by increasing the head, the hydraulic discharge levels increase linearly, and so do the output power levels for all CATs. To further increase the discharge rate (Q) and, therefore, the output power level, the test results recommend using the larger CATs, allowing them to enable more flow and extract more hydraulic energy for greater output power (P_t). This is consistent with the equation $P_t = \eta \cdot \gamma_w \cdot Q \cdot H$. The four-parameter map has not been presented in previous CAT studies [24], [25].

The chart shows that the PC78US-7 and PC130-6 CATs delivered almost the same discharge and power characteristics at the lowest levels for all steadily controlled head levels due to their almost identical dimensions. In terms of discharge and output power, the chart also shows that the PC200-6 delivered slightly lower output than the PC300-6, but their outputs were higher than the two smallest CATs mentioned above. The PC400 exhibits much better output at 750 Watt than the other four smaller CATs. The ultimately highest power produced was 774 Watt, achieved by the largest CAT of the PC500, with an efficiency of 70% at a head level of 12 m and a discharge rate of 0.009442 m³/s.

The obtained graph is also useful for selecting a suitable CAT model based on the available site discharge, used as the optimal discharge data and maximum power output target. Smaller CAT units are more appropriate for low-flow pico-hydro sites, while larger units such as the PC400 and the PC500 are more suitable for higher-flow sites that enable higher power generation. The figure shows that each CAT has a specific operating range for pico-hydropower applications, and proper matching among the head, discharge, and CAT size plays an essential role in achieving the highest output power.

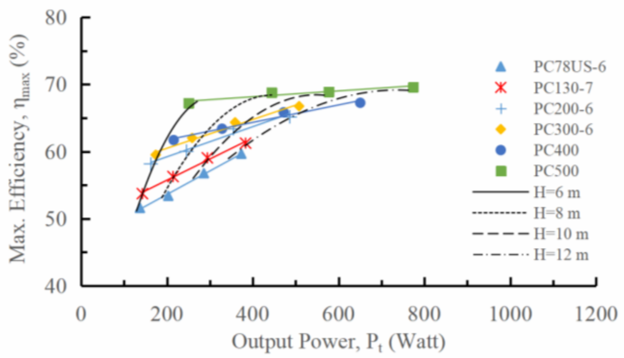

Figure 13. Local maximum efficiency values of six CAT types versus local maximum output power at four different head levels.

Figure 13 presents the efficiency–output-power characteristics for six CAT units at different head levels of 6, 8, 10, and 12 m. As mentioned above, based on the test data, each maximum output power value was achieved simultaneously with the highest efficiency. The black and colored lines in the chart represent the linear and polynomial trend lines of the efficiency versus output power relationship for the same CAT at different head levels and

https://doi.org/10.25077/jnte.v15n2.1605.2026

for the same head across different CATs, respectively. Trend-line analysis has shown very strong polynomial curve-fitting correlations, with R^2 of 0.9258–0.9493. In general, this result indicates that, at a constant head, increasing output power by opening the control gate valve leads to a nonlinearly increased efficiency for larger CATs. At an increased head, by increasing the output power level, the efficiency improves linearly for all CATs. To further increase the power level and, therefore, the efficiency value, the test results imply the use of larger CATs, allowing them to experience less flow friction and turbulence when extracting hydraulic energy for output power.

The figure indicates that CAT efficiency generally improves with increasing power, suggesting that the CATs run more effectively and efficiently as the hydraulic head and flow better match the runner size and rotational speed. The smaller CAT models, particularly PC78, PC130, and PC200, generate lower output power, indicating that their individual maximum efficiencies are generally between approximately 52–65%. By comparison, the larger CATs, such as PC300, PC400, and PC500, produce higher power output and exhibit improved efficiency (60–70%). The CAT of PC400 operates over a broader range, retaining favorable efficiency with increasing power. The CAT of PC500 shows individual maximum efficiencies in the range of approximately 67–70% at produced power levels of 251–774 Watt.

These findings in the new CAT power-efficiency map suggest that higher-capacity CATs offer superior hydraulic input matching and energy-extracting efficiency, making them more suitable for pico-hydropower units that require higher output power. Hence, appropriate sizing is crucial to prevent underloading, overspeeding, or operating far from the BEP.

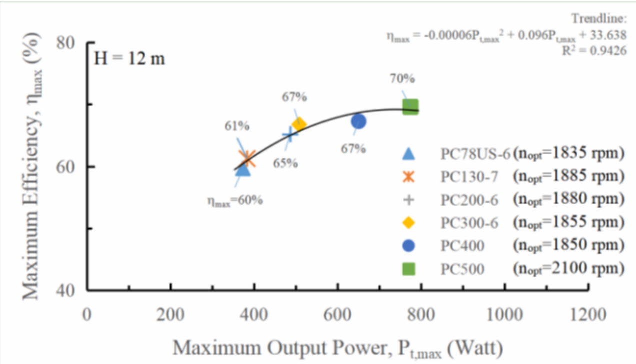

Figure 14. Individual maximum efficiency values of six CATs from a single product family versus individual maximum power

Figure 14 presents the special performance characteristics of individual maximum efficiency values versus individual maximum output power for all six Garrett PC-family CAT units tested at optimum rotational speeds. In this test, the maximum output power was simultaneously accompanied by the best efficiency, and the best efficiency values of all CATs tested were actually achieved at a head of 12 m. The smaller-sized CATs of PC78US-6 and PC130-7 generate maximum output powers of about 373–383 Watt, accompanied by top efficiency values of approximately 60–61% at nearly the same discharge of 0.005316 m^3/s and rotational speeds of 1835–1885 rpm. The medium-sized CATs of PC200-6 and PC300-6 produce higher output power, delivering around 486–508 Watt, along with top efficiency values of approximately 65–67% at discharges of 0.006331–0.006465 m^3/s and rotational speeds of 1855–1880 rpm. The larger-sized CATs of PC400 and PC500 deliver much higher power, reaching around 651–774 Watt, which occurs simultaneously with top efficiency values of approximately 67–70% at discharges of 0.008216–0.009442 m^3/s and rotational speeds of 1850–2100 rpm. Ultimately, the PC500 CAT achieved the highest individual maximum performance, with $P_{t,max}$ = 774 Watt and η_{max} = 70% at H = 12 m, Q_{opt} = 0.009442 m^3/s , and n_{opt} = 2100 rpm. With the energy conversion to the electrical power using a generator with an efficiency of 95%, the achieved output powers of 373–774 Watt would decrease to approximately 354.6–735.3 Watt.

This result generally indicates that larger CATs allow better runner and volute sizing to maximize the extraction of available hydraulic energy. The characteristic also shows that the efficiency enhancement increases slightly as output power increases significantly, implying that the efficiency approaches an upper performance limit point (probably at 70%) for the Garrett PC-family air-compressor products when used as water turbine units. The maximum power-efficiency map, which has not been systematically presented before, is also useful for selecting the Garrett PC-family CATs according to the targeted maximum output power and the expected best efficiency under an available head condition of 12 m. Smaller CATs are appropriate for lower-output pico-hydropower plants, while larger ones, such as PC400 and PC500, are more suitable for higher-power, better-efficiency pico-hydro applications. The increase in best efficiency with improved maximum output power occurs because larger CATs feature wider flow passages, larger runner diameters, and a greater capacity to convert hydraulic energy. These features improve the matching between water flow, blade peripheral speed, and runner geometry, resulting in more effective energy extraction.

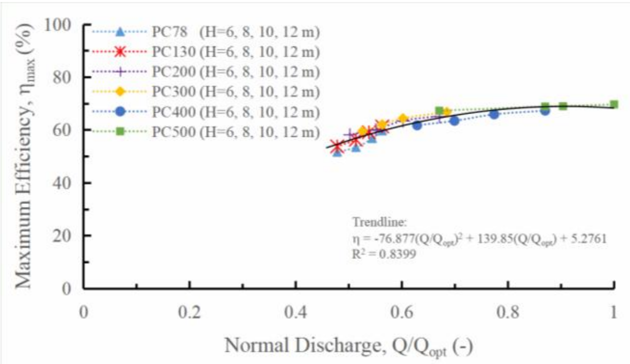

Figure 15. Local maximum efficiency values of six CAT units from a single product family versus normal discharge

Figure 15 illustrates the characteristics of the local maximum efficiency values for all CAT units versus the normal discharge tested under different head levels of 6, 8, 10, and 12 m at certain optimal rotational speeds. The term "normal discharge" used here refers to the optimum discharge delivered to the PC500 CAT during the test at a head of 12 m. All local best efficiency values for the CATs are plotted against the normal discharge, forming a parabolic trend line within the efficiency span of 52–70%. In general, the chart shows that the local best efficiency values improve with the normal discharge and then tend to experience a less steep rate at higher normal discharges, suggesting that an upper efficiency limit (again, probably at 70%) has already been reached for the Garrett PC-family CATs.

Smaller CATs, particularly PC78 and PC130, run with the lower discharge, while larger ones, such as PC400 and PC500, operate with higher discharge to achieve their best efficiency. Despite their distinct runner and volute sizes, all Garrett PC-family turbocharger CAT models follow a relatively similar trajectory line of increasing efficiency, which suggests that all CATs tested demonstrate highly comparable hydraulic characteristics. The polynomial trend line exhibits the overall tendency of efficiency–discharge in the CAT family, with a high R^2 value of 0.8399, indicating a reasonably strong efficiency–discharge correlation. This result shows that discharge is a primary factor in selecting an appropriate CAT for pico-hydropower systems. Again, smaller CATs are more suitable for lower-discharge conditions, while larger units are better matched to sites with higher flow.

Although this indication is not complete proof of the similarity of the CATs, it can be considered supporting evidence. The polynomial trend line, with its high R^2 value, also suggests that the six Garrett PC-product family CATs exhibit relatively similar characteristic patterns with respect to normal discharge. This may be caused by the fact that they belong to a product family with similar geometry and flow design principles. To further scientifically indicate the similarity, it would be recommended to include nondimensional analysis, such as the coefficients of flow, head, and power; the specific velocity; or runner and volute geometry ratios. Moreover, the maximum efficiency versus the normal discharge map of CATs has not been systematically reported in previous studies, including in [24] and [25].

For summary, the power-efficiency performance of CATs for pico-hydropower plants has been experimentally evaluated based on the CAT model/size, head, discharge, and rotational speed, providing the appropriate operating window as a practical performance map for matching a specific CAT unit with pico-hydro site conditions that have different water-head and discharge characteristics. This thereby reduces the risk of selecting an undersized or oversized turbine with low efficiency and output power.

CONCLUSIONS

Experimental power and efficiency investigations of compressors as turbines (CATs) for pico-hydropower plants using different models from a single turbocharger compressor product family have already been conducted. Commercial turbocharger compressors can be practically repurposed as low-cost pico-hydroturbines with quite high efficiency, whereas the selected unit, with expected output power at high efficiency, is carefully matched to the water head, discharge, and rotational speed.

The six geometrically almost-similar CAT units from the same Garrett PCxx turbocharger product family at four different low head levels have been tested and specially analyzed using several four-parameter relationships between optimal discharge and head, local maximum power and optimal discharge, local maximum efficiency and power, individual maximum efficiency and power, and local maximum efficiency and normal discharge.

All CAT units exhibit the characteristic parabolic efficiency–rotational-speed relationship of Francis-type turbines. The power and efficiency performance of the CATs was significantly affected by runner size, hydraulic head, flow discharge, and rotational speed. Larger CAT units generally achieved higher individual maximum power outputs and individual peak efficiencies. The resulting test graphics can be used as a practical guideline for selecting a suitable CAT model for target pico-hydro sites based on the available hydraulic head, discharge, and rotational speed. Based on this study, low-cost turbocharger compressors used as turbine alternatives have favorable prospects for pico-hydro systems.

Further CAT investigation should be expanded to other families of compressor products under the same trademark and from other companies to meet pico-hydropower conditions up to 5 kW, and to develop a wider selection map for matching type/size, water head and discharge, efficiency, as well as target output power. Future applied studies should also develop efficient runner and spiral-case designs for reverse-flow operation by employing low-cost trimming for runner blades, spiral-case passage streamlining, inlet-angle settings, and surface smoothings to reduce leakage, turbulence, and friction losses, thereby increasing maximum energy conversion. This may significantly improve efficiency up to the conventional Francis turbine BEP, extend the operating range, and adapt mass-produced compressors to cover low-cost turbine requirements. Furthermore, CAT similarity evaluation for the same compressor product family should involve nondimensional analysis with the coefficients of flow, head, and power, the specific speed, and the runner and volute dimension ratios to predict scalable performance of a CAT without assessing all compressors experimentally.

ACKNOWLEDGMENTS

This study was facilitated by the Fluid Dynamics Laboratory, Mechanical Engineering Department, Engineering Faculty, Universitas Andalas.

REFERENCES

[1] M. Bazilian, P. Nussbaumer, H. H. Rogner, A. Brew-Hammond, V. Foster, S. Pachauri et al., "Energy access scenarios to 2030 for the power sector in sub-Saharan Africa," Utilities Policy, vol. 20, no. 1, pp. 1–16, Jan. 2012. Available: DOI: 10.1016/j.jup.2011.11.002. [Accessed Jul. 1, 2023]

[2] U.S. Energy Information Administration, "Electric generation transforms primary energy into electricity," Today in Energy, Sep. 5, 2019. Available: https://www.eia.gov/todayinenergy/detail.php?id=41193. [Accessed Jul. 11, 2026]

[3] Energy Institute, "Statistical Review of World Energy 2025," Energy Institute, London, 2025. Available: https://www.energyinst.org/statistical-review. [Accessed Jul. 11, 2026].

[4] International Hydropower Association, "2025 World Hydropower Outlook," International Hydropower Association, London, 2025. Available:

https://doi.org/10.25077/jnte.v15n2.1605.2026

https://www.hydropower.org/publications/2025-world-hydropower-outlook. [Accessed Jul. 11, 2026].

[5] D. Singh, Micro Hydro Power Resource Assessment Handbook, Asian and Pacific Centre for Transfer of Technology of the United Nations Economic and Social Commission for Asia and the Pacific, 2009. Available: https://www.apctt.org/sites/default/files/2020-08/Micro%20Hydro%20Power%20Resource%20Assessment%20Handbook.pdf. [Accessed Jul. 11, 2026].

[6] I. Imawati, G. I. Kurniawan, M. R. Ghifari, M. Nauval, F. Arisandi, H. Setiawan, and H. Mubarok, "Harnessing sustainable energy: Portable pico-hydro power generation using an undershoot water wheel turbine in irrigation canals," Jurnal Nasional Teknik Elektro, vol. 14, no. 2, pp. 52–62, Jul. 2025. Available: DOI: 10.25077/jnte.v14n2.1252.2025. [Accessed Jul. 11, 2026].

[7] P. Maher, N. Smith, and A. Williams, "Assessment of pico hydro as an option for off-grid electrification in Kenya," Renew. Energy, vol. 28, pp. 1357–1369, July 2003. Available: DOI: 10.1016/S0960-1481(02)00149-8. [Accessed Jul. 1, 2023]

[8] S. Mishra, S. K. Singal, and D. K. Khatod, "Optimal installation of small hydropower plant – A review," Renew. Sustain. Energy Rev., vol. 15, no. 8, pp. 3862–3869, Nov. 2011. Available: DOI: 10.1016/j.rser.2011.07.012. [Accessed Jul. 1, 2023]

[9] K. Kusakana, "A survey of innovative technologies increasing the viability of micro hydropower as a cost-effective rural electrification option in South Africa," Renew. Sustain. Energy Rev., vol. 37, pp. 370–379, Sept. 2014. Available: DOI: 10.1016/j.rser.2014.05.011. [Accessed Jul. 1, 2023]

[10] C. S. Kaunda, C. Z. Kimambo, and T. K. Nielsen, "A technical discussion on microhydropower technology and its turbines," Renew. Sustain. Energy Rev., vol. 35, pp. 445–459, July 2014. Available: DOI: 10.1016/j.rser.2014.04.034. [Accessed Jul. 1, 2023]

[11] K. Motwani, S. Jain, and R. Patel, "Cost analysis of pump as turbine for pico hydropower plants−A case study," Procedia Eng., vol. 51, pp. 721–726, 2013. Available: DOI:10.1016/j.proeng.2013.01.102.[Accessed Jul 1, 2023]

[12] M. A. Ismail, A. K. Othman, S. Islam, and H. Zen, "End suction centrifugal pump operating in turbine mode for microhydro applications," Adv. Mech. Eng., vol. 6, pp. 1–7, 2014. Available: DOI: 10.1155/2014/139868. [Accessed Jul. 1, 2023]

[13] M. Arriaga, "Pump as turbine – a pico hydro alternative in Lao People's Democratic Republic," Renew. Energy, vol. 35, pp. 1109–1115, Apr. 2010. Available: DOI: 10.1016/j.renene.2009.09.015. [Accessed Jul. 1, 2023]

[14] S. V. Jain and R. N. Patel, "Investigations on pump running in turbine mode: A review of the state of the art," Renew. Sustain. Energy Rev., vol. 30, pp. 841–868, Feb. 2014. Available: DOI: 10.1016/j.rser.2013.10.049. [Accessed Jul. 1, 2023]

[15] S. Derakhshan and A. Nourbakhsh, "Theoretical, numerical and experimental investigation of centrifugal pumps in reverse operation," Exp. Therm. Fluid Sci., vol. 32, pp. 1620–1627, Oct. 2008. Available: DOI: 10.1016/j.expthermflusci.2008.05.008. [Accessed Jul. 1, 2023]

[16] J. Fernandez, E. Blanco, J. Parrondo, M. Stickland, and T. Scanlon, "Performance of a centrifugal pump running in inverse mode," Proc. IMechE Part A: J. Power Energy, vol. 218, pp. 265–271, Apr. 2004. Available: DOI: 10.1243/0957650041200632. [Accessed Jul. 1, 2023]

[17] S. Derakhshan and A. Nourbakhsh, "Experimental study of characteristic curves of centrifugal pumps working as turbines in different specific speeds," Exp. Therm. Fluid Sci., vol. 32, no. 3, pp. 800–807, Feb. 2008. Available: DOI: 10.1016/j.expthermflusci.2007.10.004. [Accessed Jul. 1, 2023]

[18] S. S. Yang, S. Derakhshan, and F. Y. Kong, "Theoretical, numerical and experimental prediction of pump as turbine performance," Renew. Energy, vol. 48, pp. 507–513, Dec. 2012. Available: DOI: 10.1016/j.renene.2012.06.002. [Accessed Jul. 1, 2023]

[19] M. Binama, W. T. Su, X. B. Li, F. C. Li, X. Z. Wei, and S. An, "Investigation on pump as turbine (PAT) technical aspects for micro hydropower schemes: A state of the art review," Renew. Sustain. Energy Rev., vol. 79, pp. 148–179, Nov. 2017. Available: DOI: 10.1016/j.rser.2017.04.071. [Accessed Sept. 18, 2025]

[20] A. N. Bachtiar, I. Yusti, F. Pohan, Santosa, I. Berd, and U. Gatot, "Performance of a centrifugal pump as a pico hydro scale turbine," Adv. Appl. Sci., vol. 4, no. 4, pp. 88–96, Oct. 2019. Available: DOI: 10.11648/j.aas.20190404.11. [Accessed Dec. 5, 2020]

[21] A. N. Bachtiar, A. F. Pohan, I. Yusti, R. Ervil, Santosa, I. Berd, and U. G. S. Dinata, "Effect of head variations on performance four sizes of blowers as turbines (BAT)," Int. J. Renew. Energy Res., vol. 10, no. 1, pp. 343–353, Mar. 2020. Available: DOI: 10.20508/ijrer.v10i1.10482.g7879. [Accessed May 8, 2020]

[22] A. N. Bachtiar, A. F. Pohan, R. Ervil, Nofriadiman, Santosa, I. Berd, and U. G. S. Dinata, "Effect of geometric differences impeller blades on performance blower-as-turbine (BAT) on pico-hydro scale," Int. J. Renew. Energy Res., vol. 11, no. 3, pp. 1124–1135, Sep. 2021. Available: DOI: 10.20508/ijrer.v11i3.11943.g8243. [Accessed Jan. 10, 2022]

[23] U. G. S. Dinata, A. Hasan, P. Fithri, A. Suresti, and R. Wati, "Analysis of a portable generator turbine for small and medium industry by using a business model approach," Qual.-Access Success, vol. 25, no. 200, pp. 274–280, May 2024. Available: DOI: 10.47750/qas/25.200.28. [Accessed Aug. 18, 2024]

[24] A. N. Bachtiar, A. F. Pohan, Santosa, I. Berd, and U. G. S. Dinata, "Performance on compressor as turbine (CAT) piko hydro scale," Int. J. Renew. Energy Res., vol. 9, no. 4, pp. 2073–2081, Dec. 2019. Available: DOI: 10.20508/ijrer.v9i4.9331.g7830. [Accessed Jan. 15, 2020]

[25] Y. Hizhar, U. G. S. Dinata, D. A. Saputra and A. Suryadi. "Experimental study of head variations on the mechanical performance of a compressor as turbine (CAT)," in Proc. ISAIME-2025, 8-9 October 2025, Padang, Indonesia. Available: Journal of Physics: Conference Series 3186 (2026) 012047, IOP Publishing. Available: DOI:10.1088/1742-6596/3186/1/012047. [Accessed: Apr. 1, 2026]

NOMENCLATURE

CAT	Compressor as Turbine	
BAT	Blower as Turbine	
PAT	Pump as Turbine	
BEP	Best Efficiency Point	
Max	maximum	
A	inducer diameter	mm
B	exducer diameter	mm
C	blade height	mm
D	inlet diameter	mm
E	outlet diameter	mm
p_i	inlet pressure	bar
H	head	m
Q	discharge	m^3/s
n	rotational speed	rpm
F	braking load	N
T	shaft torque	Nm
Q_{opt}	optimal discharge	m^3/s
Q/Q_{opt}	normal discharge ratio	-
n_{opt}	optimal rotational speed	rpm
P_w	water input power	Watt, W, kW
P_t	turbine output power	Watt, W, kW
$P_{t,max}$	maximum turbine output power	Watt, W, kW
r	pulley radius	m, mm
h	water level	m, mm
R^2	curve-fitting correlation	-

Greek Letters:

η	turbine efficiency	%
η_{max}	maximum turbine efficiency	%
γ_w	water specific weight	N/m^3
ω	angular velocity	rad/s

AUTHOR(S) BIOGRAPHY

Yul Hizhar

is a researcher in the Department of Mechanical Engineering, Faculty of Engineering, Universitas Andalas. He is a team member working on research into renewable energy and micro- and pico-scale hydropower applications. He is focused on studying pico-hydropower applications, turbine performance, experimental hydrotesting, and the use of turbocharger components for inexpensive energy schemes. In this work, he contributed to the experimental measurement and evaluation of CAT parameters under various hydraulic-head conditions.

Uyung Gatot Syafrawi Dinata

is a senior lecturer and researcher in the Department of Mechanical Engineering, Faculty of Engineering, Universitas Andalas. He conducts research primarily in the fields of renewable energy engineering, experimental turbomachinery, pico-hydropower schemes, wind tunnel testing, and wind energy conversion. His work includes the improvement and examination of alternative turbine schemes for small-scale hydropower and wind energy conversion. In this research, he contributed to the research concept, experimental analysis, and the interpretation of CAT performance for pico-hydropower plants.

Dendi Adi Saputra

is a lecturer and researcher in the Department of Mechanical Engineering, Faculty of Engineering, Universitas Andalas. He is a research team member working on experimental investigations of renewable energy conversion and small-scale hydropower. He is interested in studies of CAT schemes, fluid-thermal measurement, data acquisition systems, and laboratory-scale turbomachinery testing. In this work, he contributed to the experimental setup, measurement activities, and performance testing of CAT systems at varying head levels.

https://doi.org/10.25077/jnte.v15n2.1605.2026