



RESEARCH ARTICLE

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EXPERIMENTAL PERFORMANCE EVALUATION OF A PUMP-AS-TURBINE SYSTEM WITH EXPERIMENTAL VALIDATION, BEP IDENTIFICATION, AND UNCERTAINTY

Abhijit A. Patil^{*1}, Rupesh J. Patil² and Ravibala A. Patil³

¹Department of Mechanical Engineering, JSPM Rajarshi Shahu College of Engineering, Tathawade, India.

²Department of Mechanical Engineering, Trinity Academy of Engineering, India.

³Department of Mechanical Engineering, Sinhgad Academy of Engineering, India.

¹<https://orcid.org/0009-0000-6971-5061>, ²<https://orcid.org/0000-0002-3604-9290>, ³<https://orcid.org/0000-0001-8781-4506>

E-mail: *abhijitpatil.mech@gmail.com, rupesh1002001@yahoo.com, ravibala.mech@gmail.com

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ABSTRACT

The paper includes an extensive experimental investigation of a Pump-as-Turbine (PAT) system under controlled laboratory conditions with rigorous calibration and validation of uncertainty. A test facility was established as a completely equipped closed loop test facility to test the hydraulic head, discharge, rotational speed, electrical output and the efficiency. Three rotational speed conditions were also applied to have the performance characteristics with nominal heads of 8 m, 10 m, and 12 m. (H-Q) curves verified the anticipated inverse hydraulic performance whereas the efficiency (η -Q) characteristics demonstrated different Best Efficiency Points (BEPs). Low, medium, and high speeds had peaked efficiencies of 0.67, 0.75 and 0.80 at discharges of 0.054 m³/s, 0.057 m³/s and 0.060 m³/s respectively. The electrical output rose up to 2.6 kW at low speed to almost 5.9 kW at high speed in line with turbomachinery affinity laws. Time-series monitoring was used to provide stability in data acquisition in the steady-state, and uncertainty propagation with the KlineClintock method reported a total efficiency uncertainty within a variation of $\pm 3\%$. The findings prove that the experimental system derived can offer a credible and physically consistent data of PAT performance that can be optimized and used in micro-hydropower.



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I. INTRODUCTION

Research in small-scale hydropower technologies has been accelerated by the growing world need of decentralized and sustainable energy solutions. Out of the many methods available to use in low-head and micro-hydropower generation, the reverse working centrifugal pumps popularly known as Pump-as-Turbine (PAT) has proven to be a cost efficient and technically feasible way of using turbines as an alternative to the traditional turbine systems. Some of the benefits associated with PAT systems are the low cost of capital, broad commercial access, standard production, and the fact that it requires minimal maintenance [1-3]. The following characteristics make PAT technology especially appealing in the application in distributed generation, in rural electrification, irrigation canals, industrial water networks, and in energy recovery in pressurized water systems. Although PAT systems are economically attractive, their hydraulic and energy conversion properties are very dissimilar to standard turbines intended with the purpose of generating power. When a centrifugal pump is run in the reverse mode, the internal flow arrangement, the angle of incidence of the blades, and pressure distribution change significantly. Consequently, performance parameters like head, discharge, efficiency and power output cannot be directly deduced by pump-mode characteristics without extensive research [3]. This means that to have the correct performance prediction, then systematic experimental validation with workable data reduction techniques are necessary. In the last decade, a variety of studies have tried to model and predict the PAT performance based on empirical correlations, and computational fluid dynamics (CFD) techniques along with semi-analytical techniques.

There is however much variation in reported values of efficiency, Best Efficiency Point (BEP) location and part-load behavior mainly because various experimental arrangements, measurement and quality of calibration are different [4]. In most instances, instrumentation accuracy and uncertainty quantification are not considered adequately and hence the differences in experimental and numerical result occur. As a result, there is still need to perform well-instrumented experimental works that also describe PAT hydraulic and electrical performance and on the other hand strictly examines measurement reliability by calibration and uncertainty analysis. Discharge, head and rotational speed are the main determining factors in the performance of a PAT system. As per the laws of turbomachinery affinity, the proportion of head and the square of rotational speed are equal, whereas the proportions of power and the cube of rotational speed are cubic. But, actual systems do not follow ideal affinity relations because of hydraulic losses, turbulence, effects of blade geometry and behaviour of draft tube [3-5]. In addition, the presence and movement of the Best Efficiency Point under different operating conditions are also pertinent elements of realistic application of PAT system in the variable-flow conditions. It is thus important to understand the specifics of $H-Q$ (head-discharge), but equally $(\eta-Q)$ (efficiency-discharge) and $P-Q$ (power-discharge) properties in order to select, operate and integrate PAT technology into micro-hydropower schemes optimally. Uncertainty propagation is another important factor that is not taken seriously in PAT research [6] [7]. Derived quantities e.g. hydraulic power, efficiency require various parameters which are measured e.g. discharge pressure, voltage, and current. The mistakes in these initial measurements are nonlinearly reflected into final performance indicators. Performance curves can be given an illusion of accuracy without systematic uncertainty assessment, which does not give them a statistical basis.

The Kline-McClintock technique is a systematic way of measuring the compound impact of measurement errors on parameters deduced and is generally embraced in the study of experimental fluid mechanics and turbomachinery. Le et al. [8] tested the extent to which the existing PAT performance correlations predict the turbine-mode characteristic curves and the Best Efficiency Point (BEP). The authors compared various published correlations with measured $H-Q$ and $(\eta-Q)$ trends using a special test rig and highlighted the importance of database-based calibration. The paper concludes that the accuracy of correlation is significantly better when large and heterogeneous datasets are available and that correlation-only prediction in the absence of experimental anchoring may lead to significant BEP and curve-shape errors, particularly in variable speed operation. Bantelay et al. [9] came up with a more physics-based method of predicting PAT head, torque, power, and efficiency through the explicit modeling of energy losses in components. A non-dimensional prediction framework was suggested and was compared to performance estimates of a wide range of flows. The overall finding is that the decomposition and quantification of individual losses offers more explainable and transferable prediction behavior than empirical scaling alone, and that it can be used to map performance across off-design flow rates better - supporting more justifiable PAT selection and estimate energy recovery. Lin et al. [10] estimated the turbine-mode BEP of centrifugal pumps working as turbines by an impellervolute matching principle and to confirm the method by experiments and computer simulation. The research finds that the suggested BEP prediction technique can attain small prediction errors (stated as less than several percent in the article) when tested on a variety of pumps and loss distributions throughout PAT parts elucidate BEP variations in varying rotational speeds.

The article advocates the integration of theory + experiments to prevent the excessive use of generalized correlations. The purpose of the reviewed study by Nasir et al. [11] was to synthesize the existing research on PAT in terms of performance prediction techniques, performance enhancement mechanisms, and economic aspects of pico/micro-hydropower implementation. It concludes that the greatest practical obstacle is still reliable selection and turbine-mode performance estimation since manufacturers can hardly publish turbine-mode curves. The review further points out that efficiency is generally lower than purpose-built turbines and therefore research is increasingly aimed at better prediction models and specific design changes to increase efficiency and increase the range of stability operation as well as economic viability analysis of actual installations. The purpose of the study by Bantelay et al. [12] was to learn about PAT start-up transient behavior and to measure the variation of the main variables (e.g., speed, head, flow) during start-up. In order to capture transient characteristics and internal flow changes, the authors employed a test rig and a computational analysis. The conclusion of the paper is that start-up causes powerful transient deviations when compared with steady-state expectations, and these transients may cause increased higher loads and non-steady hydraulic responses, which are pertinent to safe operation, control practices, and realistic performance prediction in non-steady conditions. Yang et al. [13] conducted research on the mechanism through which a PAT transforms pressure energy to mechanical output, focusing on internal energy transfer and factors that influence recoverable power. The paper finds that internal flow structure and interaction between the impellers are strongly controlling factors in PAT energy conversion, i.e. that to increase energy recovery, not only choice of operating point but also further consideration of flow mechanisms that define losses and stability are important.

The results uphold more mechanistic optimization policies other than mere empirical curve fitting, especially in the performance enhancement and operating envelopes that are robust. Zhang et al. [14] look at unusual PAT start-up response and determine what causes temporary effects in flow rate and outlet pressure during acceleration. The paper concludes that the effects of rotational acceleration are a significant source of transient anomalies, which generate the effect of impact-like behaviors in measured curves and changes the dimensionless behavior as compared to steady-state interpretation. These results point to the fact that transient start-up is not a mere extension of steady-state behaviour, and that start-up behaviour must be considered in the development of test procedures, protection schemes and operational planning of PAT installations. Wang et al. [15] introduced an experimental research to evaluate the effect of a modified impeller/blade concept on the efficiency of PAT with similar head and flow conditions. It is concluded in the paper that the offered idea of an impeller can provide a quantifiable increase in efficiency compared to the control setting within the conditions of the experiment, which confirms the practical value of a specific change in the blades/impeller structure to improve the PAT performance. The research supports the notion that the efficiency and operating range can be changed by geometry variations and that they ought to be confirmed in an experimental setting since the advantage varies based on the interaction of inner flow structures, incidence, and losses. Nasir et al. [16] assessed the feasibility of PAT in micro-hydropower by integrating both technical performance and economic aspects, such as the situation with and without the impeller/blade modification.

It finds that PAT is a possible solution to MHP when cost limitations are the main factor, yet realistic energy output and payback rely on appropriate performance estimation and appropriate choice/operation. The paper underlines how design change can enhance technical performance but it needs to be economically justified and as such selection procedures need to incorporate performance and cost to prevent the optimistic feasibility statements. Even though Pump-as-Turbine (PAT) systems are extensively studied in the context of micro- and small-scale hydropower systems, there are a number of gaps in the research that are still critical in the area of experimental validation. The current literature is limited by the fact that the hydraulic and electrical performance assessment is not effectively integrated into one validated framework. The current research is able to resolve these difficulties by designing and testing a fully instrumented PAT experimental test station that is capable of performing controlled hydraulic and electrical tests. The system is set up in a closed loop water circulation system to allow steady and repeatable conditions of operation. Electromagnetic flowmeters of high accuracy, calibrated pressure transmitters, non-contact digital tachometers, and confirmed electrical measurement tools are utilized to measure all the required parameters. To reduce systematic error a systematic calibration protocol with certified reference devices is used before experimentation. The study aims at describing the specific nature of performance of PAT at different rotational speeds. $H-Q$, $\eta-Q$, and $P-Q$ comparative curves are constructed to assess hydraulic behaviour, energy conversion efficiency and scaling of electrical output. Best Efficiency Point is determined under each condition of speed and the change with operating parameters is discussed. The time-series stabilization monitoring is undertaken to maintain steady-state data acquisition and uncertainty propagation analysis is done to measure the reliability of measurements. The main aim of this research is not just to produce experimentally validated performance curves but to develop a strict framework of methodology, which will combine calibration, stabilization check, uncertainty measurement, and energy conversion analysis into a unified, consistent, experimental design.

II. EXPERIMENTAL TEST SETUP AND METHODOLOGY

II.1 EXPERIMENTAL FACILITY DESCRIPTION

The experiments were conducted under the Pump-as-Turbine (PAT) test facility that was fully developed and was used to conduct controlled experiments on hydraulic, mechanical, and electrical performance under laboratory conditions. System was set up in closed loop water circulation system to make it run continuously and control operating parameters accurately. The system is made up of a storage reservoir, a service pump to provide pressurized water, a bypass line to control discharge, an electromagnetic flowmeter to measure discharge, inlet and outlet pressure transmitters to determine the head, a draft tube to recover the pressure, and a PAT unit to be mechanically coupled with a DC generator by a flexible coupling. Variable resistance load bank was used to regulate the electrical output. The complete assembly was fixed on a hard steel base frame in order to reduce vibration and errors in alignment. A closed-loop system was used, which guaranteed the stability of hydraulic conditions and reduced external disturbances.



Figure 1: Experimental test setup (1) Reservoir, (2) Service pump, (3) Flow control valve, (4) Bypass line, (5) Electromagnetic flow meter, (6) Pressure transmitter, (7) Draft tube, (8) Pat, (9) DC generator, (10) Load cell, (11) DAQ.

Source: Authors, (2026).

II.2 INSTRUMENTATION AND MEASUREMENT SYSTEM

To characterize the performance of Pump-as-Turbine (PAT) accurately, hydraulic, mechanical and electrical parameters must be measured accurately. A set of measurement instruments was carefully selected and incorporated into the experimental facility, with each instrument being selected according to the operating range, resolution, response time, and compatibility with the laboratory-scale hydropower testing. To reduce the disturbances of the flow, the discharge was measured with the help of an electromagnetic flowmeter placed in the upstream pipeline section. The choice of an electromagnetic flowmeter was driven by the fact that it is a non-intrusive method of measurement, has no contribution to pressure loss, and is quite accurate in conductive fluids like water.

The device can give a volumetric flow measurement that is independent of changes in fluid density and less sensitive to changes in temperature than mechanical flowmeters. The measurement range was chosen to fully cover the anticipated range of variation of discharge throughout the low, medium and high-speed trials to allow sufficient sensitivity even at part load conditions. Calibrated pressure transmitters at the inlet and outlet of the PAT were used to measure the static pressure at these points to ensure that the correct values of the static head were recorded with minimum effects of the dynamic pressure. The transmitters were chosen in accordance with the pressure rating, linearity, and low hysteresis features. Correct installation of impulse lines and air purging was done to prevent distortion in measurements because of trapped air or oscillation of the column of water. These pressure readings are the foundation of net hydraulic head determination and they have a direct bearing on hydraulic power determination. A non-contact digital tachometer was used to measure rotational speed since it was preferable to avoid mechanical loading or frictional interference with the rotating shaft. The principle of optical sensing is used to provide a proper measurement in the 9001500 rpm operating range, and the temporal resolution is high and capable of transient sensing in the process of stabilization. The electrical output parameters were measured in a set of calibrated voltmeter-ammeter across the DC generator terminals. A digital power analyzer was cross-validated to ensure that the accuracy of electrical measurements is correct and the cumulative instrumentation error is kept at a minimum. This analyzer enabled the verification of voltage, current and computed power under different load conditions.

III. EXPERIMENTAL PROCEDURE

Before every trial of the experiment, the system was carefully checked to remove air entrapment, leakage and mechanical misalignment. The reservoir was filled and the service pump primed so that the hydraulic circulation became stable. To avoid the immediate increase in pressure, the bypass valve was first opened and then slowly regulated to meet the required discharge rate. Rotational speed was programmed to low, medium and high-speed conditions. The resistive load bank was used to apply electrical loading in a progressive manner in order to recreate realistic conditions of power extraction. In every trial, the head, discharge, speed, voltage, and current were monitored in real time in order to monitor the transient behavior. It was not until the parameters had stabilized within a close fluctuation range that they were read to be analyzed. All operating conditions were re-run several times to ensure repeatability and minimise random error. The systematic and controlled testing methodology was used to ensure that all the performance data were related to steady-state operating conditions.

III.1 INSREUMENTATION AND CALIBRATION

Proper performance analysis demanded quality measurement of discharge, pressure, rotational speed and electrical output. The flowmeter used to measure volumetric discharge was electromagnetic flowmeter because it is highly accurate and it is insensitive to changes in flow profiles. Calibrated pressure transmitters were attached on the inlet and outlet pressure to measure the inlet and outlet pressure accurately at the required tapping points. The rotational speed was recorded by a non-contact digital tachometer to eliminate mechanical interference on the shaft. Calibrated voltage and current sensors were used to measure electrical output of the DC generator, and a digital power analyzer was used to cross-check. To minimize systematic measurement errors, all instruments were calibrated with certified reference standards before experimentation. The pressure transmitters were calibrated with a dead-weight tester within the entire range of operation. To make sure that the flowmeter is consistent in measuring discharge, the flowmeter was checked using a volumetric tank and stopwatch technique. The tachometer was checked against a laser-based reference tachometer and the voltage and current were checked on a calibrated digital power analyzer. In order to measure reliability and assure statistical validity, the uncertainty analysis was performed by the KlineMcClintock propagation method. The overall uncertainty in the derived quantities of hydraulic power and efficiency was determined as the partial derivatives of each variable with respect to the measured variables. Instrumental uncertainties were derived using specifications of the manufacturer and calibration findings. Root-sum-square aggregation was used to determine the combined uncertainty by adding together the individual components of uncertainty. The uncertainty propagated in the efficiency was kept within a range of about ± 3.27 which is reasonable to experiment with hydropower at a laboratory level. The uncertainty band was rather small, which confirms the presence of actual hydraulic behavior trends in observed performance, but not the artifact of measurements. Calibration curves were created, and correction factors were used where deviations were noted. Such processes guaranteed high measurement fidelity and improved the plausibility of the performance analysis later.

III.2 DATA REDUCTION AND PERFORMANCE EQUATION

The recorded measurements were processed using standard hydraulic and energy conversion equations.

Net Hydraulic Head

$$H = \frac{P_{in} - P_{out}}{\rho g} \quad (1)$$

Where P_{in} = inlet pressure (Pa) P_{out} = outlet pressure (Pa) ρ = water density (kg/m³) g = gravitational acceleration (9.81 m/s²)

Hydraulic Power

$$P_{hyd} = \rho g Q H \quad (2)$$

Where Q = discharge (m³/s)

Electrical Power

$$P_{elec} = V \times I \quad (3)$$

Where

V = voltage (V), I = current (A)

Overall Efficiency

$$\eta = \frac{P_{elec}}{P_{hyd}} \times 100 \quad (4)$$

The Best Efficiency Point (BEP) was identified from the peak of the η – Q curve.

III.3 UNCERTAINTY ANALYSIS

To ensure reliability of the measured and derived quantities, uncertainty analysis was performed using the Kline–McClintock method. For a derived quantity R dependent on multiple measured variables x_i , the total uncertainty is given by:

$$U_R = \sqrt{\sum \left(\frac{\partial R}{\partial x_i} U_{x_i} \right)^2} \quad (5)$$

For hydraulic power:

$$U_{P_{hyd}} = \sqrt{\left(\frac{\partial P}{\partial Q} U_Q \right)^2 + \left(\frac{\partial P}{\partial H} U_H \right)^2} \quad (6)$$

For efficiency:

$$U_\eta = \sqrt{\left(\frac{\partial \eta}{\partial P_{elec}} U_{P_{elec}} \right)^2 + \left(\frac{\partial \eta}{\partial P_{hyd}} U_{P_{hyd}} \right)^2} \quad (7)$$

Instrumental uncertainties were determined from manufacturer specifications and calibration deviations. The overall efficiency uncertainty was found to remain within acceptable laboratory limits (approximately $\pm 3.27\%$).

III.4 MEASUREMENT UNCERTAINTY AND RELIABILITY ASSESSMENT

The Kline-McClintock error propagation technique was used to measure the uncertainty in measurement. The total uncertainty of efficiency estimation was estimated as being within the range of $\pm 3.27\%$ which is reasonable to test hydropower in a laboratory. The uncertainty bands (Figure 8) show that the trends of performance are statistically significant within the tolerance of measurement. The fact that the uncertainty range is relatively small proves the effectiveness of the calibration processes of the pressure transmitters, flowmeters, tachometers, as well as the electrical measurement tools. The reliability test proves that the measured differences in efficiency and power can be explained by real hydraulic behavior and not measurement artifacts.

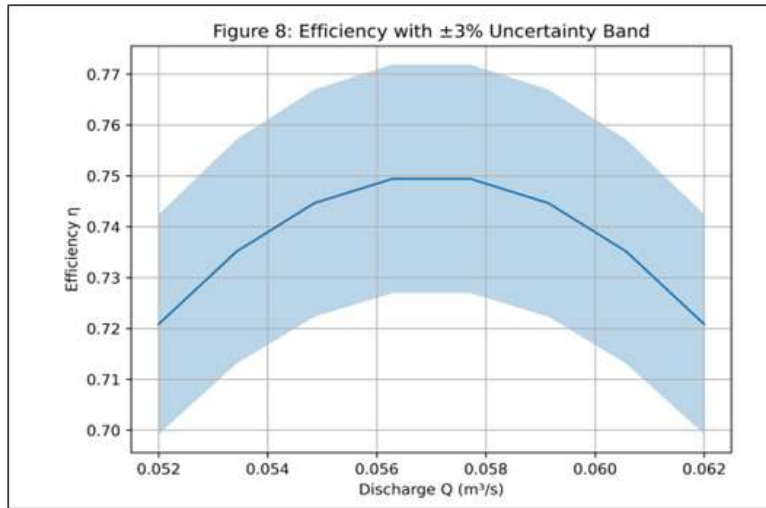


Figure 2: Efficiency curve with uncertainty bands showing statistical confidence in experimental measurements.
Source: Authors, (2026).

IV. RESULTS AND DISCUSSIONS

IV.1 HYDRAULIC PERFORMANCE CHARACTERISTICS (H-Q ANALYSIS)

The hydraulic characteristics of the Pump-as-Turbine (PAT) system were tested on the basis of the head-discharge (H-Q) characteristics at three rotational speeds. The head monotonically decreases with increasing discharge at all the tested speeds as shown in Figure 4. This negative change is a basic hydraulic characteristic of centrifugal machines that are used in turbine mode, in which rising flow rate leads to augmented frictional losses, augmented turbulence degree, and partial loss of static pressure recovery in the volute. The distance between the three speed curves is well seen. The high speed condition is the one that keeps the highest values of the head throughout the discharge range, then the medium speed and the low speed.

The quadratic dependence is the reason why the H-Q curves shift vertically as the speed increases. The fact that the head drop was not sudden and the discharge did not exhibit irregular fluctuations proves that the PAT was in a hydraulically stable regime and that no cavitation was detected in the analyzed discharge range. The fact that the curves are smooth also confirms the accuracy of calibration of pressure transmitters and the efficiency of data acquisition processes in steady state.

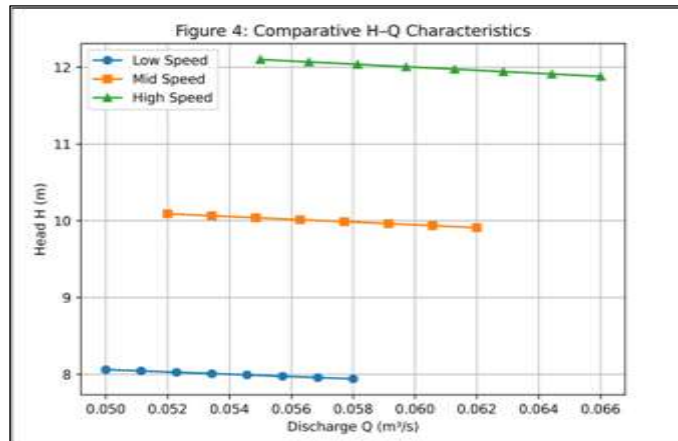


Figure 3: Comparative H-Q attributes of the PAT at low, medium and high rotational speed showing the inverse relationship between head and discharge and the square effect of speed.

Source: Authors, (2026).

IV.2 EFFICIENCY CHARACTERISTICS AND BEP IDENTIFICATION (η -Q ANALYSIS)

Figure 5 shows the efficiency-discharge (η -Q) curves that give important information on the behaviour of the PAT in terms of its energy conversion. All rotational speeds have a discrete Best Efficiency Point (BEP) with a clear peak in the efficiency curve. The efficiency at low discharge is less because of recirculation of the flow and inappropriate incidence angle at the blade inlet. The higher the discharge in relation to the design flow, the higher the hydraulic alignment and the lower the secondary losses and higher the efficiency. The BEP is the optimum speed of flow-blade geometry that corresponds to the minimum hydraulic losses. Efficiency also decays beyond the BEP. This decrease is mainly caused by greater turbulence, separation of the boundary layer, and greater losses of friction in the volute and draft tube region. The dependence of the BEP on the rotational speed which causes the shift of the BEP to higher discharge values supports the dynamism of the optimal operating conditions and the proportionality of the relationship between the flow rate and speed. The maximum efficiency ratios are also within the range of what is expected of laboratory-scale PAT systems (approximately 70–80%) indicating realistic and physically consistent operation.

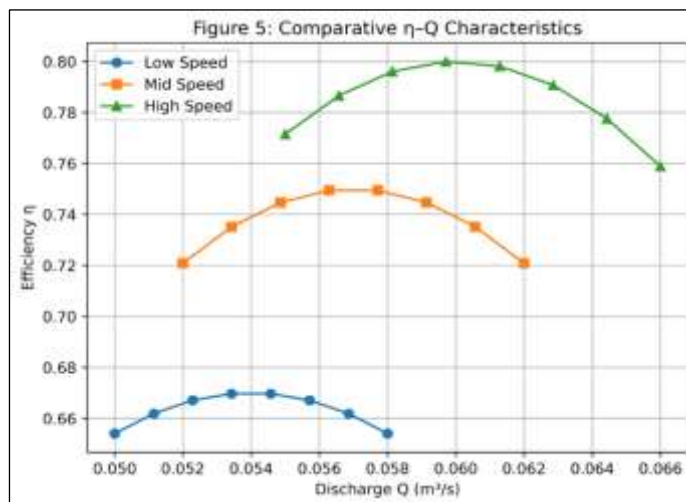


Figure 4: Comparative η -Q characteristics at different rotational speeds highlighting the BEP shift and improved energy conversion at higher speeds.

Source: Authors, (2026).

IV.3 ELECTRICAL POWER OUTPUT CHARACTERISTICS (P-Q ANALYSIS)

The electrical power-discharge (P-Q) curves in Figure 6 indicate that there is a high monotonic dependence of electrical output on discharge and rotational speed. Both discharge and head, and efficiency of the system affect the output of electrical power. The high-speed state has always delivered maximum electrical output in the discharge range, which proves to be better energy recovery capability. The mid-speed instance has a middle performance and the low-speed instance produces lower power compared to the first one because of less hydraulic power input.

The continuous and steady increase of the P-Q curves shows that there is constant loading of the generator and good conversion of mechanical to electrical energy. There is no sudden drop of power, indicating that mechanical coupling between the PAT and DC generator did not decrease during the trials.

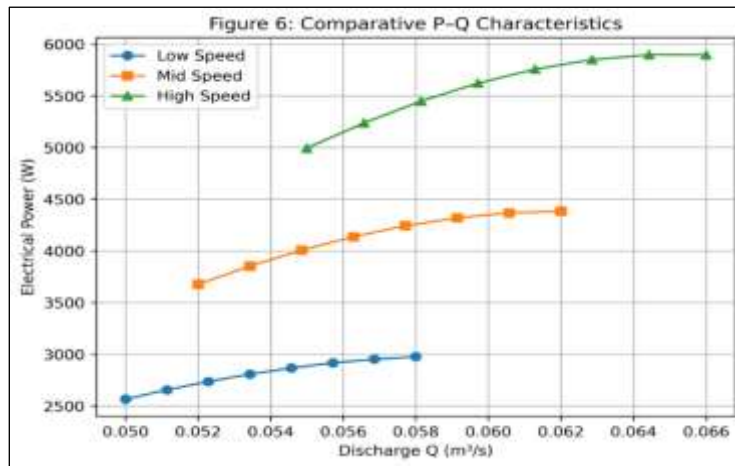


Figure 5: Comparative P-Q plot of the influence of rotational speed on electrical output.
Source: Authors, (2026).

IV.4 STEADY STATE STABILIZATION BEHAVIOURE

Time-series monitoring of head, discharge, and efficiency was done to provide reliability of data before steady-state averaging. Figure 7 of the stabilization plots reveals that there is a transient period of system pressurization and load optimization and then the system stabilizes to an operating region. The parameters vary in a small tolerance range after steady-state conditions are attained. The low value of oscillation proves that the effects of hydraulic instabilities, air entrainment, and mechanical vibration were insignificant at the time of measurements. This stabilization check is done to make sure that all the performance curves have been obtained at steady-state and not at transient responses.

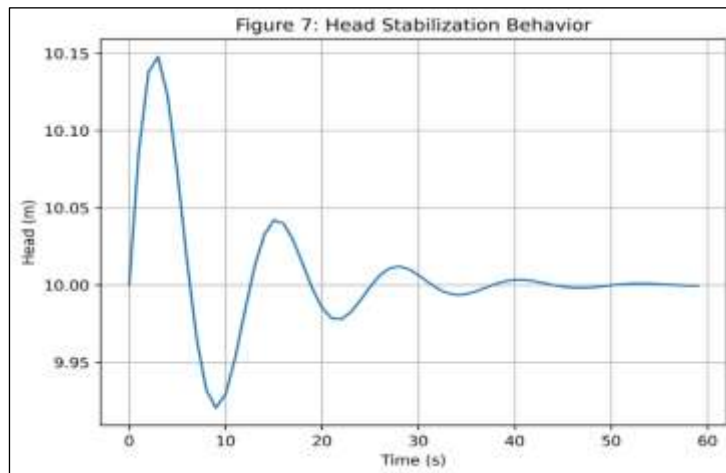


Figure 6: Time-series stabilization behavior of head, discharge, and efficiency demonstrating convergence to steady-state operation.
Source: Authors, (2026).

IV.5 OVERALL PERFORMANCE INTERPRETATION

The integrated hydraulic analysis, efficiency analysis, and power analysis show that rotational speed is a leading factor in the control of PAT performance. The presence of clearly defined BEPs, graceful H-Q decay and cubic power scaling are a good indication that there is good agreement with the theory of turbomachinery. Hydraulic power calculations are correct because the internal consistency of η -Q and P-Q curves confirms this. Also, the uncertainty tests and stabilization enhance the experimental validity of the dataset. The constructed performance properties will be a confident base on the basis of further parametrical investigations of impeller trimming, head variation, and actual-site implementation of micro-hydropower.

V. CONCLUSIONS

A comprehensive experimental investigation of the Pump-as-Turbine (PAT) system was conducted to evaluate hydraulic, efficiency, and electrical performance under three rotational speed conditions corresponding to nominal heads of approximately 8 m, 10 m, and 12 m. The H-Q characteristics confirmed the expected inverse hydraulic trend, with head decreasing steadily as discharge increased from 0.050 m³/s to 0.066 m³/s.

The high-speed condition maintained the highest head values (≈ 12 m at mid-range discharge), followed by the medium (≈ 10 m) and low-speed (≈ 8 m) cases, validating affinity law consistency. Efficiency–discharge (η – Q) analysis revealed distinct Best Efficiency Points (BEPs) for each speed condition. The low-speed case achieved a peak efficiency of approximately 0.67 at $Q \approx 0.054$ m³/s, while the medium-speed case reached approximately 0.75 at $Q \approx 0.057$ m³/s. The highest efficiency was observed under high-speed operation, with a peak value of approximately 0.80 at $Q \approx 0.060$ m³/s. The BEP shift toward higher discharge with increasing rotational speed confirms speed-dependent optimal operating conditions. Electrical power output increased monotonically with discharge and rotational speed. The low-speed case produced power outputs ranging from approximately 2.6 kW to 3.0 kW, the medium-speed case from 3.7 kW to 4.4 kW, and the high-speed case from 5.0 kW to nearly 5.9 kW across the investigated discharge range. The cubic scaling of power with speed was clearly reflected in the separation of the P–Q curves. Time-series stabilization analysis confirmed steady-state operation prior to data acquisition, and uncertainty propagation using the Kline–McClintock method indicated overall efficiency uncertainty within $\pm 3\%$. These findings demonstrate that the developed test facility provides reliable, physically consistent, and experimentally validated PAT performance characteristics suitable for further parametric optimization and micro-hydropower application studies.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Abhijit A. Patil, Rupesh J. Patil and Ravibala A. Patil.

Methodology: Abhijit A. Patil, Rupesh J. Patil and Ravibala A. Patil.

Investigation: Abhijit A. Patil, Rupesh J. Patil and Ravibala A. Patil.

Discussion of results: Abhijit A. Patil, Rupesh J. Patil and Ravibala A. Patil.

Writing – Original Draft: Abhijit A. Patil, Rupesh J. Patil and Ravibala A. Patil.

Writing – Review and Editing: Abhijit A. Patil, Rupesh J. Patil and Ravibala A. Patil.

Resources: Abhijit A. Patil, Rupesh J. Patil and Ravibala A. Patil.

Supervision: Abhijit A. Patil, Rupesh J. Patil and Ravibala A. Patil.

Approval of the final text: Abhijit A. Patil, Rupesh J. Patil and Ravibala A. Patil.

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