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A Comparative Study between Theoretical and Measured Performance of Standard Centrifugal Pumps Running as Turbines

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Abstract: High cost of custom-made conventional turbines and the lack of local manufacturing facilities have created significant obstacles to the development of Pico/micro hydroelectric schemes in the country. In this context it has been identified pump as turbine (PAT) electric schemes can have distinct advantages over conventional turbines because pumps are manufactured locally at mass scale and available in various sizes. But not all pumps are suitable for use as PAT because they have different design details and manufacturing qualities. The performance of a pump used as a turbine is assessed based on two primary parameters: turbine mode head and flow at the Best Efficiency Point (BEP). There are various methods available in the literature for predicting PAT theoretical head and flow at BEP. These methods aim to estimate how the pump will perform when used as a turbine. Despite these prediction methods, there is a consistent deviation of approximately ±20% between the theoretical estimates and the actual measured performance. This indicates that real-world conditions and factors not accounted for in theoretical models can significantly affect the performance of PAT systems. The primary objective of the present study was to measure the deviation between the actual performance and the predicted performance of two PAT systems in terms of head and flow at BEP. This deviation was then compared to the commonly mentioned figure of ±20% in the literature. The study focused on using what it considered to be the most accurate prediction method among those presented in the literature to estimate PAT head and flow at BEP and involved running reverse, 1.1 kW, and 1.6 kW direct-drive standard centrifugal type water pumps in a test rig to measure the actual performance of the two PATs. The results of the study showed a deviation of +27% and -22% between the actual measured head and flow at BEP, and the values predicted by the theoretical method. This deviation is slightly outside the commonly mentioned range of ±20% found in the literature, but this is not expected to have a detrimental effect on the generation of electric power. This implies that, even with the observed slight deviation, the prediction method used in this study can be satisfactorily employed to estimate PAT head and flow at BEP.

Keywords: Best Efficiency Point (BEP), Error, Theoretical and Measured, Pump as Turbine (PAT)

1. Introduction

One major hindrance to wider use of PATs is the lack of characteristic curves specific to their operation as turbines. Manufacturers typically provide pump performance curves, which may not directly translate to turbine performance. Therefore, insufficient understanding of pump as turbine performance is a major problem encountered in the PAT selection. However, researchers have proposed various methods to predict PAT performance. These methods include empirical, theoretical, and computational fluid dynamics (CFD) approaches. Despite these methods, none are perfect. There is often a discrepancy between theoretical predictions and actual measured performance. The ±20% deviation mentioned suggests that even the most accurate methods (like Sharma's method in this study) may still have some margin of error [1], [4]. While theoretical methods like Sharma's can provide valuable insights into PAT performance, local validation is essential due to the inherent uncertainties and variability of locally manufactured pumps. This approach can help bridge the gap between theoretical predictions and practical application, ultimately increasing confidence in using PAT systems for Pico/micro-hydroelectric projects.

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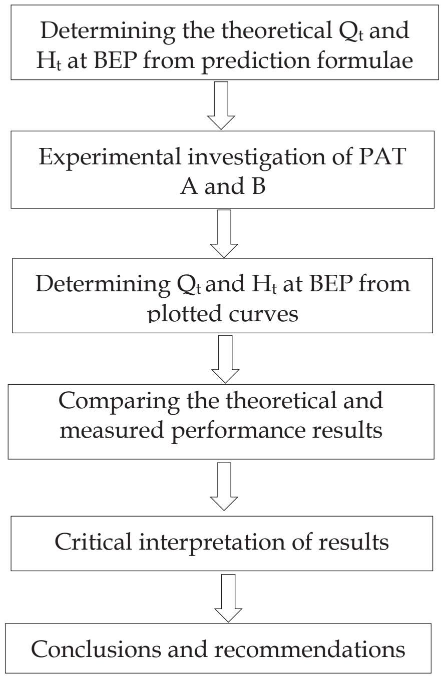
2. Literature Review

A large number of theoretical and experimental studies have been done by researchers in this field of study for performance prediction of PATs. But no method is reliable for the entire specific speed range and results obtained by these relations had almost ±20% deviation from measured results [1]. Sharma and Nour bakhsh [7] introduced a new method to predict PAT BEP, using experimental data of several centrifugal pumps (specific speed < 60). They were able to develop two equations to estimate the complete characteristic curves of centrifugal pumps as turbines based on their pump best efficiency point and a procedure was also presented for selecting a suitable pump to work as a turbine in a small hydro-site. The conversion factors predicted by this method were found to be in good agreement with experimental data.

Williams [2] presented a comparative study carried out on eight different prediction methods. The performance results on 35 pumps of different types and sizes were used for the comparison. It was concluded that no method could provide an accurate PAT prediction for all pumps. Many researchers have presented some theoretical and empirical relations for predicting the PAT characteristics in the best efficiency point (BEP). But the results predicted by these methods are not reliable for all pumps with different specific speeds and capacities. Derakhshan and Nourbakhsh [7] attempted through computational fluid dynamics (CFD) and compared with experimental results of pump (specific speed of 23.5), running in direct and reverse mode. CFD results supported the experimental results in pump mode, but the results were not within acceptable limits in turbine mode. Suarda et al. [9] carried out an experimental investigation by using two small pumps (diffuser pump and volute pump) to determine turbine mode performances. It was concluded that centrifugal volute-pump as turbine was a more potential alternative solution. Chapallaz et al. [4] carried out investigation on PAT conversion factors. Conversion factor graphs were developed on the basis of the specific speed of pumps. The conversion factor obtained from the graphs were found to be within acceptable limits even for the points away from BEP.

3. Methodology

Each step of the methodology is as follows.



3.1 Determining PAT theoretical Q_t and H_t at BEP

Sharma's method [7], which is considered the most accurate among the proposed prediction methods in the literature, is as follows.

$$Q_t = [N_t / N_p] \text{ X } Q_{bep} \,/\, \eta_{max,p}^{0.8} \quad \text{... (1)}$$

$$H_t = [N_t/N_p]^2 \text{ X } H_{bep} / \eta_{max,p}^{1.2} \quad \text{...(2)}$$

where H & Q denotes turbine head and flow rate, N is rotational speed in rpm and where subscripts bep: best efficiency point, p: pump mode, t: turbine mode.

Table 1 shows performance details of the two direct drive centrifugal pumps used in this study.

Table 1 - Pump Performance Details

Pump	Q_{bep} (l/s)	H_{bep} (m)	$\eta_{max,p}$ (%)	motor power (kW)
A	4.1	12.5	54	1.1
B	6. 3	20	67	1.64

3.2 Determining PAT Theoretical Overall Efficiency at BEP

PAT shaft power output $P_{out,t}$ is,

$$P_{out,t} = \eta_{bep,t} \times Q_t H_t 9.81 \quad \ldots(3)$$

Assumption ($\eta_{bep,t} = \eta_{max,p}$)

Then inductor generator power output P_{gen} is

$$P_{gen} = P_{out,t} \times \text{generator efficiency} \quad \ldots(4)$$

Induction generator efficiency is taken as 2% less than motor efficiency at its rated power [5].

The overall efficiency in turbine mode is,

$$\eta_{overall,t} = P_{gen} / Q_t H_t 9.81 \quad \ldots(5)$$

Table 2 shows PAT theoretical performance results calculated as shown in section 3.1 and section 3.2.

Table 2 - PAT theoretical performance results

PAT	$Q_{bep,t}$ (l/s)	$H_{bep,t}$ (m)	$\eta_{overal,t}$ (%)	P_{gen} (W)
A	7.3	31	36	800
B	9.4	38	49	1715

4. PAT Measured Performance Investigation

4.1 PAT Test Procedure

As shown in Figure 1, apparatus was set in a test rig and tested PAT performance for several heads and flow rates. The test runs were conducted by increasing load on the induction generator by switching ON incandescent lamps (230 V, 50 Hz) in a number of steps while the generator frequency was maintained at 50 Hz by increasing head and flow through the PAT. The excitation capacitors were connected in delta for 3Ph power generation. The capacitor values used in PAT A and PAT B were 10 µf and 18 µf, respectively, and calculated from no-load tests of the two induction motors. During testing, electrical load on the induction generator was manually governed. The flow rate was measured by timing the PAT discharge into a 460 liters tank. The inlet and outlet pressures were measured using two PSI-TRONIX PG-100 digital pressure gauges, and electrical parameters were measured using a NANOVIP digital power meter. When integral pump motor units are used extra care should be taken to ensure that the winding current in the induction generator does not exceed its rated value. The measuring instruments were cross-checked for their accuracy before taking the readings. Figures 2 and 3 show a captured view of the experiment in the test rig.

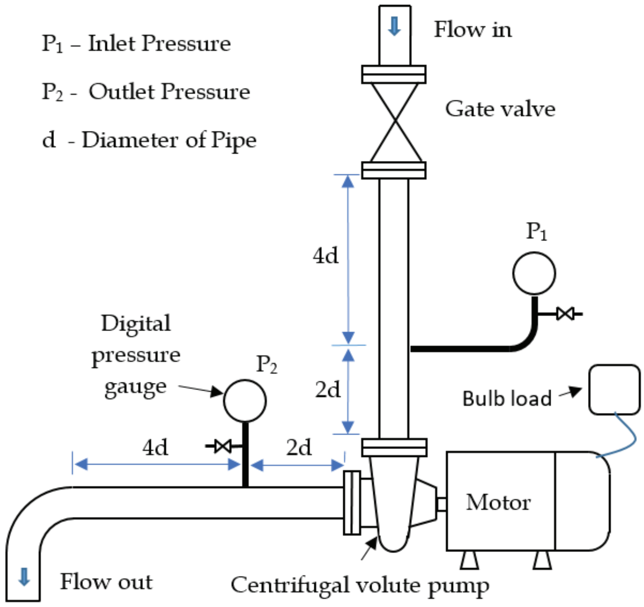


Figure 1 - PAT test setup

$$N_{gen} = \{240f/p\} - N_{mo} \quad \ldots(6)$$

where subscripts gen: generator, p: number of poles, mo: motor. Then synchronous speed, N_{gen} of the induction generator is 3150 rpm, f:frequency (50 Hz)

4.2 Determining PAT Overall Efficiency

The pressure difference P across PAT is,

$$P = P_1 - P_2 \text{ (psi)} \quad \ldots(7)$$

The net turbine head across PAT is,

$$H_t = P \times 0.703 \text{ m} \quad \ldots(8)$$

$$\eta_{overall,t} = P_{gen} / H_t Q_t 9.81 \quad \ldots(9)$$

Tables 3 and 4 show the measured performance data of PAT A and PAT B. As shown above, the overall efficiency of each test run was calculated and tabulated in Tables 5 and 6. The load test was carried out using a star connected balance load of incandescent lamps (230V, 50Hz).

Figure 2 - Pump A Running as a Turbine

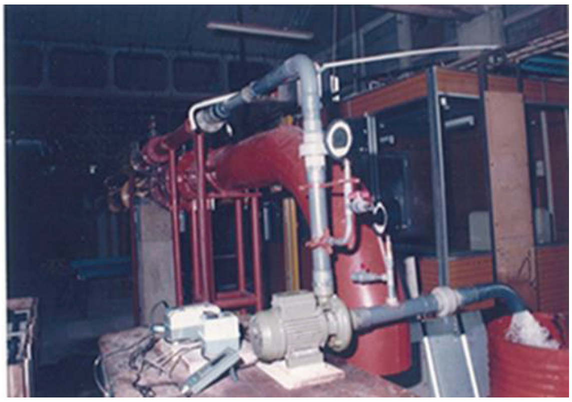


Figure 3 - Pump B Running as a Turbine

Table 3 - Measured Performance Data PAT A (Excitation Capacitance Value 10 µf)

Test no	V (Volts)	I_{gen} (A)	P_{gen} {W)	Bulb load (W)	F (Hz)	P_1 (psi)	P_2 (psi)	T (m,s)
1	443	2.48	0	0	50	31.3	3.97	1,15
2	434	2.49	336	300	50	37.0	4.05	1,00
3	427	2.54	529	480	50	37.6	2.70	57
4	423	2.55	603	600	50	38.4	2.20	56
5	417	2.57	674	675	50	39.3	1.66	54
6	406	2.62	873	900	50	42.3	1.13	51
7	402	2.67	948	975	50	43.4	1.14	50
8	397	2.70	1040	1080	50	44.9	1.14	48
9	387	2.74	1150	1230	50	47.0	1.13	46
10	376	2.86	1210	1350	50	48.5	1.08	46
11	365	2.94	1310	1530	50	50.7	1.15	44

Table 4 - Measured Performance Data PAT B (Excitation Capacitance Value 18 µf)

Test no	V (Volts)	I_{gen} (A)	P_{gen} (W)	Bulb load (W)	F (Hz)	P_1 (psi)	P_2 (psi)	T (m,s)
1	424	4.21	0	0	50	29.2	2.90	1,22
2	421	4.20	331	300	50	32.8	3.35	1,07
3	417	4.23	480	450	50	34.7	3.56	1,02
4	414	4.21	589	600	50	35.9	3.67	58
5	407	4.20	884	900	50	39.0	4.34	51
6	400	4.27	1110	1200	50	41.7	4.31	47
7	391	4.38	1380	1500	50	45.0	4.06	44
8	385	4.44	1480	1650	50	46.1	3.92	43
9	374	4.50	1610	1830	50	46.5	3.77	42
10	378	4.53	1690	1950	50	47.4	2.00	41
11	359	4.54	1750	2130	50	47.0	1.80	41

Table 5 - Measured Performance of PAT A (Calculated using the Test Data in Table 3)

Test no	1	2	3	4	5	6	7	8	9	10	11
H_t(m)	19.2	23.2	24.5	25.4	26.5	28.9	29.7	30.8	32.3	33.4	34.8
Q_t (l/s)	6.1	7.6	8.1	8.2	8.5	9.0	9.1	9.5	9.8	10.0	10.4
P_{gen}W)	-	336	529	603	674	873	948	1040	1150	1210	1310
$\eta_{overall,t}$ (%)	-	19	27	29	31	34	35	36	37	37	37

Table 6 - Measured Performance of PAT B (Calculated using the Test Data in Table 4)

Test no	1	2	3	4	5	6	7	8	9	10	11
H_t (m)	18.5	20.7	22.0	22.6	24.4	26.3	28.8	29.6	30.0	31.9	31.8
Q_t (l/s)	5.6	5.6	6.8	7.4	8.9	9.7	10.4	10.7	10.8	11.0	11.2
P_{gen} W)	-	331	480	589	884	1110	1380	1480	1610	1690	1750
$\eta_{overall,t}$ (%)	-	24	30	33	41	44	47	48	50	49	50

5. Results and Discussion

Figures 4 and 5 show the turbine mode performance curves of PAT A and PAT B. PAT A shows that it can produce about 1200 W electric power at an overall efficiency of 37% at BEP, whereas in PAT B the respective values are 1650 W and 50%. It can be seen that the overall efficiency drops slightly when running at their recommended operating point. Tables 7 and 8 show that the maximum recommended electric power outputs of PAT A and PAT B are 880 W and 1300 W respectively, and the overall efficiencies are 35% and 48% respectively (Figures 4 and 5).

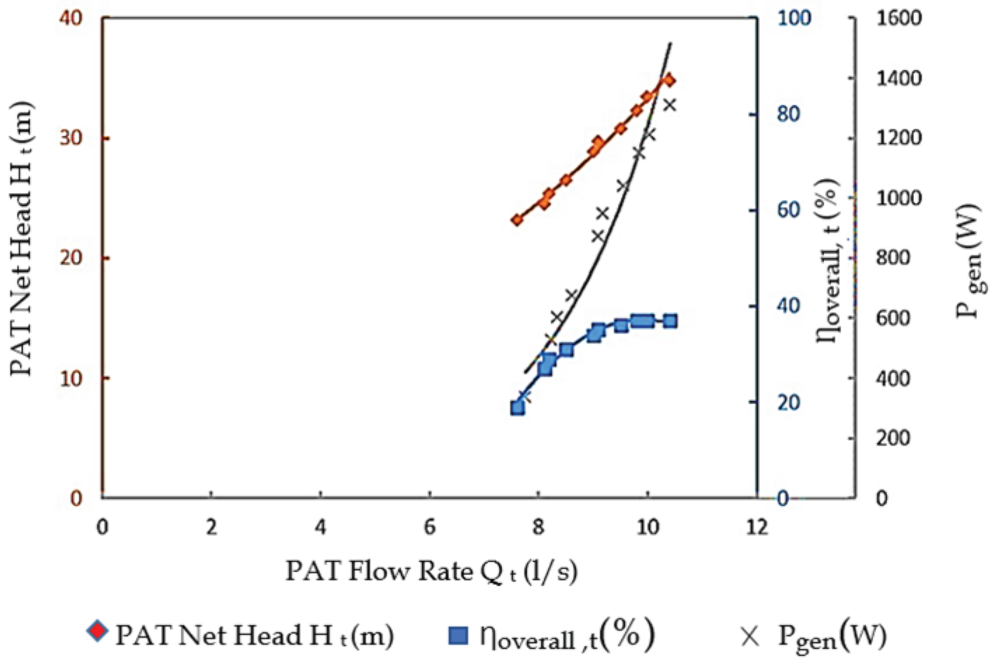


Figure 4 - Performance Curves - PAT A

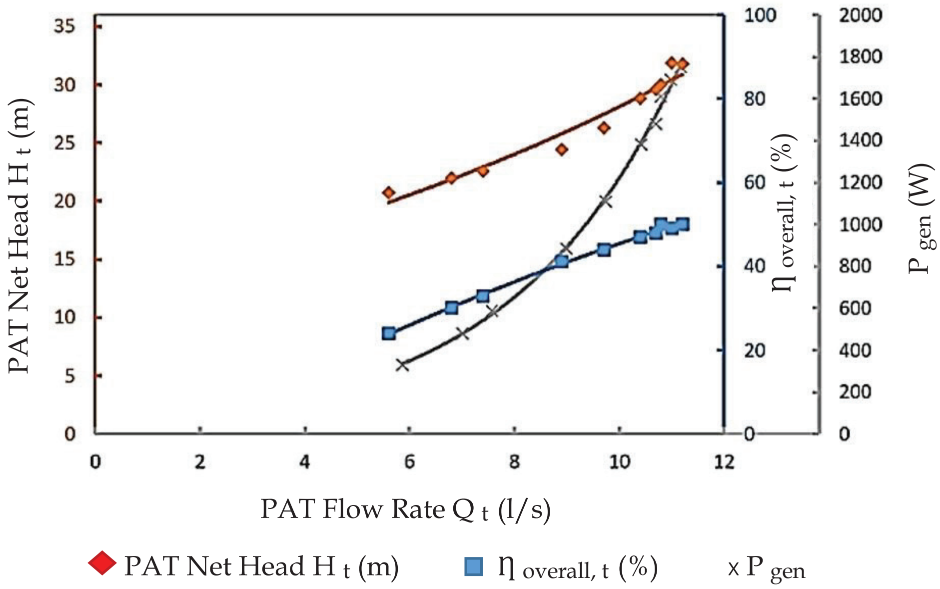


Figure 5 - Performance curves - PAT B

5.1 Comparison of PAT Performance at BEP and Rated Generator Power

The Comparison of the performance of PAT A is shown in Table 7 and PAT B in Table 8.

Table 7 - Comparison of Performance: PAT A

PAT A	at BEP	at generator rated point
H_t (m)	33	28
Q_t(l/s)	10	9.2
$\eta_{overall,t}$ %)	37	35
P_{gen} (W)	1200	880 (rated)

Table 8 - Comparison of Performance - PAT B

PAT B	at BEP	at generator rated point
H_t (m)	31	26
Q_t(l/s)	11	10.3
$\eta_{overall,t}$ (%)	50	48
P_{gen}(W)	1650	1300 (rated)

The maximum recommended power output of the induction generator was considered as 80% of its rated motor power [5] (i.e. de rating factor is 0.8).

5.2 Comparing the Theoretical and Measured Performance at BEP

The Comparison of the performance of PAT A is shown in Table 9 and PAT B in Table 10.

Table 9 - Comparison of Performance: PAT A

PAT A	Measured	Theoretical
H_t (m)	33	31
Q_t (l/s)	10	7.3
$\eta_{overall,t}$ (%)	37	36
P_{gen} (W)	1200	880

Table 10 - Comparison of performance: PAT B

PAT B	Measured	Theoretical
H_t(m)	31	38
Q_t (l/s)	11	9.4
$\eta_{overall,t}$ (%)	50	49
P_{gen} (W)	1650	1715

The comparable results of PAT A in Table 9 show the deviation between the theoretical and measured value is in the range of - 6% and +27% whereas Table 10 indicates a range of +14% and - 22% in PAT B. A similar study done by researchers [9] shows the deviation is in the range of +5.3 and - 6.6. This shows a good agreement between the theoretical and measured values when compared to the range found in the present study. Further, Tables 1 and 7 indicate that to operate PAT A at its BEP, the required turbine head (H_t) and flow (Q_t) are respectively 160% and 145% higher than in its pump mode head and flow. Tables 1 and 8 indicate that the respective values of PAT B are 130% and 75%.

6. Conclusion

The study aimed to determine the degree of accuracy of the most reliable theoretical prediction method proposed in the literature for calculating PAT theoretical head (H_t) and flow (Q_t) at BEP. The performance results of the two PATs indicated a deviation between theoretical and measured values ranging from +27% to -22%. This deviation, although slightly larger than the typical ±20% often reported in the literature, is deemed acceptable as it did not adversely affect the ability of the selected PATs to generate electric power effectively. It can be concluded that the prediction formulae used in the study can satisfactorily be used to estimate PAT head and flow at BEP. Further, this comprehensive study will help address the gap in knowledge and build confidence among Pico/micro hydro developers regarding the use of these systems in the Sri Lankan context.

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