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Technical note

Impulse (Turgo and Pelton) turbine performance characteristics and their impact on pico-hydro installations

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ABSTRACT

Pico-hydropower is a viable technology that can be integrated into a decentralized, off-grid approach to rural electrification in regions that currently have only limited access to electricity. The Turgo turbine is classified as an impulse turbine, similar to the Pelton wheel, often used in pico-hydro systems. Both offer high efficiency for a broad range of site conditions, but the primary difference is that the Turgo can handle significantly higher water flow rates, allowing for efficient operation in lower head ranges and thus potentially expanding the geographic viability. Published data on Turgo operating performance are limited; despite the differences, discussion thereof in design manuals is generally lumped in with the discussion of Pelton wheels. In this study, a laboratory-scale test fixture was constructed to test the operating performance characteristics of impulse turbines. Tests were carried out to determine the effect on turbine efficiency of variations in speed ratio and jet misalignment on two Turgo turbines. The results were compared to similar tests in the same fixture on a Pelton turbine. Under the best conditions, the Turgo turbine efficiency was observed to be over 80% at a speed ratio of approximately 0.46, which is quite good for pico-hydro-scale turbines. Peak efficiencies for both the Pelton and the Turgo turbines occurred at lower than theoretical ideal speed ratios based on a momentum balance; the reduction in speed ratio at which peak efficiency occurs is likely caused by inefficiencies in the turbine. Tests of jet misalignment showed that moving the jet to the inside or outside edge of the turbine blades caused a drop in Turgo efficiency of 10–20% and reduced the optimal speed ratio by 0.03 (6.5%). Radial misalignment had a significant adverse impact on both Turgo and Pelton turbines, however, angular misalignment of the jet is more of a concern for the Turgo turbine. The results stress the importance of proper system design and installation, and increase the knowledge base regarding Turgo turbine performance that can lead to better practical implementation in pico-hydro systems.

1. Introduction

Across the globe, 1.4–1.6 billion people have no access to electricity at all while another one billion are dependent on unreliable electrical grids [1]. The United Nations (UN) has underscored the importance of global access to electricity and other forms of energy by setting a goal to achieve what it refers to as "universal access to modern energy services" by 2030 [2]. Many of those lacking access to modern energy live in rural areas, thus decentralized, off-grid energy projects will play a vital role in achieving the UN's energy goal by 2030 [3].

Over the last 30 years, pico-hydropower (hydropower facilities generating less than 5 kW [4])[1] has been proven as a cost-effective, clean, and reliable method of generating electricity and mechanical power for off-grid applications and will play an important role in rural electrification into the foreseeable future. In Nepal for instance, 300 pico-hydro schemes constructed by Practical Action are producing electricity, while 900 others are used for mechanical power only [5]. Practical Action has also been involved with the construction of another 70 installations in Sri Lanka and 15 in Peru in recent years [5]. In the last decade, pico-hydro has become more prevalent in Sub-Saharan Africa as well, where electrification rates are some of the world's lowest [6]. As of 2003, as many as 50 million households worldwide receive electricity from

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[1] Hydropower is commonly classified by power output as large (>10 MW), small (<10 MW), mini (<1 MW), micro (<100 kW), and pico (<5 kW).

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hydropower on mini-grids, with several hundred thousand units installed [7].

While pico-hydro presents significant advantages, including cost, over other types of electricity generation, implementation can present a challenge [8], including a heavy dependence on site-specific conditions for scheme design [9]. Off-the-shelf systems have been designed to reduce the site-specific design but this does not completely eliminate the need for technical expertise [10]; in order to ensure long term success of projects, proper design and installation are important, as is community cooperation for day-to-day management, though maintenance is not typically overly difficult or time consuming.

1.1. Motivation

For implementation of pico-hydropower in developing countries, it is necessary to ensure that (1) appropriate technology exists and (2) understanding and awareness of such technology exists [8,10]. One area of appropriate technology for pico-hydro that has lacked adequate attention up to this point is the use of Turgo turbines. While Turgo turbines offer many of the same advantages of Pelton turbines, such as high efficiency for a broad range of site conditions, there are differences that are worth noting. Fig. 1 shows photos of both a Turgo and a Pelton turbine. Currently, pumps-as-turbines (PATs), a type of reaction turbine, are commonly used for medium head schemes; however Turgo turbines are also a viable solution in this range. A chart showing the applicable head ranges for different turbine types is provided in Table 1.

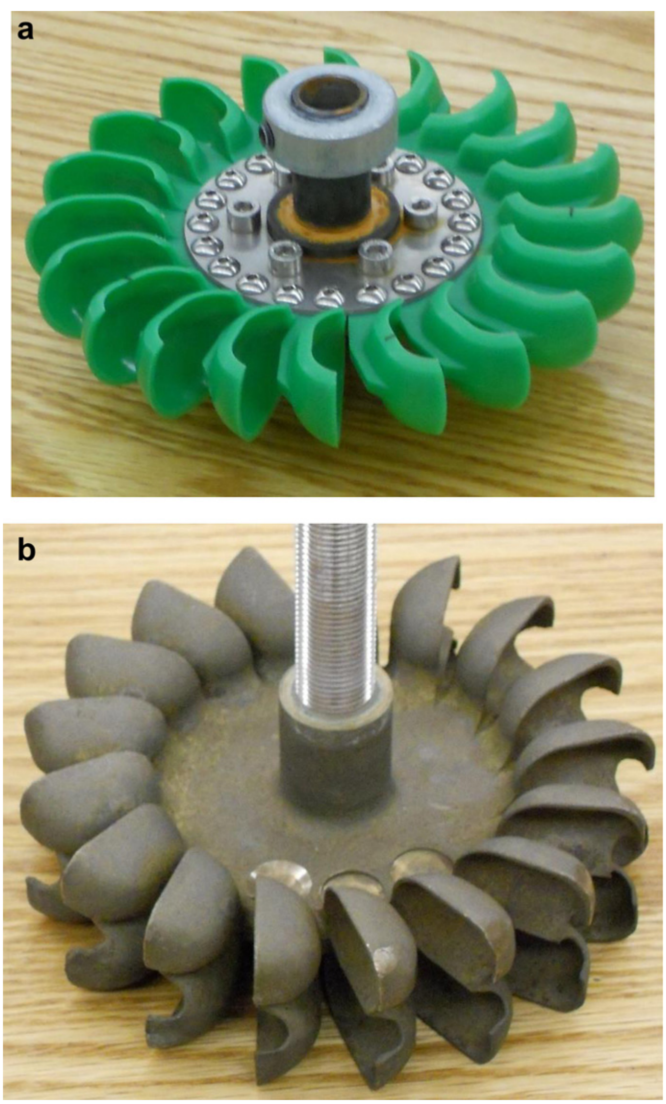


Fig. 1. Photos of (a) a Turgo turbine and (b) a Pelton turbine.

Table 1
Classification of turbines used for pico-hydro based on hydraulic head and type (adapted from Paish [21]).

Turbine type	Low (<10 m)	Medium (10–50 m)	High (>50 m)
Impulse	Crossflow	Crossflow Turgo Pelton	Turgo Pelton
Reaction	Francis Propeller Kaplan	Francis	

Turgo turbines have been in use for hydropower since 1919 [11], yet published work in typical design manuals [12,13] about their operating performance is limited. Oftentimes, despite their differences, the discussion of Turgo turbines is lumped in with a discussion of Pelton wheels. The most important difference is that the Turgo can handle significantly higher water flow rates, allowing for efficient operation in lower head ranges (than a Pelton wheel) and potentially expanding the geographic viability of pico-hydro. Several off-the-shelf turbine-generator sets are available with Turgo turbines in North America [14–16] though performance specifications are only provided as water-to-wire efficiencies leaving specific turbine efficiency ill-defined. In and of itself, the lack of access to off-the-shelf turbine-generator sets in developing countries is not prohibitive for installation; many installations start with individual components, and manufacturing (e.g. casting and machining) of a Turgo turbine and Pelton wheel are comparable. A number of documented installations of Turgo turbines [17] show low operating efficiencies (20–30% rather than 50–60%) [15] suggesting room for improvement on the design and installation of the systems.

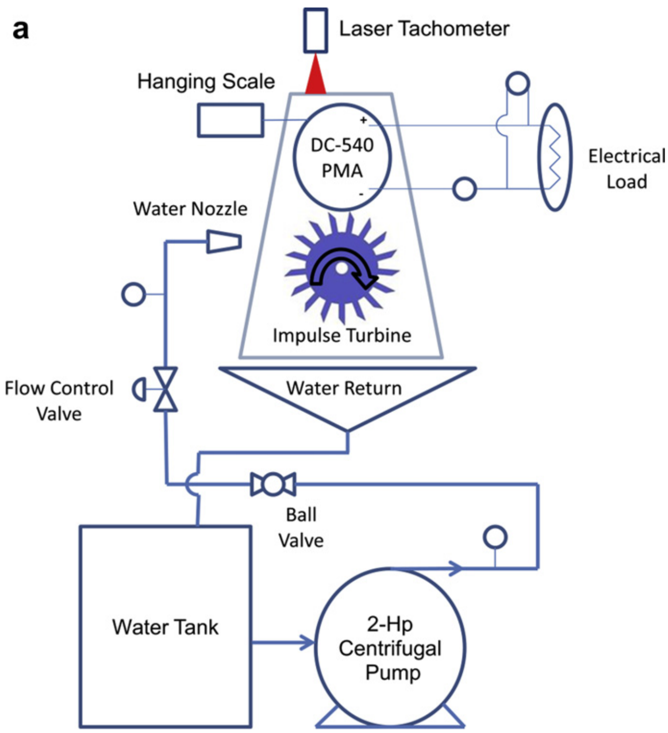
This study aims to demonstrate how parameters such as speed ratio (ratio of tangential turbine velocity and jet velocity), system design, and installation impact turbine efficiency, thereby increasing the knowledge base in this area and improving Turgo turbine implementation.

1.2. Objectives

This study seeks to experimentally validate the following hypotheses: 1) Turgo turbine efficiency has a dependence on speed ratio similar to the dependence observed with Pelton turbines; and 2) jet misalignment must be minimized in order to maximize energy transfer from the water jet to an impulse turbine. Several potential pitfalls of poorly-managed pico-hydro installations are also investigated. While Turgo turbine use is emphasized herein, based on our concurrent Pelton wheel testing [18], the findings are broadly applicable to both turbine types.

2. Materials & methods

A laboratory test set up (Fig. 2), constructed to simulate a typical pico-hydro scheme, consists of a vertical axis impulse turbine directly coupled with a WindBlue Power DC-540 permanent magnet alternator (PMA) and a 2-hp MP Pumps centrifugal pump driving the flow of water to create a water jet that turns the turbine. A 100-mm PCD brass ABS Alaskan Harris Pelton turbine, a 131-mm PCD plastic Turgo turbine, and a 169-mm PCD plastic Hartvigsen-Hydro Turgo turbine were tested. The generator (and associated a



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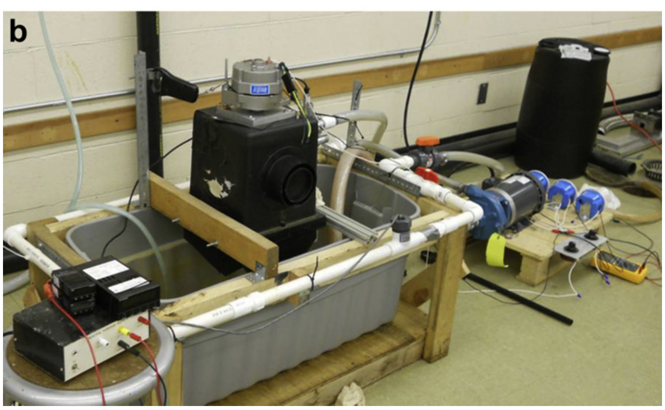

Fig. 2. (a) Schematic of laboratory-scaled test fixture and (b) photo of the text fixture.

bearing) is mounted atop an inverted catch basin containing the turbine and nozzle, and the mount allows the generator to spin freely about the shaft. Isolation and flow control valves are located in the Polyvinyl chloride (PVC) pipe flow loop.

Various instruments were installed throughout the system in order to characterize the performance of the principle components, the nozzles, turbine and PMA. An FP-7001A paddle wheel flow sensor (range of 0–50 gpm) measures the volumetric flow rate of water through the flow loop. An Omega PX309-050 GV pressure transducer (range of 0–50 psig) is used to monitor pressure in the loop. A Fluke 189 and a Sears Model 982015 digital multimeter are used to measure voltage and current produced by the PMA. Shaft speed, ω_{rev}, is measured using an Extech Instruments Model 461920 laser tachometer.

3. Calculations

As in a typical pico-hydro scheme, hydraulic head H can be calculated at any location where elevation z, pressure p, and velocity v are known using

$$H = z + \frac{p}{\rho g} + \frac{v^2}{2g}. \tag{1}$$

where ρ is the density of the fluid and g is gravity. In this experiment, the flow meter and pressure transducer were used to directly determine net head, H_n, located upstream of the nozzle. Jet head H_j and jet velocity v_j, the head and velocity downstream of the nozzle, are related to H_n via the nozzle's velocity coefficient C_v as follows:

$$H_j = C_v^2 H_n \tag{2}$$

$$v_j = C_v \sqrt{2gH_n}. \tag{3}$$

Over the range of jet velocities investigated here, the velocity coefficient depends primarily on nozzle geometry. For a 60° rounded nozzle C_v=0.97 and for a 14° tapered nozzle $C_v = 0.98$ [12]. The brass nozzles used for this study all fall between these two geometries so $C_v = 0.975$ was assumed.

The power in the jet, shaft and electrical output are found using flow rate, Q, which was directly measured, and the calculated jet head.,

$$\dot{W}_j = \rho g Q H_j. \tag{4}$$

The power transferred to the turbine/shaft is found by relating the shaft speed ω (rpm) and torque T:

$$\dot{W}_s = \frac{2\pi T \omega}{60}. \tag{5}$$

Shaft power is then converted to DC electrical power by the generator:

$$\dot{W}_{elec} = IV, \tag{6}$$

where I is the current through the circuit and V is the voltage across the alternator terminals.

The efficiencies of the turbine and generator are calculated based on the ratio of power at the various points within the system respectively:

$$\eta_t = \frac{\dot{W}_s}{\dot{W}_j}, \tag{7}$$

$$\eta_{gen} = \frac{\dot{W}_e}{\dot{W}_s}. \tag{8}$$

In the case of Turgo and Pelton Turbines, speed ratio, x, the ratio of the turbine speed to jet velocity, is important to identifying the best operating point and is defined as

$$x = \frac{N\pi(\mathrm{PCD})}{60 v_j}, \tag{9}$$

where N is the turbine (or shaft) speed in revolutions per minute (rpm) and PCD is pitch-circle-diameter. Best efficiency is achieved with a speed ratio of about 0.45–0.50 for Pelton turbines [8,12].

Specific speed is another non-dimensional parameter that enables comparison of different turbines and operating conditions and is thus useful for scaling turbines and flow conditions. In practice, the most common form is dimensional:

$$N_s = \frac{N\left(\dot{W}_t\right)^{1/2}}{(H_n)^{5/4}}, \tag{10}$$

where units are $(\mathrm{rpm})(\mathrm{kW})^{1/2}/(\mathrm{m})^{5/4}$.

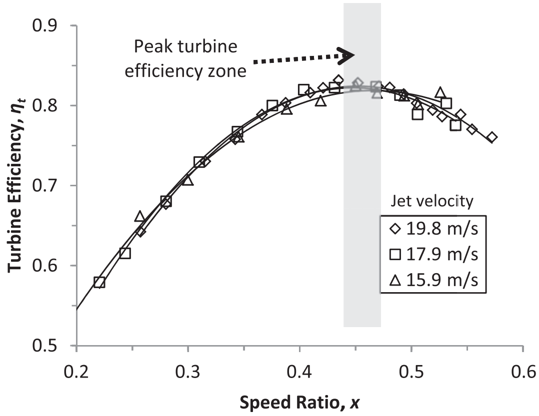

Fig. 3. Turbine efficiency vs. speed ratio for a 169-mm Turgo turbine with a 9.53-mm nozzle and three different jet velocities.

4. Results & discussion

4.1. Effects of speed ratio

Given that turbine efficiency is heavily influenced by speed ratio, it is an important parameter to consider in selecting the proper turbine speed for a given jet velocity. A momentum balance on a Turgo turbine dictates that the theoretical speed ratio should be set at 0.53 for a jet angle of 20°, whereas experimental studies put the actual value between about 0.46 and 0.48. Near peak efficiency, small changes in speed ratio have a limited impact on efficiency; losses increase more rapidly the further the deviation from its ideal (peak efficiency) speed ratio. Changing the speed ratio after installation may not be practical; therefore, accurately approximating speed ratio in the design stage is essential.

Plotting the measured turbine efficiency vs. non-dimensional speed ratio collapses the curves from multiple experiments onto one curve, with a peak efficiency occurring around a speed ratio of 0.45 (Fig. 3). Other tests on the two Turgo turbines used for this work showed that peak efficiency consistently fell in the speed ratio range of 0.45–0.50 (The tested Pelton wheel showed peak efficiency at speed ratios of 0.40–0.42, lower than the Pelton theoretical ideal value of 0.5.).

One potential explanation for the deviation from the ideal Turgo speed ratio of 0.53 may be a result of non-ideal flow conditions in the cups (e.g. losses introduced by flow inside the cups that reduce the velocity of the stream leaving the turbine). Peak efficiency for the 169-mm Turgo turbine was measured at over 85% while the best efficiency for the 133-mm model was just over 81%. Compared to Pelton turbines tested in the same power range, the Turgo turbines performed quite well. Typical Pelton turbines in pico-hydro tend to operate in the 75–85% peak turbine efficiency range [12] while other Turgo turbine designs have been found to operate at over 70% efficiency [8]. (The highest efficiency measured for a Pelton turbine using this test fixture was 73%.) Gilkes [19], a hydropower company in the UK, reports peak turbine efficiencies around 85% for their Turgo turbines used in applications with power outputs ranging from 20 kW to 10 MW.

Another noteworthy finding from these tests is the sensitivity of the turbine efficiency to changes in speed ratio. As Fig. 3 shows, from a speed ratio of about 0.40–0.55, efficiency only changes by about 3 percentage points but outside that range turbine efficiency drops off significantly. Similar trends in terms of efficiency drop-off were observed with the tested Pelton turbine [18].

4.2. Effects of jet misalignment

A number of tests were conducted to determine the significance of the effects of poor jet alignment. Radial misalignment of the incoming jet with the tested Pelton turbine by half a cup width caused a drop of 15–20 percentage points in efficiency. Like the Pelton turbine, the Turgo turbines can be heavily impacted by improper radial jet alignment. The drop in peak turbine efficiency can be as much as 15 percentage points for the outside misalignment with a smaller reduction for the inside misalignment (Fig. 4). Fig. 4 also clearly shows a reduction in the speed ratio at peak turbine efficiency for the outside case and an increase for the inside case. The shift in speed ratio, nearly 20% for the outside misalignment, is due to the effective change in pitch circle diameter (PCD) of the turbine caused by a change in location at which the jet hits the turbine blades. There may also be added energy losses in the turbine from the altered flow pattern in the blades. For misalignment to the outside, it may be more likely that water from the jet will miss the turbine altogether; whereas on the inside, all the water should still hit the turbine. The most important point to take is that a modest radial misalignment can have a noticeable negative impact on turbine performance by reducing the peak efficiency by over 20% and

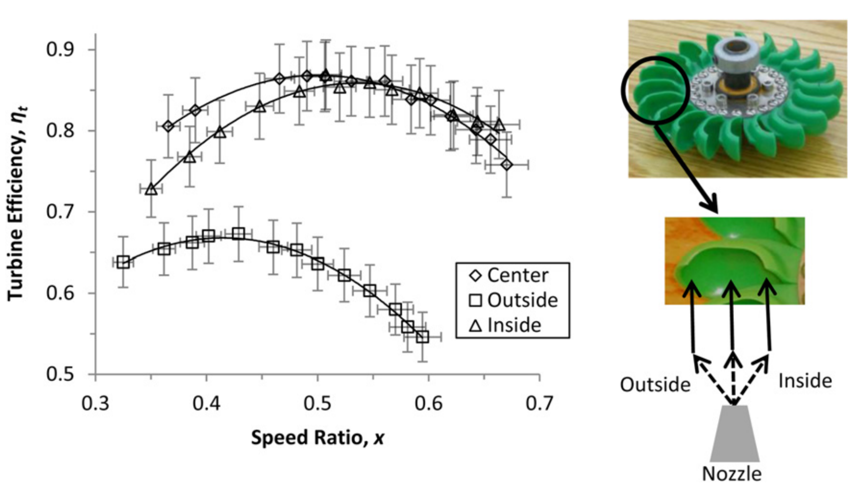

Fig. 4. Turbine efficiency vs. speed ratio for a 169-mm Turgo turbine with an 11.11-mm nozzle for three radial jet positions. Error bars are shown for speed ratio (horizontal) and turbine efficiency (vertical).

shifting the speed ratio at which peak efficiency occurs by up to 20%.

Angular misalignment is more of a concern for Turgo turbines than it is for Pelton turbines for the simple reason that the installed jet angle is intended to be around 20° (i.e. not 0°). Reducing the jet angle from the commonly used angle 20° [20] to 18° appears to reduce efficiency by a little less than 5 percentage points, and by close to a 10-point reduction for 14° and 24° jet angles. For the jet angle above 20°, peak efficiency appears to occur at a higher speed ratio. This latter effect is caused by the jet striking the turbine closer to the inside of the blades for the 24° test, resulting in a smaller effective PCD. For the tested Pelton wheel, the experiments indeed reflected the expected smaller sensitivity to angular misalignment; the efficiency drop was less than 5 percentage points for a 10° misalignment.

4.3. Scaling of results

To verify that results from this research would be applicable to flow and head conditions outside of those tested, the impact of changes in head, specific speed, and flow rate were investigated for both Pelton and Turgo turbines. For medium head applications, where Turgo turbines are most likely to be used, head is below 50 m [21]. The system used in this study is capable of producing heads up to about 30 m, thus covering a meaningful range for Turgo turbine use in practice [19]. For the lower power applications encountered with pico-hydro (<5 kW), the impulse turbines used are generally not much larger than those used in this study, so changes in turbine size were not investigated.

Over the variable range of hydraulic head tested here (13–28 m), experiments confirmed effectively no difference in Turgo efficiency or the speed ratio at which peak efficiency occurred from one head to another (holding nozzle diameter, and thus specific speed constant). A second evaluation of the impact in a change in head was conducted; this time, however, the change in head was accomplished by a change in nozzle diameter. Since a centrifugal pump was driving the flow in the experimental set-up, a change in nozzle size resulted in a higher flow rate and lower head due to a change in pump efficiency corresponding to the pump performance curve. These experiments showed that even when specific speed is not held constant, changes in head have no noticeable impact on peak efficiency for Turgo turbines within the range of parameters tested.

Under more extreme operating conditions, such as very low or high head, other factors could have a significant impact. Factors such as bearing or windage losses should be considered for such extreme cases, as they can affect efficiency at high turbine or shaft speeds. For medium head, between 10 and 50 m, these other factors are not expected to have a major influence on turbine performance. Another potentially important consideration is nozzle size. Guidelines for maximum nozzle diameter for a particular turbine are not widely available, though above some point turbine efficiency will most certainly be negatively impacted. For this study, the maximum nozzle diameter used was 1/2" corresponding to roughly 10% of PCD and 33% of the cup width with no apparent impact on turbine efficiency.

5. Summary & conclusion

Pico-hydropower is a viable technology for rural electrification in some of the most distant, impoverished regions of the world. Provided adequate consideration is given to site-specific conditions and installation [9], pico-hydro can be a very economical solution. As shown by the experiments in this study, proper equipment selection and installation are key components to achieving reasonable system efficiencies, and thereby raise power output.

For impulse turbines, proper speed ratios (ratios of about 0.4–0.5) are essential for efficient energy transfer from the water jet to the generator shaft. Theoretically, the peak efficiency point for the Turgo turbine should occur at approximately $x = 0.53$ for a jet angle of 20°. Experimentally, peak efficiency occurs at a slightly lower speed ratio, approximately 0.46–0.48. Similarly, the theoretical peak efficiency point for the Pelton is at a speed ratio of 0.50, but experimentally it occurs closer to 0.41. A second consideration pertaining to speed ratio is the shift in peak efficiency point for systems with low turbine efficiency. For example, if jet misalignments and frictional losses within the turbine lower turbine efficiency, the speed ratio at which peak efficiency occurs is also lowered. Correctly accounting for the shift in speed ratio can prevent a 5–10 percentage point loss in turbine efficiency. The effect that the speed ratio can have on turbine efficiency also means it is important to accurately determine the net head prior to installation, since it is required for determining jet velocity.

Proper jet alignment is another essential consideration. Even small misalignments (a few centimeters or degrees) can have significant negative effects on turbine efficiency. Care must be taken in the installation process to make certain the jet strikes the turbine in such a way that an efficient transfer of energy can occur. Results from this study demonstrate that visual adjustments are not adequate for achieving the highest turbine efficiency. A standardized turbine housing with built in nozzle mounts would simplify alignment. The housing would need to allow for large scale adjustments to accommodate different turbine sizes, as well as for fine adjustments to optimize the position during testing.

There are several areas for future work on this project that have the potential to improve pico-hydro. The flow limitations for Turgo turbines need to be established in relation to PCD and/or cup size (similar to the way it has been established for Pelton turbines). A Turgo turbine and turbine-generator set that can be easily built using basic manufacturing techniques should be identified. Most importantly, a general awareness and technical understanding of successful pico-hydro technology needs to be developed and fostered at the local and regional levels so that rural electrification projects can be implemented effectively.

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