Methodological Approach of Performance Evaluation for Using Pump as Micro Hydro-turbine

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Abstract

The pumps work differently in terms of performance characteristics when operated in reverse mode to generate mechanical rotational energy driven by the water energy. The performance characteristics related to head, flow rate, specific speed and efficiency have been predicted differently from available conversion methods. Also, the procedure of selecting pump as hydro-turbine varies from different conversion methods. This article presents the methodological approach of evaluating the pump as hydro-turbine related to selection procedures, performance characteristics and challenges.

Keywords: Challenges, pump as hydro-turbine, performance characteristics, selection procedures.

1. Introduction

The micro or small hydropower is very potential for electricity generation in the remote areas of Africa continent, especially in the sub-Saharan African regions (Kaunda et al, 2012). The communities need a simple design, ease manufacturing and affordable technology that will sustain extreme local conditions, inexpensive and low maintenance cost for electricity generation (Mbabazi and Leary, 2010). Locally manufactured of hydro-turbine in a developing country will enable the costs per unit of energy output to be lower than the use of small diesel or petrol generators, solar PV systems or wind turbines (Williams and Simpson, 2008).

The selection of hydro-turbine depends on the site characteristics i.e, head and flow rate. Micro hydropower schemes can use the standardized equipment, low-cost approaches and off-the-shelf equipment (Patel et al, 2015). But, the main problem is to get a proper hydro-turbine within the remote market areas (Suarda et al, 2006). The equipment like pump that is used in water pumping for domestic and industrial use, irrigation, livestock and sewage systems in the off-grid remote areas are used as hydro-turbine for micro hydropower (Muttalli et al, 2014; Popescu et al, 2013). The off-the-shelf pump still limited to the less than 100 kW (Garay, 1990).

This article presents the methodological approach of getting the off-the-shelf Pump as Hydro-turbine (PAT) for potential micro hydropower. The selection procedures help to find the possible pump that fits the specific hydropower site. Through testing by using numerical analysis i.e., Computational Fluids Dynamics (CFD) or test rig in the laboratory is possible to get the PAT performance characteristics include head, flow rate, power delivered, efficiency and losses. Also, the conversion methods used to convert the pump performance characteristics to PAT characteristics. Therefore, the main objective of this article is to review the procedures of selecting the off-the-shelf pump, performance characteristics and challenges of using pump as turbine for hydropower schemes development.

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1.1. Pump as Hydro-turbine Application

The principle operation of pump is depending on the centrifugal force, cross-sectional area and fluid velocity. The main parts of pump are presented in Fig. 1 (a). The centrifugal force exerted on the water by the rotating impeller, moves the water away from the suction eye and out along the impeller vanes to their extreme tip where the liquid is then forced against the inside walls of the increasing cross-sectional area between impeller with blades and casing to convert kinetic energy of the water into pressure energy at the discharge part. For PAT as presented in Fig. 1(b), water pressure inflow at the discharge part and strike the impeller with blades to generate mechanical rotation connected to the shaft and rotate in the opposite direction of pump rotational speed. Motor or generator connected to the shaft for electricity generation.

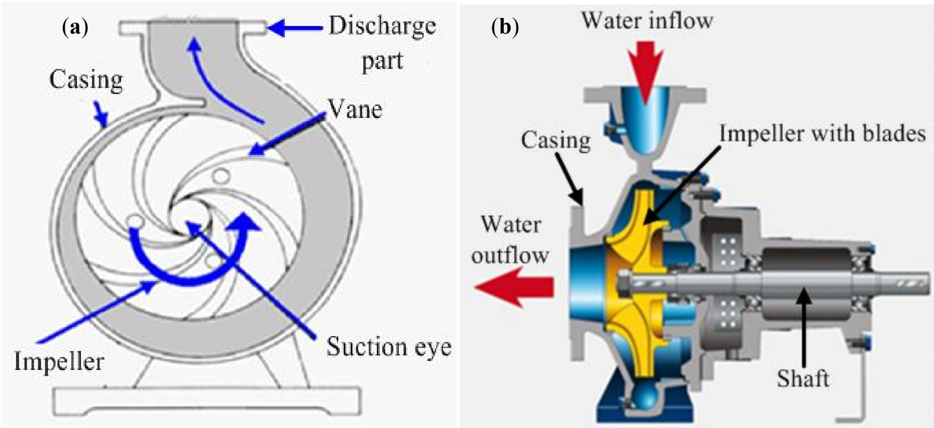

Fig. 1: Principle operation of pump. (a) sectional view of pump showing main parts (Chaurette, 2005). (b) sectional view of pump in reverse mode showing the direction of water flow and shaft connected to impeller (Orchard, 2009)

2. Methodological Approach

The methodological approach of selecting PAT is based on the methods used to convert pump performance characteristics related to head, flow rate, power and efficiency to the PAT characteristics (Fig. 2). The detail descriptions of the methodological approach is presented in the next sub-sessions.

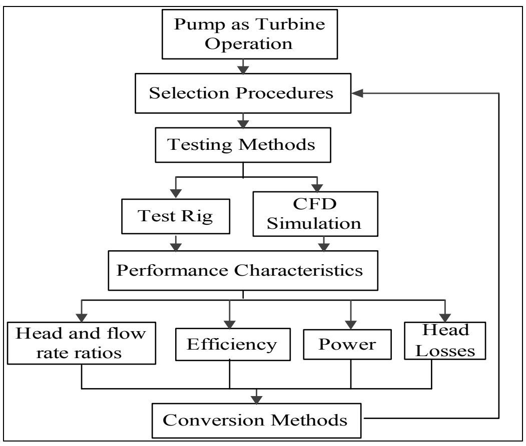

Fig. 2: Methodological approach of pump as turbine application

2.1 Selection Procedures

The selection procedures are based on the geometric shape of the pump controlled by calculating the specific speed. The procedures are as follows:

i. To calculate the hydro-turbine specific speed (n_{st}) related to head and flow rate for given hydropower site at a given rotational speed.

ii. To collect the pump datasheet that consists of head, flow rate, rotational speed, horse power and efficiency and used to calculate the specific speed (n_{sp}).

iii. To calculate the specific speed of PAT by using the conversion equations from Tan and Engeda (2016), Yang et al (2012), Singh and Nestmann (2011) and Chapallaz et al (1992). When the four conversion equations are compared to each other, indicated to have the fit-line of squared R of 0.944 as presented in Fig. 3. This step used to control the geometric shape of the pump related to hydro-turbine head and flow rate.

iv. Then, calculated PAT specific speed should be about equal to step (i) to select the pump related to the pump datasheet information.

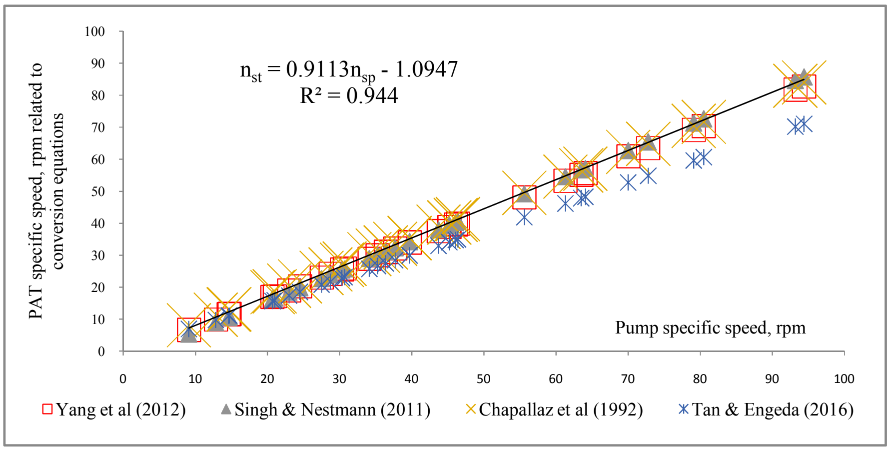

Fig. 3: Variation of PAT specific speed from various empirical equations

v. To regulate the rotation speed of pump as turbine by using modified affinity laws described in Carravetta et al (2014) or unmodified affinity laws described in Chapallaz et al (1992). Williams (1995) also regulated the head and flow rate ratios by using the efficiency and rotational speed.

2.2 Testing Methods

The PAT is tested by using a test rig or/and numerical analysis based on CFD simulation. The test rig simulates the site conditions and results can be very useful for predicting the real situation in the potential hydropower site. Krivichenko (1994) indicated the test rig can measure the PAT performance characteristics and cavitation effect. But, the use of CFD simulation helps to investigate the internal losses and flow patterns in the impeller with blades, draft tube and casing which could not be measured experimentally (Nigussie and Dribssa, 2015; Agarwal, 2012).

2.3 Performance Characteristics

Pump performance characteristics for reverse mode is not declared from the off-the-shelf pump datasheet provided by the pump manufacturer (Buono et al, 2015). But, pump operated in reverse direction indicated to change their performance characteristics include head, flow rate, efficiency and specific speed. The PAT performance characteristics are still very complex to find a relationship to cover all pumps performance characteristics given in the datasheet (Baburaj et al, 2013). Fortunately, Nautiyal et al (2011) indicated the running of pump in reverse mode works without technical complications. The most common performance characteristics are presented below:

2.3.1 Head and flow rate

The ratios of head and flow rate for pump operating in reverse and pump modes is greater than 1. The conversion equations use slope/gradients method to correlate head and flow rate from optimum condition. More than twenty conversion equations are found in Bogdanovic-Jovanovic et al (2014); Nautiyal and Kumar (2011); Teuteberg (2010); Derakhshan and Nourbakhsh (2008); Singh (2005); Alatorre-Frenk (1994) and Williams (1994). The ratios of pump head and flow rate are calculated separately for most existing conversion methods. The head obtained in reverse mode is divided by pump head to get the head ratio and flow rate obtained in reverse mode is divided by pump flow rate to get flow rate ratio. The correlation of head and flow rate ratios related to specific speed for twenty eight (28) experimental data, separately collected from Tan and Engeda (2016), Singh (2005), Qian et al (2016), Fernández et al (2004), Derakhshan and Nourbakhsh (2008), Couzinet (2013) and Barbarelli et al (2017) as presented in Fig.4. The squared R is greater than 0.7.

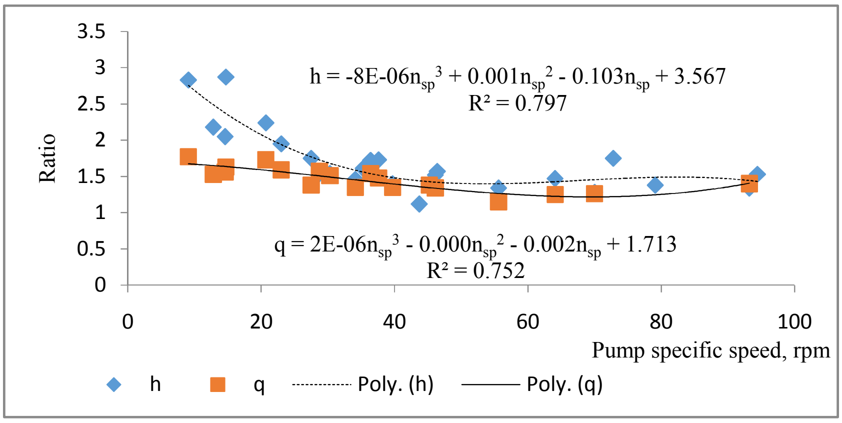

Fig. 4. Correlation of head and flow rate ratios versus specific speed

2.3.2 Power

The PAT power is the ratio of pump horsepower and its efficiency (Ventrone and Navarro, 1982). The efficiency data is collected from pump datasheet (Pedrollo, 2016). Alternatively, PAT power is estimated by using Equation (1) given the PAT efficiency conversion equations collected from Bogdanovic-Jovanovic (2014), Chapallaz et al (1992) and Williams (1994). Fig. 5 presents the variation of PAT power against standard pump rated power. The method is more suitable during the desk work studies. H, Q, g, η, ρ and P present the head, flow rate, acceleration due to gravity, efficiency, density of water and power. Subscripts t presents turbine mode.

$P_t = \rho * g \cdot H_t \cdot Q_t \cdot \eta_t$ (eq. 1)

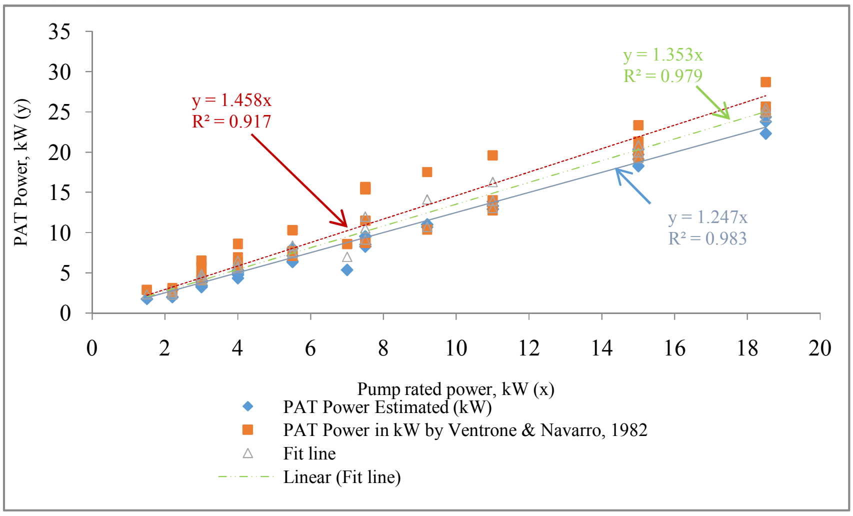

Fig. 5. Comparison of the PAT power with pump horsepower

2.3.3 Efficiency

The PAT efficiency tested from different research works for a range of the off-the-shelf pump (14.6 to 93.2rpm) is presented in Fig. 6. The efficiency-curves were digitized by using a Getdata software (GetData, 2017). Steller et al (2008) presented the overall efficiency of PAT against the percentage of flow rate. Tan and Engeda (2016) indicated the pump specific speed of 30.7, 43.7, 63.5 and 80.5 rpm operated with flow rate coefficient of less than 0.08 with constant flow rate coefficient. But, Singh (2005) indicated the pump specific speed range from 35, 36.4, 39.4, 45.2 and 46.2 rpm operated with flow rate coefficient less than 0.4 with percentage flow rate coefficient of less than 25 %; 61.3 and 79.1rpm operated with flow rate coefficient from 0.25 to 0.75. The flow rate coefficient variations do not affect the efficiency of the PAT. But, pump with low efficiency when operated in reverse mode has also a low efficiency. Also, the pump with higher specific speed delivered the highest efficiency and allowing the larger variation of flow rate coefficient compared to the low specific speed PAT. The overall-PAT efficiency is less than 86 %.

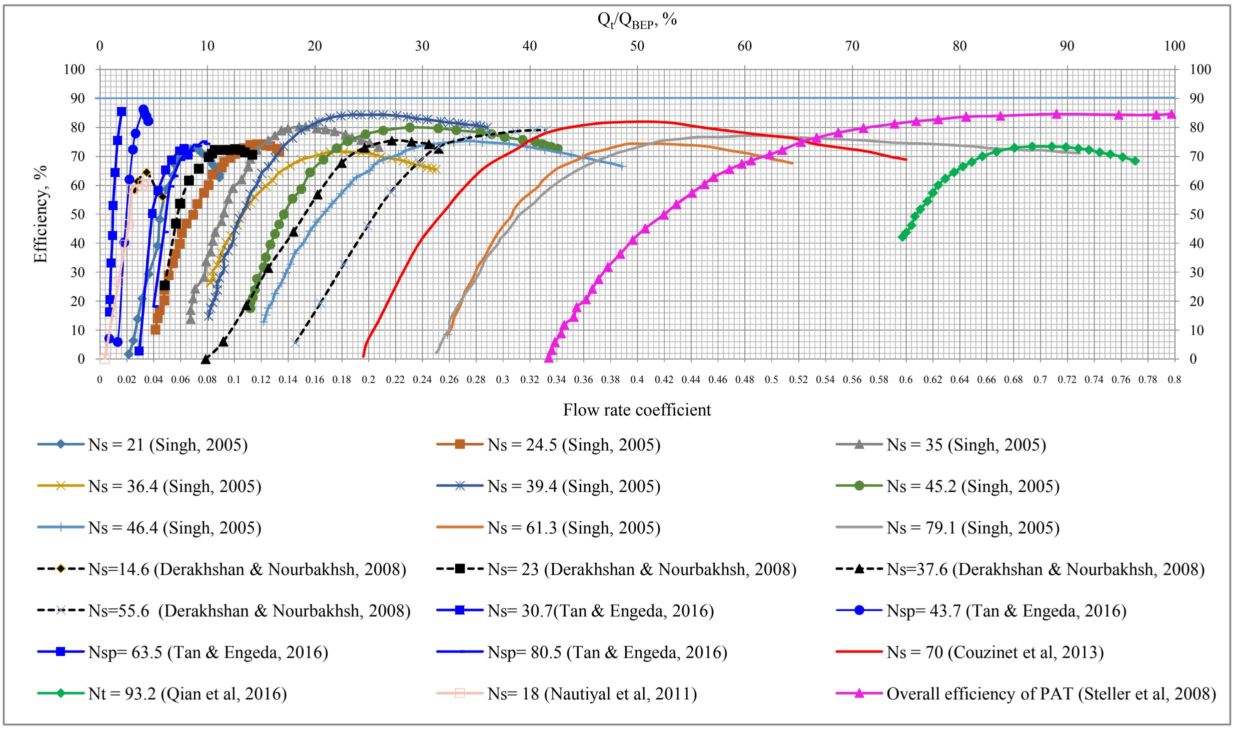

Fig. 6: Overall operating efficiencies for PAT from pump specific speed range from 14.6 to 93.2 rpm

2.4. Head losses

The difference of hydraulic pressure between the intake/forbay to the hydropower plant over the product of density and acceleration due to gravity presents the gross head. The head loss lower the available gross head that decreases the net head available to strike the impeller with blades. The head losses in the penstock, casing, impeller with blades and draft tube are discussed below.

2.4.1 Penstock

Water flowing through a penstock or canal encounters head losses due to friction and fittings (including elbow, tees, etc.). The head losses in the penstock are calculated by using friction loss tables, curves or a nomograph provided from the penstock/pipe manufacturer (Moran, 2016). For instance, 20 % increase in penstock diameter leads to a 60 % decrease in head losses (Gatte and Kadhim, 2012). Fernandez et al (2002) indicated that friction losses is reduced by increasing the diameter and/or reducing the equivalent length of the pump suction side. Alternatively, head loss estimated by using Equation (2) (Williams, 1995). Q_m is the pump flow rate given by the manufacturer based on the penstock diameter. L is the penstock length.

$$H_l(\%)= \frac{L}{H_t} * \left(\frac{Q_t}{Q_m}\right)^2 \qquad \text{(eq.2)}$$

Also, the Darcy-Weisbach equation used to calculate the head loss (Penche, 2004). Different penstock materials are based on the roughness height of commercial pipes for a given diameter and the Reynolds number obtained by using the Moody chart to interpolate the value of the friction factor (Moody, 1944). The roughness of commercial pipes is described in White (2011). Fig. 7 presents the variation of head loss against flow rate for 100 feet of PVC class 160 plastic pipe with a diameter less than 152.4 mm or 6 inches (Pipeline, 2017). Head loss reduces the available gross head as well as the expected power generation, but Penche and de Minas (1998) indicated that a power loss of 4 % is usually acceptable.

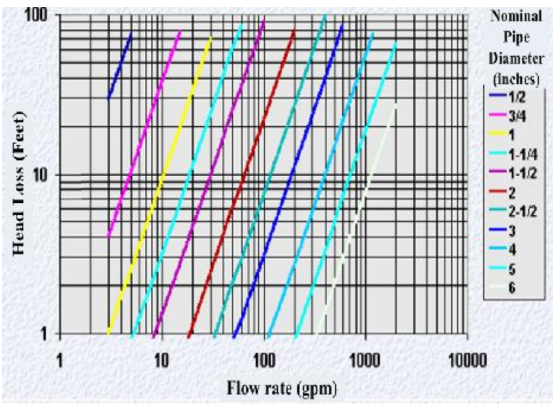

Fig. 7: Relationship of head loss versus flow rate (Pipeline, 2017).

2.4.2 Hydropower system

Water flow in the PAT from the inlet to strike the impeller with blades surrounding with casing is an exit at the outlet pipe connected to the draft tube. The most common micro hydropower head loss installed with PAT based on the rule of thumb and experimental data are presented in Table 1. Head loss varies from 5 to 33 % of the total penstock length and mostly are occurred for small and micro hydropower system (Williams, 1995). It is still indicated the head loss in the impeller with blades is higher compared to the draft tube and casing (Rawal and Kshirsagar, 2007).

Table 1: Percentage of head loss from PAT hydropower system

Head loss as percentage of total penstock length (%)	Applied condition	Source
5-25	Rule of thumb	Klingeman and Wheeler (1982)
10-20		Williams (1995)
10-15		Canyonhydro (2017)
10		Renewables First (2017)
12.2	Installed PAT	Smith and Ranjitkar (2000)
13.2	Installed PAT	Arriaga (2010)
< 33 for small systems	Rule of thumb	Gatte and Kadhim (2012)

3. Challenges of Using Pump as Hydro-turbine

The different challenges and description for PAT application in hydropower schemes are presented in Table 2.

Table 2. List of challenges and description for pump as hydro-turbine

Challenges	Description	Sources
Flow rate leakage	Leaking back of fluid from the high pressure side to the low pressure side that tends to lower the performance	Chapallaz et al (1992)
Range of flow rate	Particular pump can operate as much less that for a conventional turbine	Popescu et al (2003); Williams (1995)
Major design changes	Changing are based on the bearings design and checking the seals, stress and threaded of shaft	Chapallaz et al (1992)
Material types	i. Built-with carbon-impregnated nylon without many hard particles, broze or cast iron and eye-clearance fit the suction inlet ii. It also the shaft material should not easily scratched by knife	Williams (1995)
Head and flow rate	Pump operates at higher head and flow rates values in water turbine mode at the same rotational speed	Popescu et al (2003); Nautiyal et al (2011)
Efficiency	Efficiency of PAT is usually lower than that of conventional turbines	Patel et al (2015); Motwania et al (2013); Nautiyal et al (2011)

Torque	Reduction of rotation speed can lower the torque	Dribssa et al (2015)
Conversion equations	The performance characteristics related to head, flow rate, power, specific speed and efficiency are predicted differently from one pair to another by ±20 %	Williams (1995)
Runaway	Characteristic of runaway in PAT is more dangerous and essentially associated with increase of operating head compared to the actual operating head when is in load condition	Singh (2005)
Pump datasheet	Lacking of performance datasheet as the major limitation of using PAT	Buono et al (2015); Agarwal (2012)
Fixed geometric shape	PATs are very sensitive towards changing of head and flow rate within the fixed geometric shape i.e impeller and casing results to poor part-load performance	Ramos and Borga (2000); Singh (2005)
Constant flow rate	The construction of reservoir for PAT as small system is not a good option	Williams (1996)

4. Conclusions

This methodological approach helps to increase the awareness of harnessing the potential micro hydropower in off-grid remote areas by using off-the-shelf pump. The performance characteristics of pump that are changed when operated as turbine include head, flow rate, power, specific speed and efficiency. This article discusses the selection procedures, performance characteristics and challenges of using off-the-shelf pump. PAT efficiency indicates to have the maximum efficiency of about 86 % against the flow rate coefficient based on the twenty (20) collected tested characteristics for pumps specific speed range from 14.6 to 93.2 rpm and flow rate coefficient greater than 0 to 0.8. It also indicates the efficiency is constant when the percentage for flow rate coefficient variation is less than 25 %. Furthermore, this paper presents the main challenges of using PAT include the low range of flow rate, replacement of bearing, fixed the geometric shape, reduced of torque and lack of pump datasheet.

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