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AN EFFICIENT SIMPLE REACTION TYPE WATER TURBINE FOR PICO HYDRO APPLICATION

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ABSTRACT

The focus of the study is on the performance characteristics of an efficient Z-Blade turbine, which is classed as a simple reaction type water turbine that may be used in pico hydro applications. As a result, the geometrical design of the turbine as well as experimental results are provided. The test unit's applicability in low-head, low-flow situations was also investigated in this study. Using the governing equations that have been created using the principles of conservation of mass, momentum, and energy, the Z-Blade turbine has been investigated for an ideal and practical condition. Using various frictional losses factors (k-factors) for different working heads, the correlation between rotor diameter, angular speed, flow rate, power output, and efficiency is illustrated and analysed with reference to experimental data. The data were compared to theoretical results using inlet water pressures ranging from 30 to 50 kPa, turbines with rotor diameters ranging from 0.4 to 1.8 metres, and a nominal PVC pipe diameter of 25 mm (1”). This hydraulic reaction turbine, which has a simple fabrication method, can produce high power output and minimal power loss with an overall energy conversion efficiency of 68 percent under low-head low-flow water resources.

Keywords: low-flow, low-head, reaction turbine, pico-hydro, Z-Blade.

1. INTRODUCTION

Pico hydro is often underestimated and neglected by many people where they assume that the wind, PV, and the diesel-fuelled generator is more effective overall. The fact, pico-hydro operates 24 hours a day if there is a source of water from the streams [1-2]. However, most water turbines have an intricate design, which is a typical challenge with pico-hydro producing systems [3]. It necessitates high-tech machining by highly skilled people, which drives up manufacturing costs. Furthermore, most imported pico-hydro systems are incompatible with all sites, necessitating a custom-made design and equipment [4]. Once the turbine is installed, there is very little room for improvement. As a result, the most cost-effective technology is required to reduce costs, resulting in the pico-hydroelectric generation system being the top choice for rural families, followed by other green technologies [5-6].

Presently, too many turbines are produced in high-head and high-flow water condition [6-7]. Even if the potential energy available at low-head and low-flow is limited, a well-designed turbine will undoubtedly increase the captured energy efficiency [8]. Surprisingly, there are many water resources in nature with a depth of less than 5 metres, which is the most useable head for pico-hydro turbines [9]. However, there is currently no commercially produced reaction hydraulic machine type turbine that can run at low-head with very low-flow. Split reaction turbine (SRT) is probably the closest, however its application domain is only for low-head and not for weak flow hydro sites.

2. Z-BLADE WATER TURBINE BASIC DESIGN

The Z-Blade turbine is a low-cost outward-flow reaction turbine that has been created to help overcome technical and economic constraints. It can be used in water resources with low head (3 to 5 meter) and low flow (3 L/s and lower). The easiest hydro turbine to build is a Z-Blade turbine that is adapted and upgraded from CPT, influenced by SRT, and inspired by a water sprinkler. Due to the simple design and use of ordinary plumbing pipes and fittings made of PVC pipe, no specialist employees are required.

The study will primarily focus on the development and testing of a unique Z-Blade reaction water turbine for low-head low-flow applications that operates on the same concept as SRT and CPT in the pico-hydro range. Based on the shortcomings of SRT and CPT, Z-Blade as shown in Figure-1 has improved features that are given in this study. The design and building of a Z-Blade turbine using locally accessible materials is detailed, which addresses cost and applicability issues for minor water resources. The Z-Blade turbine does not experience jet interference, which is a major problem of reaction type turbines, and the non-interference rotational speed has been calculated. The test unit's performance will be investigated and analysed, as well as potential areas for improvement.

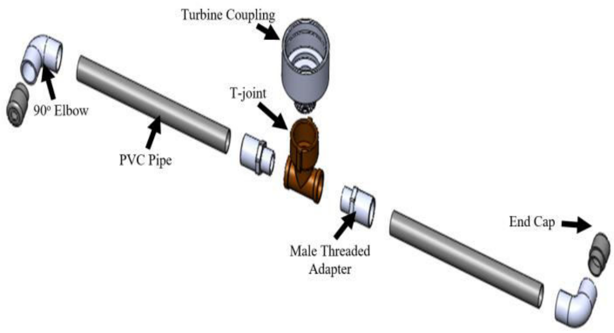

Figure-1. Z-Blade water turbine.

The SRT was developed after the Cross Pipe Turbine (CPT) was investigated and found to be inefficient for producing electrical power at low head hydro [10]. CPT, which was first implemented in 2009, has several flaws [11]. Due to the set dimensions of the 3” standard galvanised iron pipe (GI) fittings, the turbine diameter and nozzle exit area are limited [12]. Furthermore, when low head water circumstances exist, the CPT prototype rotates slowly and inefficiently, especially when the turbine has a big diameter [13]. When the CPT rotates, it loses a large amount of energy, with the V-ring lip seal causing the most power loss [14]. Due to these constraints, the CPT design (illustrated in Figure-2) is abandoned in favour of the SRT.

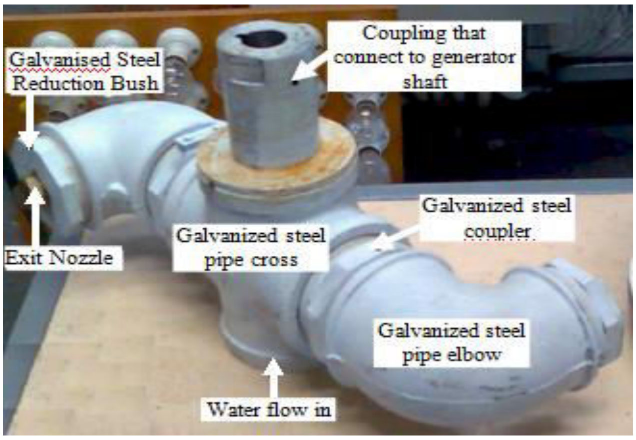

Figure-2. Cross pipe turbine (CPT) [10].

3. EXPERIMENTAL WORK

The performance of the Z-Blade turbine was measured using the test rig configuration depicted in Figure-3. The water collected from a tiny drainage near the laboratory is stored in a polypropylene water tank with a capacity of 150 litres. The water tank is supported by a six-meter-high metal framework tower, and it is set up so that water from the polypropylene tank enters the Z-Blade turbine from the top.

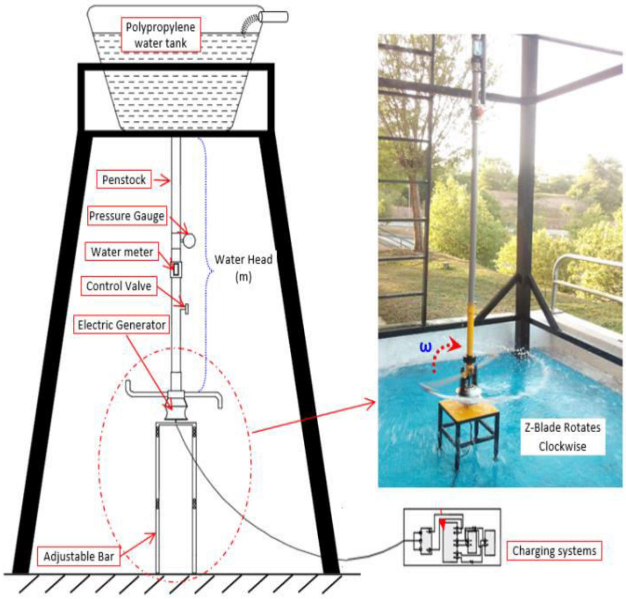

Figure-3. Z-Blade turbine test rig.

The test rig can produce water at a height of up to 5 meter and a flow velocity of up to 3 litres per second. Clogging of hydro-kinetic turbines by floating debris is also a major issue in many waterways [15-18]. This test rig will not have this clogging problem since all the water that goes into the water tank will be filtered beforehand to ensure that there are no pollutants in the water tank. The water in the poly tank flowed to the blade’s arm through the penstock made from PVC pipe with 3” outer diameter. Then, the water is divided into two after it flows through the T-joint pipe and finally, the water is sprayed out from the blade through the nozzle drilled at the end cap of PVC pipe. When fluid exits the nozzle tangentially, a reaction force is generated, forcing movement in the opposite direction, and driving the rotor to rotate clockwise, producing mechanical power [4].

The actual water flow through the turbine was measured using a digital flow metre (GPI Model TM 100). A control valve on the main supply line can regulate the flow rate of water delivered to the turbine. Before the water metre, a pressure gauge with a range of 0.1 to 1.0 bar was installed. Furthermore, a 250 W AC Motor (Golden Motor Model 902-24R-902) is used to create electricity, and the generator's output is connected to the charging system. A rectifier, voltage controller, batteries, and a light bulb as a load make up the charging system. Before being used for any electrical equipment, all the generated electricity is stored in the batteries.

4. PRINCIPLE OF Z-BLADE TURBINE

` The radius of the blade, R, was altered from 0.2 metre to 2.0 metre, and the height of the water, H, was modified from 2 metre to 5 metre for the experimental work. PVC pipe, S, nominal diameter 25MM, is used for the rotor blade (1”). These are the parameters that were utilised to investigate the Z-Blade turbine's performance. Instead of being used as a garden water sprayer, the

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theoretical and practical results show that this unique turbine has a lot of promise for use in pico-hydro systems, especially at low-head and low-flow water resources. The rotor stationary reference frame is shown in Figure-4 along with the parameters involved in the ideal condition analysis.

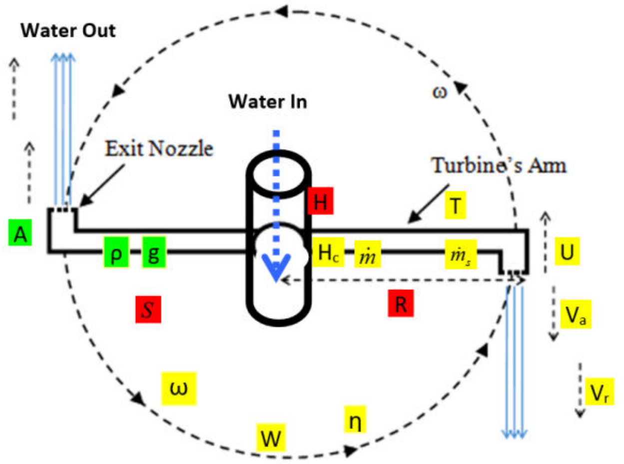

Figure-4. Parameters involve for ideal condition analysis.

The governing equations obtained and discussed by [10-14] are revisited using the principle of conservation of mass, momentum, and energy. It is used to investigate the performance of the Z-Blade reaction water turbine in the presence of incompressible water. The following are the required equations for an ideal scenario of no frictional losses:

$$U = R\omega \tag{1}$$

$$V_a = V_r - U \tag{2}$$

$$V_a = V_r - R\omega \tag{3}$$

$$\frac{1}{2}\rho V_r^2 = \rho g (H + H_c) \tag{4}$$

Centrifugal head, H_c when the turbine is not stationary,
$\omega \neq 0$,

$$H_c = \frac{U^2}{2g} = \frac{R^2\omega^2}{2g} \tag{5}$$

Combining Eqs. (4) and (5) gives,

$$V_r = \sqrt{2gH + R^2\omega^2} \tag{6}$$

Mass flow rate, $\dot{m}$ sprayed out of the nozzle can be expressed as,

$$\dot{m} = \rho A V_r \tag{7}$$

Therefore,

$$\dot{m} = \rho A\sqrt{2gH + R^2\omega^2} \tag{8}$$

The angular speed of the rotor can be calculated by rewriting Eq. (8)

$$\omega = \sqrt{\frac{\left(\frac{\dot{m}}{\rho A}\right)^2 - 2gH}{R^2}} \tag{9}$$

Torque is the product of mass flow rate, absolute velocity of water and radius of the turbine.

$$T = \dot{m}V_a R \tag{10}$$

The turbine's mechanical output power $\dot{W}$ is,

$$\dot{W} = T\omega \tag{11}$$

The system's ability to transform potential energy to work efficiency can be written as,

$$\eta = \frac{\dot{W}}{\dot{m}gH} \tag{12}$$

The overall rate of hydraulic energy provided at the inlet must be equal to the rate of mechanical work produced, according to the principle of conservation of energy. The rate of kinetic energy loss due to the water flowing out at the outgoing water jet is then added [10].

$$\dot{m}gH = \dot{W} + \frac{1}{2}\dot{m}V_a^2 \tag{13}$$

For adapting to the real-world operating environment, the power loss associated with the flow of water through the Z-Blade reaction turbine must be considered. [10,14] defined the k-factor as a factor that represents the fluid frictional power loss related with fluid flow through the turbine. Eq. (13) becomes as follows when extra power loss owing to the k-factor exists:

$$\dot{W} = \dot{m}gH - \frac{1}{2}\dot{m}V_a^2 - \frac{1}{2}\dot{m}kV_r^2 \tag{14}$$

Combining Eqs. (1), (2), (10), (11) and (14), we then have

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$$V_{r_{k-factor}} = \sqrt{\frac{1}{(1+k)}}\sqrt{2gH + R^2\omega^2} \quad (15)$$

When there are no frictional losses in ideal conditions, the k-factor equals zero, and Eq. (15) becomes Eq (6)

Combining Eqs. (7), (15), we then have

$$\dot{m} = (\rho A)\left(\sqrt{\frac{1}{(1+k)}}\right)\left(\sqrt{2gH + R^2\omega^2}\right) \quad (16)$$

Eq. (16) can be rearranged to determine the k-factor as follows:

$$k = \frac{2gH + R^2\omega^2}{\left(\frac{\dot{m}}{\rho A}\right)^2} - 1 \quad (17)$$

According to [10-14], all the parameters in Eq. (17) can be obtained empirically to estimate the value of the k-factor. When the water head and total nozzle exit area are constant, the radius of the turbine, the angular speed of the rotor, and the mass flow rate of water through the turbine all feel the impacts of any changes in the k-factor, according to Eq. (17). A high k-factor should be avoided since it lowers the rate at which mechanical output power may be generated.

5. PERFORMANCE CHARACTERISICS

The data was compatible with repeatedly carried out experiments, according to the overall performance results acquired from various experimental efforts. The governing equation was used to forecast the theoretical performance characteristics, which considered kinetic energy losses and fluid frictional losses. It is important to note that all of the data in Figures 5, 6 and 7 depict the performance of a Z-Blade turbine with rotor diameters ranging from 0.4 to 1.8 meter and a nominal PVC pipe diameter of 25 mm (1").

Power Loss

Figure-5 shows the theoretical and experimental results of power loss at different water heads and rotational speed. All the points in the power loss curves are plotted towards the longer turbine diameter of ZBT in a clockwise (CW) direction.

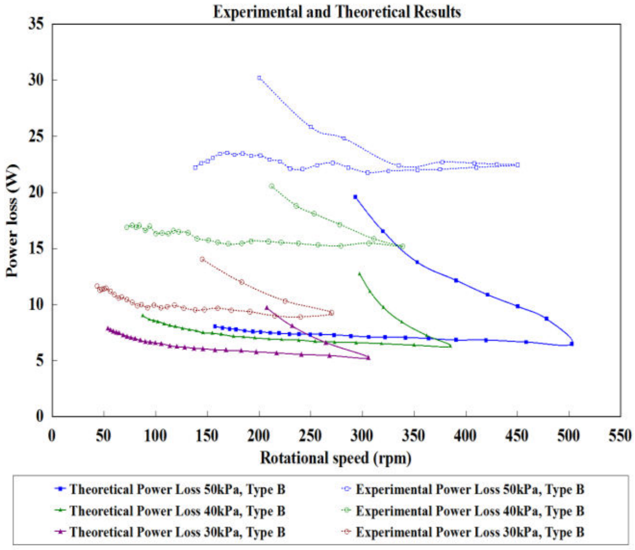

Figure-5. Power loss with rotational speed at different water heads (Type B).

By applying the conservation of energy as stated in equation 13, it is evident that there is a kinetic energy loss ($\frac{1}{2}mV_a^2$) related to the water flowing out, marking an ideal condition (k=0). Practically, for all operating water heads, other losses have been observed, namely, the k-factor where the fluid frictional losses have been introduced [14]. According to the energy balance equation shown in equation 14, the type of loss associated with the water leaving the turbine is known as kinetic energy loss ($\frac{1}{2}mV_a^2$), which occurs in both ideal and practical situations. However, another type of loss, known as a fluid frictional loss ($\frac{1}{2}mkV_r^2$), which is associated with the flow of water through the turbine, only happens at practical situations where k-factor $\neq 0$ [11].

Figure-5 shows that the k-factor has a significant impact on the power loss generated by the Ø0.025m blade for all water head. Overall, the power loss for theoretical (with k-factor = 0) and the experimental data have quite a significant difference in magnitude, especially at higher water head level. The difference becomes even more notable with the increment of the k-factor. The effect of the fluid frictional factor on power loss is considerably insufficient at low water head. Since the rotational speed, mass flow rate, and relative velocity are low in the situation of low water head, the existence of the k-factor is, in this case, insignificant.

5.1 Power Output

Figure-6 shows the mass flow rate and mechanical power versus rotor diameter of Z-Blade turbine at 50kPa water head. The theoretical results were computed as the product of mass flow rate (kg/s), radius of the rotor (m), absolute velocity (m/s) and angular velocity (radian/s). While, by knowing the value of rotor diameter, angular speed, and mass flow rate during the experiments, the mechanical power of the tests can be obtained.

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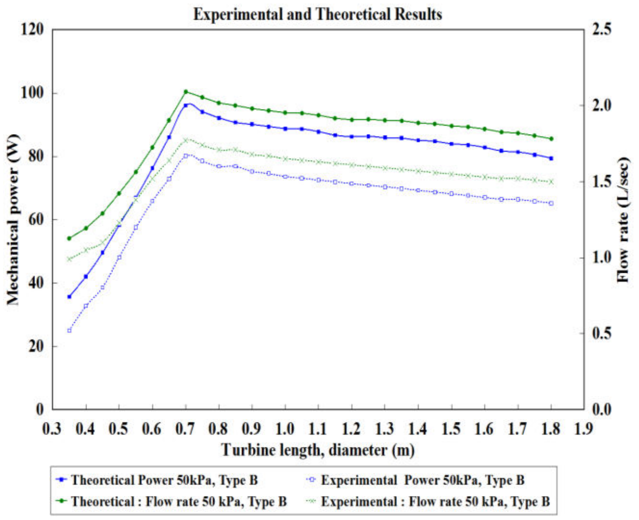

Figure-6. Mechanical power and water flow rate of Type B at 5m head with various turbine length.

The value of mass flow rate increase with the increment of water head and it is equivalent to the equation 8. In addition, the experimental mass flow rate curve is lagging to the theoretical curve. Overall, this turbine only uses 2.1 Litre of water per second at 5m water head to produce power in the range of 100Watt. It meets the research objective and proved that the Z-Blade turbine capable to operate in the low-head and low-flow water condition.

Furthermore, even when the rotor diameter is altered, the actual power output curve follows the predicted curve. The power output curve is proportional to the mass flow rate curve in a unique way. The rate of increase in mass flow rate begins to slow dramatically at a certain point (rotor diameter). This is also the point at which the growth in power output begins to diminish dramatically. As the working head grows larger, this point on the graph shifts to the right, causing the rotor diameter value to get larger. The experimental and theoretical results are likewise very similar, indicating that the experimental results are trustworthy. Overall, the turbine performance at 50kPa is better than at 30kPa.

5.2 Efficiency

According to the conservation of energy principle as shown in Equation 14, the mechanical output power perforce to be reduced because the gravitational potential energy supplied is minus with the kinetic energy lost because of absolute velocity, and losses related to the fluid flow in the blade and nozzle. Refer to the Equations (2), (11), (15) and (16), the coefficient k-factor that is associated with the relative velocity will affect the components of absolute velocity and mass flow rate. It makes the torque generated by the Z-Blade turbine experience double reduction due to reducing of absolute velocity and mass flow rate. Simultaneously, causing the efficiency of the Z-Blade turbine in converting the potential energy into output power become small.

In Figure-7, with constant water head, the higher the k-factor, the lower the efficiency, even though, the speed of the turbine is added. Furthermore, the angular speed of Z-Blade turbine is decrease towards the higher value of k-factor. If the k-factor is remained, the efficiency is increased with a low rate, even though, the speed of the turbine is added.

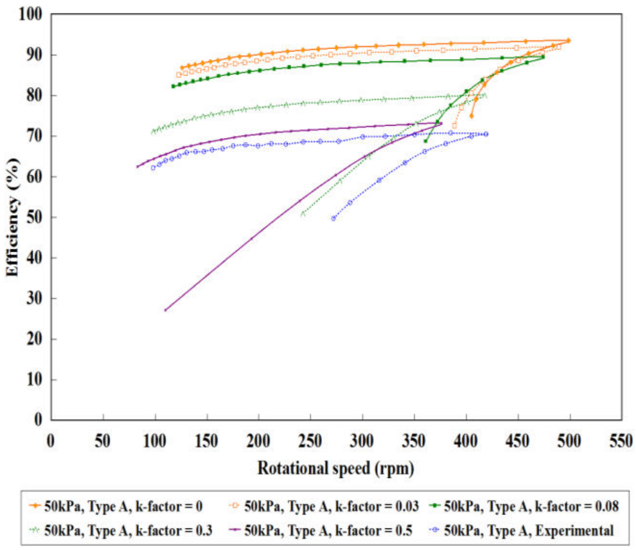

Figure-7. Efficiency of Type A at 5m water head for various k-factor and rotational speed.

6. CONCLUSIONS

Through the theoretical analysis and experiments, the turbine will have a high value of rotational speed, mass flow rate, mechanical power, energy loss and high efficiency when the operational water head is 5 m. On average, the efficiency given by the experimental data are 68% for a water head of 5 m. When compared to a little expenditure for the usage of a Z-Blade turbine in a pico hydro project, this situation is seen highly worthwhile.

Generally, to get a high speed of rotor and high output power, many hydro turbines require a larger quantity of water. Theoretically and practically, Z-Blade turbine is the only pico-hydro machine that require a very little amount of water to operate. Interestingly, when the water head is constant, and the length of the rotor is increases, the behaviour of mass flow rate, and mechanical power are similar and consistent. Furthermore, there is a unique value of the rotor diameter where this is the turning point for the mass flow rate and power output. During the initial state, the rate of increase for both parameters is very high, however once it meets the unique diameter, the rate of growth for both parameters will begin to reduce drastically. And this situation will persist, even though, the rotor diameter is increased.

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NOMENCLATURE

A	Total nozzle exit area (m^2)
g	Acceleration due to gravity (m/s^2)
H	Water height in reservoir (m)
H_c	Centrifugal head (m)
ω	Angular velocity of the rotor (rad/s)
$\dot{m}$	Mass flow rate of water through the turbine (kg/s)
$\dot{m}_s$	Mass flow rate of water through the turbine when it is stationary (kg/s)
η	Efficiency of conversion of potential energy to work
R	Radius of the rotor (m)
ω	Angular velocity of the rotor (rad/s)
δ	Midpoint of the nozzle to the turbine wall (m)
ρ	Density of water (kg/m^3)
T	Torque (N.m)
T_S	Torque when turbine is stationary (N.m)
$\dot{W}$	Output power (W)
V_r	Relative velocity of water with respect to the nozzle (m/s)
V_a	Absolute velocity of water leaving nozzle with respect to a stationary observer (m/s)
U	Tangential velocity of the nozzles (m/s)
k	Factor for viscous losses
SRT	Split reaction turbine
CPT	Cross Pipe Turbine
λ	Radius of nozzle exit area (m)

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