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A Novel Z-blade Reaction Type Turbine for Low Head Low Flow Water Condition

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***Abstract:** This paper discusses the performance characteristics on efficiency and applicability of the test unit under low-head and low-flow condition for a novel Z-blade reaction type hydraulic turbine. Unlike large hydro power system, this technology's superiority lies in the fact that it can harness electrical energy even from a small stream of water as energy sources and it does not poses any adverse environmental impact. This turbine was developed for an ideal and practical case which investigated applying the principal equations that were derived using the philosophies of conservation of mass, momentum, and energy. Assuming frictional losses factor or k-factor for different operating head, the relationship between rotor diameter, angular speed, flow rate, and power output was plotted and elaborated with allusion to the experimental data. Experiments were carried out at 5m head and below with the water flow rate less than 2.5L/sec, and it was evaluated against theoretical results. The turbine has a capability to achieve high values of rotational speed (up to 500 rpm) with minimal mass flow rate and high efficiency (up to 78%) at low head water condition (5m).*

Keywords **: Low-flow, low-head, pico-hydro, reaction turbine.**

I. INTRODUCTION

The pico-hydro power generation system is defined as a small-scale green energy generation, which utilises water power to produce electrical energy with a capacity of less than 5 kW [1,2]. Until recent years, research works on pico-hydro has been very much neglected, when related to other green energy types, such as wind, PV, and the marine [3]. This is mainly due to the lack of applications to improve the efficiency of the pico-hydro technology as well as the lack of interest because of implications of cost of production—all these despite its huge potential to continuously generate electricity, given an equally steady source of running water.

As shown in Fig. 1, majority of the available hydro turbines are made for high-head and high-flow water conditions [4], due to the markets of balance — the cost advantages that enterprises obtain due to size, output, or scale of operation — as well as popularity among power utilities. Even though the potential energy available at low-head and low-flow is considered low, with a proper design of the turbine, the potential harvested energy efficiency can be substantial. One advantage of having such turbine is its potential to continuously operate, even when water sources are scarce, particularly during the drought season. Remarkably, apart from huge water dams, there are abundant water resources in nature that have less than 10 m of water head, which is suitable for pico-hydro turbines [5].

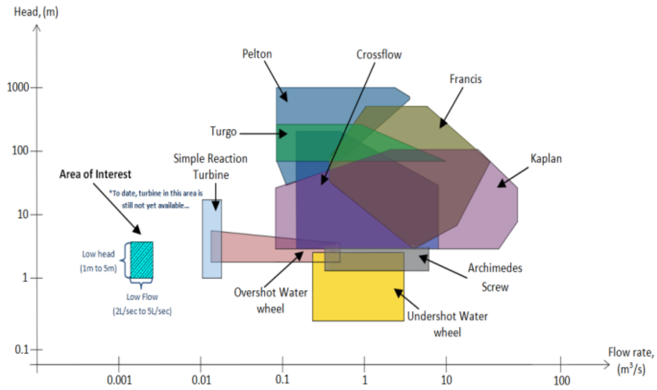

Fig. 1. Typical turbine application range chart adapted from data in [5]

Currently, there are two kinds of water turbines, namely impulse and reaction. However, until now, there is no commercially available reaction hydraulic machine type turbine that can operate at low-head and low-flow water source. The closest type of this kind is known as Split Reaction Turbine (SRT) [6-10], but its application domain is only for the low-head and not for the low water flow rate hydro sites. The SRT is developed as a replacement for its previous ancestor, the Cross Pipe Turbine (CPT) [6-7], which was introduced in 2009. Eventually, CPT was found to have many limitations and unsuitable for efficiently producing electrical power at low head hydro sites [6-7].

The next section will focus on the basic design, principle, and analysis of a new Z-Blade reaction water turbine that operates on the same standard as the SRT and CPT for the pico-hydro range for low-head, low-flow applications.

II. HYDRAULIC WATER TURBINE BASIC DESIGN

This section focused on the design methodology that has been systematically carried out to achieve the objectives. The methodology applied to explore, theoretically and experimentally, on the performance appearances of a Z-Blade reaction type water turbine (ZBT) for ideal and non-ideal condition.

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Among the significant modifications applied with reference to the CPT is the replacement of the standard galvanised iron (GI) pipe with grey PVC pipe Class D, which can be conveniently modified. As shown in Fig. 2, standard PVC pipe fittings with a nominal diameter of Ø25mm (1”) were used to develop the Z-Blade turbine.

This turbine has four important turbine parts: (a) one unit of T-joint pipe at the centre, (b) two units of arms made of PVC male threaded adapter fittings and PVC pipes of various lengths, (c) two units of 90° PVC elbow, and (d) two units of PVC end cap. The nozzle for the water stream jet is produced by drilling the PVC end cap. No spray nozzles are fixed at the exit of both elbows, as used in the CPT. The Z-blade turbine also exhibits features better than those of the CPT and SRT, given that it has no fixed dimensions for the nozzle exit area. Thus, the nozzle exit area can be easily adjusted and modified. All components, such as the male adapter fitting, PVC pipe, 90° PVC elbow, and end cap, are easily available off the shelf at local hardware stores.

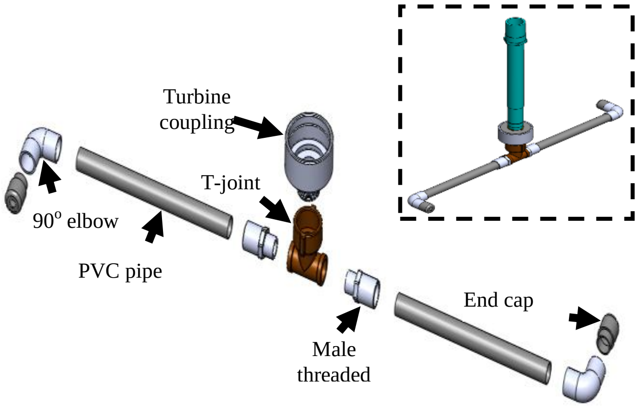

Fig. 2. Z-Blade turbine

Turbine coupling, as shown in Fig. 3, is a critical part of the Z-blade turbine because this refers to the meeting point of two pipelines; one is a stationary section, whereas the other is a rotating section. Ideally, turbine coupling must prevent supplied water from trickling out, such that supplied potential energy is maintained, and no energy is wasted.

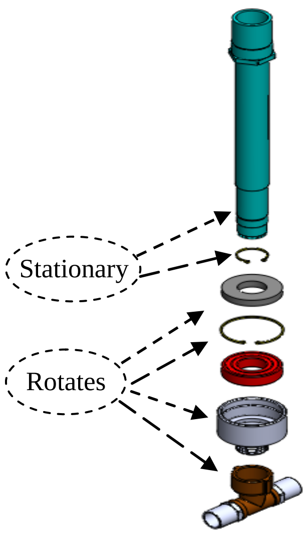

Fig. 3. Z-Blade turbine coupling

The rotating section consists of the coupling housing, radial shaft seal, bearing, 70 mm C-clip, and T-joint pipe. Meanwhile, the stationary section only consists of the inlet pipe and 30 mm C-clip. This coupling is designed to facilitate the easy removal of parts in four simple steps: i) removal of the Ø30 mm c-clip; ii) removal of the radial shaft seal; iii) removal of the Ø70 mm c-clips; and iv) removal of the bearing. Consequently, the reassembly process is simply the reverse of this procedure.

Base on the explanation given in a previously published thesis [7] and in a textbook [11[, the factors shown in Table I were considered when deciding on the use of a PVC pipe as a turbine rotor.

Table- I: Advantages of the use of a PVC pipe [7,11]

Physical Characteristics	Description
General	Most widely used in small hydro schemes throughout the world
Weight	Lightweight and can be handled, transported, and installed more quickly
Corrosion	Has good anti-corrosive properties and does not rust
Friction loss	Excellent friction loss characteristics and smoother than most materials, thus inducing less resistance for any given diameter
Cost	Relatively cheap and widely available in a range of sizes; a smaller diameter PVC pipe can be used for a given application to reduce transport and installation costs
Jointing	Simple fabrication, because the pipe section can be joined using a special glue called PVC cement or spigot; symmetry can be easily maintained and minimum balancing is required
Pressure	Highly elastic and does not induce high surge pressures; suitable for high-pressure use with different pressure ratings achieved by varying the wall thickness of the pipe; outside diameter remains constant over a range of pressure ratings for a given diameter

III. PRINCIPLE OF Z-BLADE TURBINE

A few assumptions were made when losses related to water flow from water tank or storage and piping are neglected [6-10]. Likewise, assumptions related to automated harms such as windage losses due to the turning of the turbine and bearing frictional losses of the pipe coupling were made when these, too, are neglected [6-10]. However, the power loss related with the flow of water through the turbine needed to be factored in. Hence, throughout the experiments, it was assumed that gravity and water density were constant. Fig. 4 shows the rotor stationary reference frame indicating the parameters involved for ideal condition analysis.

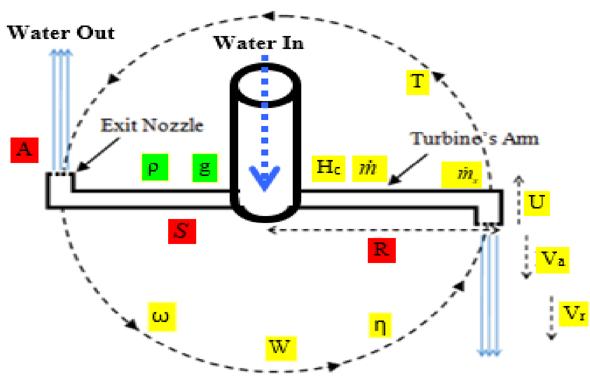

Fig. 4. Parameters involved in ideal condition analysis

By using the principle of preservation of mass, momentum and energy, the principal model and equations that have been derived and discussed by [6-10] are revisited. The mathematical model is applied to the Z-Blade reaction water turbine in order to examine the performance under the incompressible water condition. The appropriate equations for an ideal case of no frictional losses are as follows.

$$U = R\omega \quad (1)$$

$$V_a = V_r - U \quad (2)$$

$$V_a = V_r - R\omega \quad (3)$$

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

$$H_c = \frac{U^2}{2g} = \frac{R^2\omega^2}{2g} \quad (4)$$

$$V_r = \sqrt{2gH + R^2\omega^2} \quad (5)$$

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

$$\dot{m} = \rho A\sqrt{2gH + R^2\omega^2} \quad (6)$$

The angular speed of the rotor can be calculated by rewriting equation (6):

$$\omega = \sqrt{\frac{\left(\frac{\dot{m}}{\rho A}\right)^2 - 2gH}{R^2}} \quad (7)$$

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

$$T = \dot{m}V_a R \quad (8)$$

The mechanical output power $\dot{W}$ produced by the turbine:

$$\dot{W} = T\omega \quad (9)$$

The effectiveness of the system being able to transform potential energy to work can be put as:

$$\eta = \frac{\dot{W}}{\dot{m}gH} \quad (10)$$

The power loss related with the flow of water through the Z-Blade reaction turbine must be considered to assimilate the real operating situation. The k-factor introduced and defined by [5-8] is a factor that signifies the fluid frictional power loss connected with the fluid flow through the turbine. With the existence of another power loss due to k-factor, the equation becomes:

$$\dot{W} = \dot{m}gH - \frac{1}{2}\dot{m}V_a^2 - \frac{1}{2}\dot{m}kV_r^2 \quad (11)$$

For an ideal situation, when there are no frictional losses, the k-factor = 0, the mass flow rate can be expressed as:

$$\dot{m} = (\rho A)\left(\sqrt{\frac{1}{(1+k)}}\right)\left(\sqrt{2gH + R^2\omega^2}\right) \quad (12)$$

The k-factor can be deliberated by rearranging Eq. (12) as follows

$$k = \frac{2gH + R^2\omega^2}{\left(\frac{\dot{m}}{\rho A}\right)^2} - 1 \quad (13)$$

As described by [6-10], in order to determine the value of k-factor, all the parameters in Eq. (13) can be gathered experimentally.

Referring to Eq. (13), if the water head and total nozzle exit area remains constant, the change in turbine diameter, rotational speed, and the mass flow rate also will vary the k-factor value. However, a high value of k-factor should be avoided because it reduces the rate of mechanical output power.

IV. PERFORMANCE CHARACTERISTICS

This section shall discuss the experimental results and findings in assessing the Z-blade performance. The theoretical recital appearances were expected using the governing equation while considering the kinetic energy losses and fluid frictional losses.

Based on based Table II, the experimental mass flow rate is slightly decreased compared with the theoretical estimation because of the previously discussed frictional losses factor (k-factor).

From Table II, the data taken are refer to the highest efficiency for different k-factor and head. The higher the efficiency it decreased of the rotational speed.

In addition, Fig. 5 shows the theoretical and experimental curves for efficiency and mass flow rates compared to the rotating speed of the turbine.

It is necessary to note that all the points in the curves shown in Fig. 5 are plotted towards the longer turbine diameter in counter clockwise (CW) direction.

The curves show uniform and distinctive line characteristics for all water head levels. Furthermore, the experimental curve is lagging the theoretical curve with an obvious difference, especially at a high operational water head level.

Towards the highest rotational speed, the curves of mass flow rate and efficiency have a higher rate of increment. However, once the turbine reaches the maximum speed, the rate of increment for both parameters is reduced. Overall, both parameters (efficiency and mass flow rate) incline to shift towards the left of the graph with a reduction in the water head and angular speed of the rotor.

Table- II: Maximum values recorded using ϕ0.025m:1inch blade

Head (m)	Rotational Speed (rpm)		Mass Flow Rate (L/sec)		Efficiency (%)	
	Ideal	Exp.	Ideal	Exp.	Ideal	Exp.
5	560	200	2.4	2.0	95	90
3	300	100	1.3	1.2	84	84

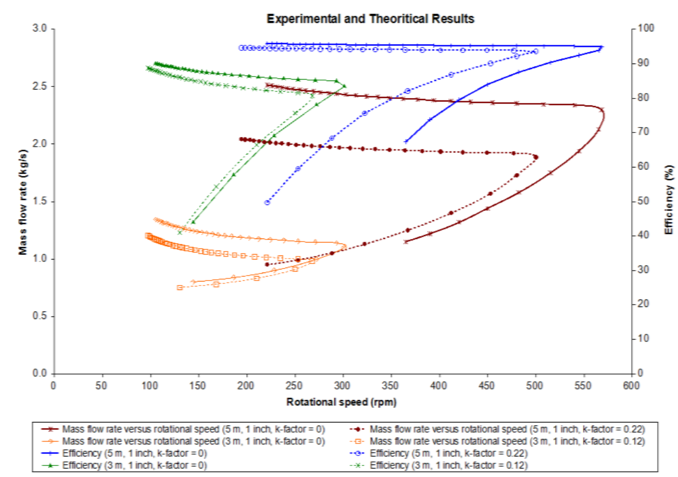

Fig. 5. Mass flow rate and efficiency versus angular speed of the rotor

According to Eq. 12, it can be seen that the rate of increase in mass flow rate is high as the turbine angular velocity increases [10]. Such increase occurs for turbine diameters of short to medium length. The mass flow rate still increases, but at a very low rate of increment, when rotational speed is reduced for a turbine diameter of medium to long length, which occurs because of the increment in turbine diameter increases the centrifugal head while influencing the mass flow rate. We can thus conclude that, with a higher water head, both rotor speed and mass flow rate increase, such that high-efficiency performance can be achieved.

In reality, the Z-Blade turbine has the capability to achieve more than 80% efficiency, thus outperforming the SRT (50%) [7] and CPT (26%) [6]. Interestingly, this innovative turbine only needs 5 m of water head and requires an extremely low mass flow rate at 2.3 kg/s. The Z-blade turbine is also predicted to have very high techno-economic characteristics.

V. CONCLUSION

The most important factors that significantly influence the performance of the Z-blade turbine are water head, mass flow rate, turbine diameter, and relative velocity. The performance of the Z-Blade turbine increases with higher water head and mass flow rate. Overall, the theoretical prediction and the experimental data exhibit a significant difference, especially at higher water head levels. In summary, the Z-Blade turbine, that is a modified concept which similar to a garden water sprinkler, has many advantages that are proven throughout this paper, both theoretically and experimentally.

VI. FUTURE WORK

The Z-blade turbine that introduced in this paper will be further tested and investigated in terms of its power production potential at a low-head, low-flow hydro site on several rural areas in peninsular Malaysia.

The method used for pico-hydro site survey will be briefly discussed, and the optimum layout design of pico-hydro system for this site will be presented. Investigations on the characteristic curve will be conducted to understand the performance of this system particularly during the rainy season and the driest period. In addition, the off-grid battery-based pico-hydroelectric system will be discussed, along with an illustration of its primary components, to prove that the system could supply electricity to meet the demand of local residents.

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