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Economic Analysis on Design of a Simple Hydraulic Reaction Type Turbine for Low-Head Low-Flow Pico Hydro

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Abstract: The purpose of this paper is to establish a techno-economic analysis on the design of a new Z-Blade turbine focusing on problems of costing and manufacturing process which focus on a low-head and low-flow pico hydro. Pico hydro generation system with a capacity less than 5kw has been gaining increasing attention as preferred methods of clean power generation. Accordingly, the design and operating procedures as well as economic analysis for a Z-Blade reaction type turbine are described in detail. Furthermore, the constructive analysis of the literature on the simple reaction type water turbine are discuss through quantitative summarization, classification, costing and comparison. In this paper also, will re-evaluated the manufacturing process of the SRT and CPT based on techno-economic analysis and the disadvantages of both turbines are identified. Meanwhile, the additional features of Z-Blade will be investigated under low-head low-flow water resources with simple geometrical design and low fabrication cost. Ideally, this hydro generation system is inexpensive and has a simple fabrication method with costing estimation at only USD76, which comprises 7.6% of total cost of hydro-electric installation and capable of producing mechanical power up to 115W under low-head and low-flow water resources.

Keywords **: Low-flow, low-head, pico-hydro, reaction turbine, techno-economic, SRT, CPT.**

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 compared to other green energy types, such as wind, PV, and the marine [3].

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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.

One of the most common problems faced by researchers in the pico-hydro generation system is that most water turbines require extremely intricate design specifications. Consequently, it requires high-technology machining by highly skilled workers; hence, due to the high financial cost of production, the system is generally deemed as not cost effective to manufacture. Furthermore, most pico-hydro systems developed are non-standard and cannot be used for all type of sites i.e., they require custom-made design and equipment [1]. Moreover, once the turbine is installed, the need to upgrade the design scheme — while very slim — may be very expensive [2]. With that in mind, better techno-economic options are needed in order to lower the cost and at the same time market pico-hydroelectric generation as a popular choice for rural households, at par with other green energy technologies such as solar and wind [3-4].

From literatures, current small scale low head and low flow type hydro turbines are expensive and complex for small power generation and small domestic consumer level. Considering this problem, a low cost and low head low flow hydro turbine are critically needed to encourage the use of hydropower available from any sources naturally like creeks and small rivers. Currently, there are two types 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) [5-9], 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) [5-6], which was introduced in 2009. Table I shows the comparison between SRT, CPT and Z-blade turbine in terms of design and materials.

Table- I: Comparison of the three types of simple reaction turbine [5,10]

Simple reaction turbine	SRT	CPT	Z-Blade
Material	Grey PVC pipe	Galvanised steel pipe	Grey PVC pipe
Design Requirement	Splitting a plastic pipe into halves and then off-setting their centres between top and bottom plates to create the exit nozzles.	Cross pipe at the centre with the two arms made out of adapter fittings. Each arm carries a reduction elbow to direct the flow in the tangential direction to the rotor diameter. Solid stream jet nozzles are attached to both the elbows at the exit.	Four important turbine parts: (a) T-joint pipe at the centre, (b) Arms made out of PVC male threaded adapter fittings and PVC pipe with variation of lengths, (c) 90^o PVC elbow and (d) PVC end cap. Nozzle is made by drilling a hole at the centre of the end cap.
Critical part/process	V-ring lip seal and process of attachment the split pipe with bottom cover plate	V-ring lip seal	Turbine coupling
Fabrication difficulty	High (a minimum of 6 hours)	Moderate (a minimum 4 of hours)	Low (a minimum of 2.5 hours)
Services & Cleaning	Difficult	Medium	Easy
Design Life	Low friction loss and resistant to corrosion	Medium friction loss but resistant to high pressure	Low fiction loss and resistant to corrosion
Inspired by	Savonius wind rotor	Lawn sprinkler	Lawn sprinkler

To address some of the costs and technical issues related to the current design of the pico-hydro turbine, an outward-flow reaction turbine that is newly improved, easier to operate, and inexpensive to fabricate has been developed. This device is known as the Z-Blade turbine. This turbine is designed for low-head (3 m to 5 m) and low-flow (2.5 L/sec and below) water resources. The Z-Blade turbine is a modified and upgraded version of the CPT and SRT and is inspired by the water sprinkler design concept. The fabrication process is less complex because of its simple and robust design, which uses only standard off-the-shelf plumbing pipes and PVC pipe fittings.

The next section will focus on the manufacturing, experimental method, and analysis of a new Z-Blade reaction water turbine that operates on the same principle as the SRT and CPT under the pico-hydro range for low-head, low-flow applications. Compared with the limitations of the SRT and CPT, the developed Z-Blade turbine presents a significant improvement. The design and construction procedures for a Z-Blade turbine using locally available materials are described. Such design and procedures address the problems associated with the cost and applicability of the device to small water resources. Jet interference, which is a common drawback of a reaction-type turbine, does not occur in the Z-Blade turbine, and the non-interference rotational speed is derived. Finally, the performance of the test unit is analysed and evaluated

II. Z-BLADE WATER TURBINE BASIC DESIGN

In the early 18th century, a study [5–9] on simple reaction turbines proposed the classification of water turbines into seven types, namely Hero's Turbine (1st century AD), Barker Mill (1740), Pupil Turbine (1775), Whitlaw Mill (1839), Quek Turbine (2003), Cross Pipe Turbine (2009), and Split Reaction Turbine (2009). In this study, the latest version of the simple reaction turbine known as the Z-Blade, which was developed in 2014, is presented in detail. Compared with the seven other turbines stated above, this innovative turbine is considered to have the simplest geometrical design with the most straightforward fabricating process. In addition, this turbine resembles a garden water sprinkler that is capable of responding with ease while requiring low water pressure and a small amount of water. Thus, this turbine is inexpensive, user-friendly, and easy to install and maintain.

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. 1, 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^o 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^o PVC elbow, and end cap, are easily available off the shelf at local hardware stores.

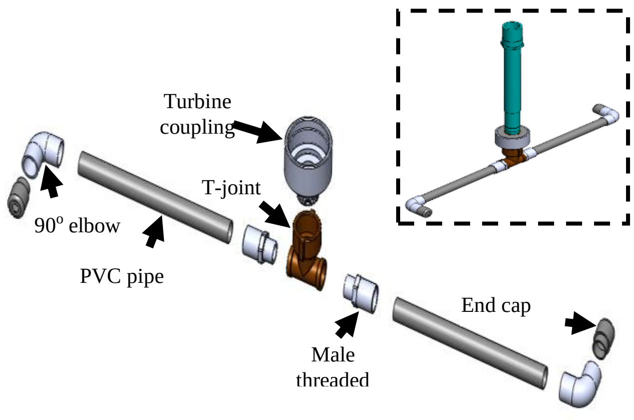

Fig. 1. Z-Blade turbine

III. WATER SUPPLY AND COSTING OPTIMISATION

With reference to [5, 6], Table II shows a cost analysis for the production of a single unit of different simple reaction types of a pico-hydro turbine. In summary, the total cost of production for a Z-Blade turbine is approximately 50% less than that for an SRT or CPT. The three types of turbines are compared in terms of material cost (only for turbine parts) and labour.

Table II shows that the total cost for the materials and fabrication of the SRT and CPT is in the range of USD150. However, the Z-Blade turbine was found to be more economical, with a total cost being equal to only half of that of the CPT and SRT at only USD75. Furthermore, the fabrication time required to construct the Z-blade turbine is approximately 2.5 man-hours, significantly less than that required for the SRT and CPT, which are 6 and 4 hours, respectively. For the SRT, 63% of the total cost can be attributed to labour cost, which amounts to USD96. Conversely, for CPT, 58% of the total cost arises from material cost, which amounts to USD87. Meanwhile, for the Z-Blade turbine, the total costs for material and labour are almost equal, as shown in Fig. 2.

Table- II: Costing of split reaction turbine, cross pipe turbine and Z-blade turbine (Capacity set at 200W)

Simple Reaction Turbine	Turbine Parts	Material Cost (USD)	Labour Hours ($16/h)	Labour Cost (USD)	Total (USD)
Split reaction turbine [7,8]	PVC pipe (250 mm x 150 mm) : OD 10”	8	0.5	8	16
	PVC discs Ø 300 mm x 4 mm : (Qty 02)	8	0.5	8	16
	Flanged transmission coupling	24	N/A	N/A	24
	Stainless steel entry port	12	3	48	60
	V-ring seal	5	N/A	N/A	5
	Assembly and balancing	N/A	2	32	32
	Total	**57**	**6**	**96**	**153**
Cross pipe turbine [7,8]	3” cross	28	N/A	N/A	28
	3” x 2” reduce elbow (Qty 02)	5.5 each	N/A	N/A	11
	3” adapter fitting (Qty 02)	8 each	N/A	N/A	16
	Ø 15 mm solid stream nozzle (Qty 02)	9.5 each	N/A	N/A	19
	Transmission coupling	8	2	32	40
	V ring seal	5	N/A	N/A	5
	Assembly and balancing	N/A	2	32	32
	Total	**87**	**4**	**64**	**151**
Z-Blade turbine	Coupling (Qty 01) ** SKF radial shaft seal 30x62x10 (Qty 01) * Sealed ball bearing 30x62x16 (Qty 01) * C-clip (Qty 02) * Inlet pipe : OD 3”(Qty 01) * Coupling housing (Qty 01)*	30	2.0	32	52
	T-joint pipe (Qty 01)	1.5	N/A	N/A	1.5
	1” PVC elbow (Qty 02)	0.5 each	N/A	N/A	1
	1” PVC end cap (Qty 02)	0.5 each	N/A	N/A	1
	1” male threaded adapter (Qty 02)	0.5 each	N/A	N/A	1
	1” PVC pipe (Length: 1 m)	1.5 per meter	N/A	N/A	1.5
	Assembly and balancing	N/A	0.5	8	8
	Total	**36**	**2.5**	**40**	**76**

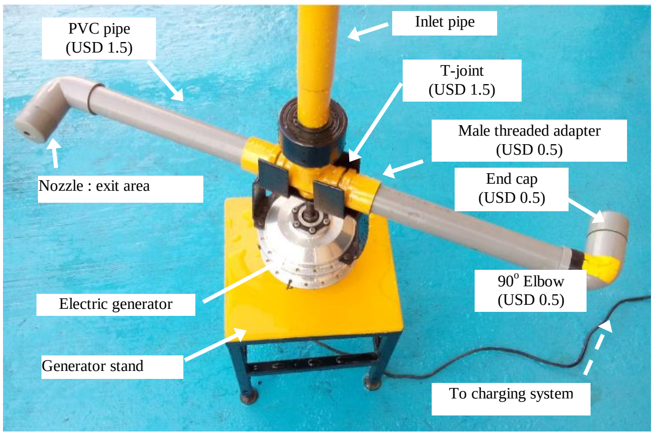

Fig. 2. Z-Blade turbine with material cost

The Z-Blade design proposed in this paper requires only a simple manufacturing method because of its simple geometrical design. The assembly of parts does not require any advanced or special skills in plumbing or turbine technology. Only one person is required to assemble the device with a total time consumption of 2.5 man-hours. Most of this time is spent on water coupling preparation (120 minutes) and assembly and balancing (30 minutes). Meanwhile, the time taken for the assembly and balancing of CPT is 90 minutes more than that for the Z-Blade.

IV. EXPERIMENTAL WORK WITH WATER HEAD OPTIMIZATION

Another drawback observed both in SRT and CPT is the way both the turbines are attached to the generator. The efficiency of the turbine is highly affected if the flange direct coupling is not aligned with the generator shaft. It creates high friction which causes the coupling to come loose and ultimately leads the turbine to spin with a sway.

Hence, the slot jointing as shown in Fig. 2 is used in order to prevent the joining mechanism particularly at turbine coupling to experience high downward frictional force.

Generally, the static water head, the load of the moving turbine, and the acceleration due to gravity cause the downward force and create high friction force to the direct coupling between the hydro turbines and the electric generator shaft. For the purpose of improving performance of the system, slot jointing enables the rotor blade to stay floating in the slot and not directly attached to the shaft generator which, in fact, facilitates the work of construction and maintenance.

The performance measurement of Z-Blade turbine was conducted by using the arrangement of the test rig as shown in Fig. 3. A polypropylene water tank with a capacity of 350 litres was used to store the water. The water tank was supported by the six-meter-high metal framework tower, and it was configured to make the water from polypropylene tank enter from the top of the Z-Blade turbine. The test rig could provide up to 5 m height of water and a water flow rate of up to 3 L/sec. Moreover, since clogging by floating debris is a major problem for hydro-kinetic turbines in many waterways [11], a filtration system was installed in the test bed to block debris or foreign materials from entering the turbine.

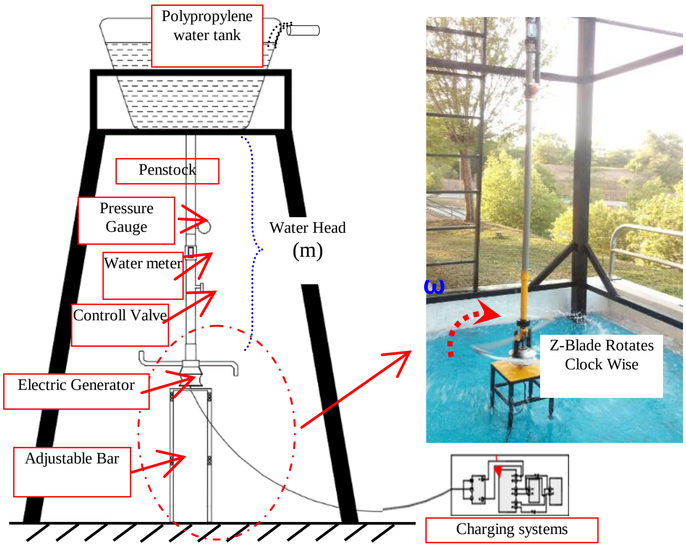

Fig. 3. Z-Blade turbine test rig

The variable parameters for the experimental work are the radius of the turbine blade, R; the water head, H; and the size of the nominal diameter of PVC pipe, S. The static water head, H, varied from 3 m to 5 m. The rotor blade constructed with the diameter of the blade was varied from 0.3 m to 2.0 m using two sizes of PVC pipe, S with the nominal diameter of Ø25MM (1") and Ø15MM ($^1/_2$").

By using the principle of conservation of mass, momentum and energy, the governing model and equations that have been derived and discussed by [5-9] are revisited. The mathematical model is applied to the Z-Blade reaction water turbine in order to investigate the performance under the incompressible water condition. The appropriate equations for an ideal case of no frictional losses are as follows:

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

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

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

$$H_c = \frac{U^2}{2g} = \frac{R^2\omega^2}{2g} \tag{3}$$

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

$$\dot{m} = \rho A\sqrt{2gH + R^2\omega^2} \tag{4}$$

V. RESULT AND PERFORMANCE CHARACTERISTICS

This section shall discuss the experimental results and findings in assessing the Z-blade performance. In general, the overall performance result, gathered from multiple experimental works conducted repeatedly, was found to be consistent throughout. The theoretical performance characteristics were predicted using the governing equation while considering the kinetic energy losses and fluid frictional losses. It is important to note that, Fig. 4 is representing the performance of Z-Blade turbine where the rotor diameter is varying from 0.3 m to 2.0 m and the nominal diameter of PVC pipe used is Ø25mm (1").

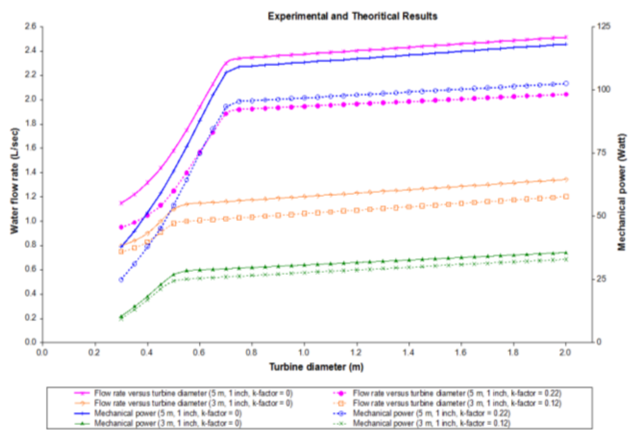

Fig. 4. Mass flow rate and mechanical power versus rotor diameter

Fig. 4 shows the mass flow rate and mechanical power versus the rotor diameter at different water heads. It shows the theoretical curve leading the actual power output curve for various diameters of turbine at 5 m and 3 m water heads. Remarkably, the power output curve is directly proportional to the mass flow rate curve. A critical point of the rotor diameter exists where the increment of mass flow rate changes drastically from higher water flow rate to lower. That is also the point when the increase rate in power output begins to scale down radically. It can be seen that this critical point tends to shift towards the right side of the graph as the operating head increases.

Hence, it causes the value of the rotor diameter (critical point) to become larger as the operating head goes higher. The experimental and theoretical results also show close outcomes, which indicates that the experimental results are indeed reliable. By and large, the turbine performance is higher at 5 m compared to the 3 m water head.

The power output is increased when the water head increases as a result of the rotational speed surge. It can be seen that the mechanical power output for a 5 m water head is higher compared to the power generated at a 3 m of water head. Ideally, at 5 m, the Z-Blade turbine is capable of producing more than 100 kgm^{2}s^{-3} mechanical power.

VI. CONCLUSION

In summary, the Z-Blade turbine, that is a modified concept based on the CPT and SRT and is similar to a garden water sprinkler, has many advantages that are proven throughout this paper, both theoretically and experimentally. These advantages include ease of fabrication, with no need for expert workers because of its non-complex design, as well as a minimum cost of fabrication because it is developed using locally available off-the-shelf materials, such as standard plumbing pipes and PVC pipe fittings. Consequently, the Z-Blade turbine introduced in this paper is a reaction-type machine that has potential for use in a pico-hydro system, particularly for low-head and low-flow water resources.

VII. 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.

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