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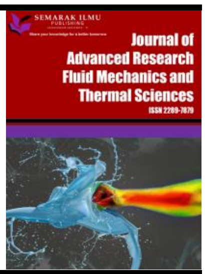


# Reliability Study of Ultra Z-Blade Water Turbine for Pico-Hydro System with Low Head and Low Flow Water Resources

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**ABSTRACT**

The term "pico-hydro" refers to hydropower that has an output of no more than 5 kW. This method has an advantage over large-scale hydropower systems in that it can extract electrical energy sources from even a small stream of water. It is interesting to note that there is not yet a hydro reaction type water turbine that has been developed commercially and is suitable for usage in low-head and low-flow places. In this work, an Ultra Z-Blade reaction type turbine is used to introduce a pico-hydro system, and the critical design parameters are demonstrated through an exploratory method (U-ZBT). For both ideal and real-world scenarios, numerical simulations and their solutions are described here. The development of the equations uses the ideas of mass, momentum, and energy conservation. The output power (W), rotor angular speed (ω), turbine radius (R), and torque (T) can all be specified. An instrumentation diagram that was utilized during the testing of the U-ZBT prototype is included in the documentation to help explain the experimental techniques. Both the mathematical model and the experimental findings have shown that the U-ZBT has a higher level of performance at operational water heads as low as 5m and ultra-low mass flow rates as low as 1.77 L/sec. In addition to this, it can achieve rotational speeds of up to 130 rpm, has a high efficiency of 66 %, and is capable of producing high mechanical power of roughly 60 watts.

## 1. Introduction

A lot of countries are concerned about sustainable development because of environmental change and the growth of metropolitan areas. By 2050, there will be 9.7 billion people on Earth, and more than a quarter of them will reside in regions with severe water shortages [1]. In recent years, the world's need for energy has also increased considerably. Despite increases of more than 30%, global temperatures are expected to remain stable at or around 2°C by 2035. These issues have become some of the most challenging in environmental sustainability [2,3]. Thus, the benefits of employing renewable energy derived from water have been established.

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By the end of our lifetime, it is predicted that 80% of the world's soil will have been destroyed by human activity. In addition, fossil fuel combustion poses a significant risk of pollution, which has grown in recent years. As a result, renewable energy sources such as hydropower, solar power, wind power, and energy obtained from ocean tides have become increasingly important to research. In addition, fossil fuel combustion poses a significant risk of pollution, which has grown in recent years. The most potential alternative energy source, in the opinion of many, is hydropower [4,5]. In August 2016, only 3.5% of Malaysia's electricity was generated by hydraulic power, down from 5.5% in the same month in 2010 [6].

According to the performance category, pico-hydro power generation systems are appropriate and advantageous in rural areas that require a minimal amount of energy. A pico-hydroelectric power plant can typically generate up to 5 kW of electricity. These systems are predominantly run-of-river, which implies that they regulate the river's flow through pipelines located in remote places [7].

Numerous low head, low flow water resource regions are underutilised for energy production installations due to a dearth of small-scale hydroelectric power innovation, according to a review of the relevant literature (pico-hydro) [8]. In most instances, rotors that have been designed and marketed are not suitable for operation in low head, low flow conditions.

Reaction turbines are better suited to sites with low head and high flow [9]. Just recently has the reactive hydraulic machine-type turbine become available on the commercial market. This form of turbine can function with water resources that have a low flow and a low head. Its closest relative is the split reaction turbine (SRT), whose application domain is confined to hydroelectric sites with low head and low water flow rates, as opposed to locations with high head and high flow rates. The SRT, which was introduced in 2009 as a replacement for the cross-pipe turbine, was created as a replacement for the cross-pipe turbine (CPT). Eventually, it was revealed that CPT had various limitations and was not suitable for generating electricity at low-head hydro sites while keeping the required efficiency [10]. Invented by Abhijit Date in the year 2009, the SRT and CPT.

The Ultra Z-Blade Turbine (U-ZBT) is described in this work as a novel solution to operational issues associated with low-head, low-flow water resources. Despite its resemblance to the CPT's geometric design, the turbine proposed in this study has been updated and upgraded. Low-head (5 m) and extremely low mass flow rates (<2 L/s) were used to test the U-ZBT described in this study. The water sprinkler and the turbine both use a similar principle to operate. A simple design means it may be made quickly and cheaply without the use of sophisticated manufacturing equipment or specialized labour. Parametric analysis using the governing equations and using the laws of mass conservation, momentum, and energy led to an investigation into the performance of U-ZBT's characteristics. Therefore, predominant parameters, such as the angular speed (ω), mass flow rate ($\dot{m}$), optimum turbine diameter ($D_T$), and nozzle exit area ($A$) for various operating water heads and various PVC pipe sizes, were examined.

## 2. The Ultra Z-Blade Innovation

Hero and Baker's mill's turbine has been widely regarded for decades to have had a significant impact on the development of basic reaction turbines [11]. For example, in addition to Pupil's turbine and the Whitlaw mill, other types of turbines like the Quek turbine and the CPT have all been evolved from these basic turbines. While it was initially thought that the results of its operation were excellent, it was later revealed that they were not suited for usage in some situations and water locations. Despite being deemed useless and uncontrollable, this type of turbine is still in use today [12].

With the launch of the SRT and U-ZBT, a new and distinct perspective on the possibilities of basic reaction turbines, which had been previously undervalued and underutilized, emerged. Both rotors are capable of functioning as pico-hydro turbines in low-head reservoirs in order to generate clean energy [13]. Comparing the SRT and U-ZBT to the other six turbines in the category of simple reaction turbines, it has been proved that the SRT and U-ZBT have comparatively basic geometric designs and are easy to construct.

As can be seen in Figure 1, this turbine is made up of four significant turbine components: i) one unit of a T-joint at the centre; ii) two units of arms comprised of PVC male threaded adapter fittings and PVC pipes of varied lengths; iii) two units of PVC elbows; and iv) two units of PVC end cap. Therefore, Table 1 provides a details specification of U-ZBT in respect of materials and construction composition.

**Table 1**
Depiction of U-ZBT

| Item | Description |
|---|---|
| Prototype Criteria | Turbines are made up of four major components:<br>a) one unit of T-joint pipe at the centre<br>b) two units of arms made of PVC male<br>threaded adapter fittings and PVC pipes of various lengths<br>c) two units of 90$^{o}$ PVC elbow<br>d) two units of PVC end cap |
| Material | Grey PVC pipe |
| Assembly difficulty | Low (a minimum of 2.5 hours) |
| Preservation | Easy |
| Consistency | Anti-corrosion and low-friction properties |
| Inspired by | Lawn sprinkle |

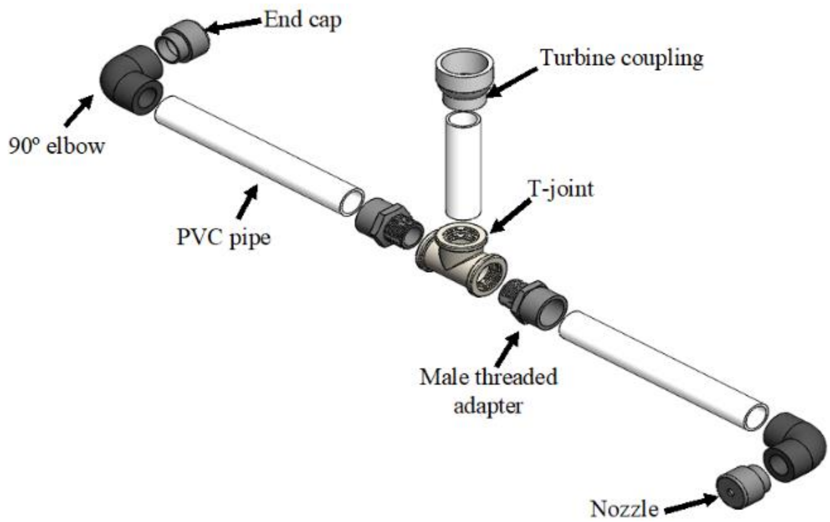


**Fig. 1.** The Ultra Z-blade turbine

This Ultra Z-Blade turbine is unique in its use of standard grey Class D PVC pipe fittings as opposed to galvanized steel tubing, with nominal sizes of 0.75 inches and 2 inches, respectively. PVC pipe is less expensive than galvanized steel pipe, is readily accessible at local hardware stores, and can be swiftly converted or changed to accommodate a far lower turbine diameter than galvanized steel pipe. Assembling is also a straightforward process that does not require technical expertise, skilled labour, or sophisticated manufacturing equipment. The fabrication procedure is made easier due to a design that is straightforward and long-lasting and makes use of conventional plumbing and PVC pipe fittings that can be purchased anywhere. The reasoning provided from Qiu *et al.,* [14] and Viollet [15], Table 2 lists the many benefits of distributing fluids in PVC piping.

**Table 2**
PVC pipe advantages

| Physical Characteristics | Characterization |
|---|---|
| Common | Most prevalently used in small hydro projects worldwide |
| Weight | In terms of portability and speed of installation, this product is ideal |
| Corrosion | Contains effective anticorrosion qualities and does not rust |
| Friction loss | It has low friction and is smoother than most materials, so it causes less resistance for a given diameter |
| Cost | PVC pipe is cheap and easy to find in a variety of sizes. For a given job, a smaller diameter PVC pipe can be used to save money on shipping and installation |
| Jointing | PVC cement or spigot can be used to join sections of pipe together, ensuring symmetry and minimizing the need for balance |
| Pressure | Excellent for use in high-pressure situations; the pipe's outer diameter stays the same across a wide range of pressure ratings for a given diameter, while the thickness of its walls determines the pressure rating. |

### *2.1 The Enhancement of costing U-ZBT*

In determining the design, development, production, and marketing of a pico-hydro system, the cost to construct any hydro turbine is one of the most essential factors [16]. The simple and complicated designs of turbines can be divided into two categories based on their design. To create a turbine, a high level of competence is required because of the fineness of the blade profile, size, blade angle, and so on [17]. On the other hand, the intricacy of the turbine's design might not necessarily be the most important aspect in determining the turbine's actual capability.

The majority of pico-hydro turbines in use are of the impulse type, followed by the response turbine type, which is more commonly utilized [12]. The expensive expense of the wheel-type pico-hydro turbine means that it is less commonly employed than other varieties. A typical pico-hydro turbine costs between USD2,200 and USD4,500 per kW [18]. In addition to this, the medium and low head units are far more affordable than the high head unit, although having the same level of power output. This is because there is a great demand for it, and also because the manufacturers are making it in bulk, which lowers the price per unit [19]. The breakdown of costs involved in producing a single unit of U-ZBT is presented in Table 3.

**Table 3**
Costing of U-ZBT

| Turbine Parts | Material Cost (RM) | Labour Hours (RM40/h) | Labour Cost (RM) | Total (RM) |
|---|---|---|---|---|
| Turbine Coupling (Qty 01) | 50 | 1 | 40 | 90 |
| T-joint pipe (Qty 01) | 2 | N/A | N/A | 2 |
| 1” PVC elbow (Qty 02) | 2 each | N/A | N/A | 4 |
| 1” PVC end cap (Qty 02) | 1 each | N/A | N/A | 2 |
| 1” male threaded adapter (Qty 02) | 2 each | N/A | N/A | 4 |
| 1” PVC pipe (Length: 1 m) | 4 per meter | N/A | N/A | 4 |
| Assembly and balancing | N/A | 0.1 | 4 | 4 |
| Total | 66 | 1.1 | 44 | 110 |

### 2.2 Analysis of Parametric Data

Figure 2 depicts, for the purpose of evaluating the U-performance, ZBT's factors for ideal and practical scenario evaluations. In order to properly appreciate the properties of this hydro generator, twelve separate parameters must be examined. On the U-ZBT performance, the influence of dominant elements, such as the mass flow rate, the ideal turbine diameter, the rotational speed, the nozzle exit area, and the relative velocity for varied operational water levels and numerous PVC pipe diameter, was explored.

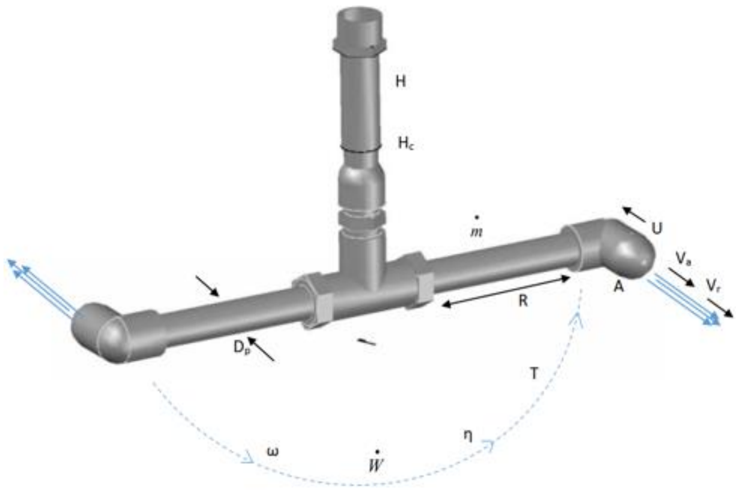


**Fig. 2.** Rotor stationary reference frame

According to the principle of conservation of energy, the gravitational potential energy supplied at the input must be proportional to the rate of mechanical work produced at the output [20]. When water flows out and appears at the outgoing water jet, the rate of kinetic energy loss is increased [21]. The quantitative method is applied to the turbine in order to characterize the ability of the viscous fluid water condition for the U-ZBT reactant hydraulic motor to produce energy. In the absence of frictional losses, these equations yield a perfect example

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

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

During non-stationary operation of the turbine, when ω is not zero, the centrifugal head *H*c is computed as follows

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

When the spray comes out of the nozzle, the mass flow rate, $\dot{m}$ can be written as

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

Calculating the rotor's angular speed can be done by reading Eq. (4).

$$\omega = \frac{\sqrt{\left(\frac{\dot{m}}{\rho A}\right)^2 - 2gH}}{R} \tag{5}$$

Hence, we may derive the torque equation, which is

$$T = \dot{m} V_a R \tag{6}$$

For this reason, the mechanical power output, $\dot{W}$, generated by the turbine is

$$\dot{W} = T\omega \tag{7}$$

## 3. Experimental Performance Characteristics

The conceptual theory and testing indicate that the U-ZBT can operate at low operational water heads. It has achieved widespread appeal due to its capacity to obtain higher rotational speeds and mechanical power while maintaining a low energy loss and high efficiency while working at a low mass flow rate (less than 2 L/sec) and a low head, especially at 5 metres. This turbine's performance is considered to be very commercially viable since, although requiring a minimal initial investment, it is capable of producing a higher power output than other turbines of a similar kind on the market [22]. Furthermore, it is envisaged that the U-ZBT will be capable of overcoming restrictions associated with the depletion of available water supplies due to situations of drought.

### *3.1 Ideal Turbine Diameter*

In Figure 3, we see the theoretical as well as empirical curves for the Ultra Z-Blade reaction water turbine with rotor diameter and water head variations of 0.4 to 1.0 meters and 4 to 5 meters, respectively. The turbine was constructed of grey PVC pipes 0.019m: 0.75-inch blade (Type I) and a nozzle with a diameter of 0.012 m. As depicted in diagrams, there is a specific rotor diameter, also known as the optimal turbine diameter, for a constant water head. At this diameter, the turbine attains its maximum rotor speed. The maximum flow rate is then determined at this location of greatest velocity. Before calculating the maximum water flow rate, it is necessary to identify the gradient or slope of each point on the curve representing the water flow rate. The steeper a line is at a given position on a graph, the greater its gradient at that point. This seeks to identify the moment where a high gradient value transitions to a lower gradient value.

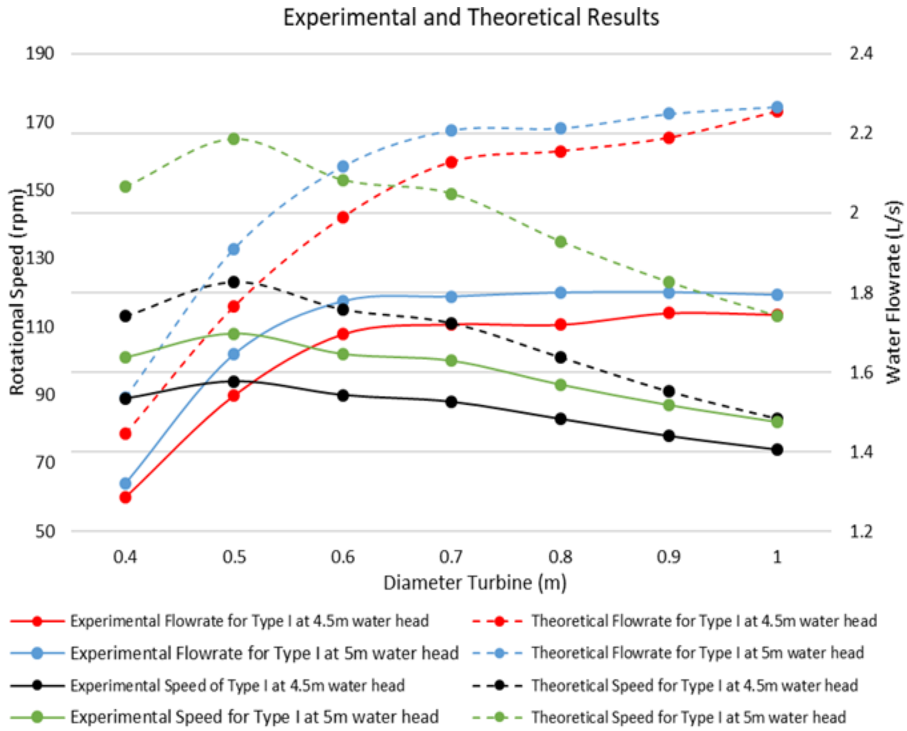


**Fig. 3.** Experimental and theoretical results for Ø0.019m: 0.75inch at different water head

Although the physical parameters have been varied, the overall measured performance curves for each rotational speed and each water flow rate exhibit a similar pattern. In Figure 3, for the 0.019m: 0.75-inch blade Type I, the maximum speed reached at 4.5 m static water head was 90 rpm at 0.5 m turbine length, while at 0.6 m turbine length, the flow rate was 1,696 L/sec. At a static water head of 5 m, the water flow rate was 1.77 L/s with a turbine diameter of 0.5 m and a maximum speed of 130 rpm. As the water head and pipe diameter were raised, it was revealed that both the maximum rotating speed and the maximum water flow rate moved to the right side of the graph. According to both theoretical and empirical evidence, the maximum angular velocity fluctuates and increases continuously with the increase in water head. Likewise, the value of the optimal turbine diameter grows according to the growth in the turbine's static head.

### *3.2 Power Output*

Figure 4 and Figure 5 presents the power output of the U-ZBT expressed in terms of the respective mechanical power. In the course of the experiments that take place in the laboratory, the actual mechanical power is determined. In addition, the findings of the tests and the findings of the theoretical analysis are strikingly comparable, demonstrating that the findings of the experiments can be trusted. The general patterns of the theoretical and experimental curves are, for the most part, extremely similar to one another. The mechanical power curve and the water flow rate curve are plotted as shown in Figure 4, beginning with the lowest length of turbine blades and progressing to the maximum length of turbine blades.

When utilizing a Type I water turbine, such as those seen in Figure 4 and Figure 5, the turbine can function with a water flow rate as low as 1.77 L/sec and a water head as low as 5 meters to provide an actual mechanical power of roughly 55 watts. A situation quite similar to the one described above can be seen in the case of Type I, in which the turbine operates at a water flow rate of only 1.58 and a water head of 4 m to generate around 31 W of real mechanical power. It has been demonstrated,

*Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*
Volume 117, Issue 1 (2024) 132-142

based on the empirical findings, that the U-ZBT is in fact capable of functioning notwithstanding the presence of low water pressure and flow rates.

Interestingly, there is a one-to-one correlation between the curves representing the output of mechanical power and the mass flow rate. When the rotor is spinning at its highest possible speed, the maximum amount of mechanical power may be gained at the diameter of the optimum rotor. This occurs when the rotor is spinning at its highest possible speed. In addition, the maximum mechanical power is reached anytime there is a sudden and considerable drop in the mass flow rate within a short amount of time. This results in a decrease in the flow rate. After that point, the gradual rise in mechanical power begins to drastically slow down, and it comes to a complete standstill eventually. This critical point has a tendency to move towards the right side of the graph when the operating head continues to be increased, as can be seen in the preceding sentence. As a consequence of this, the worth of the mechanical power climbs when the operating head increases (from 4 m to 5 m), provided that the exact same style of turbine is utilised.

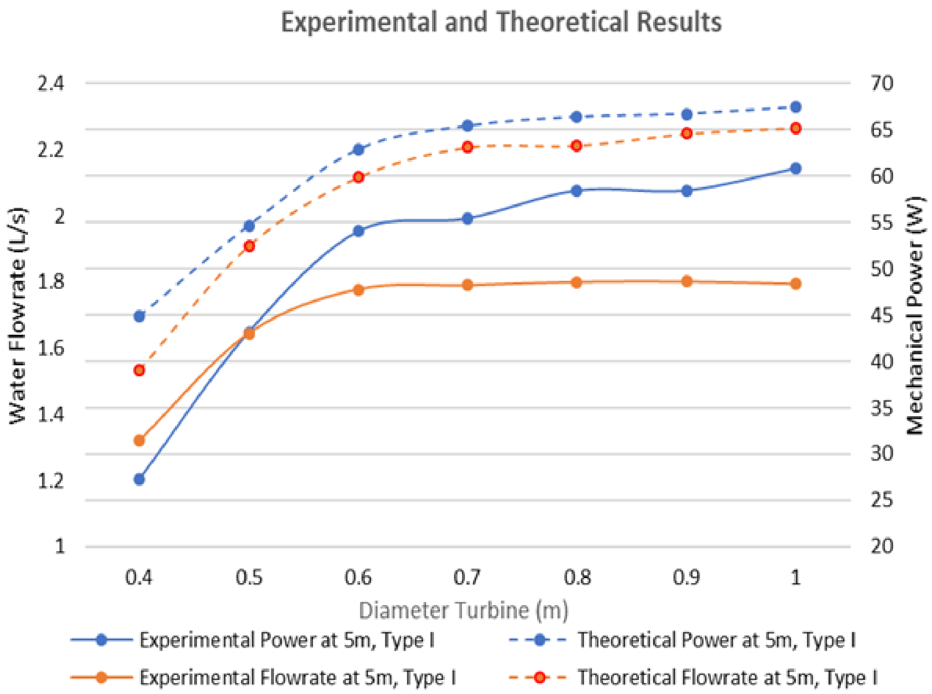


**Fig. 4.** Mechanical power and water flowrate at 5 m operating head for Ø0.019m: 0.75inch with various turbine length

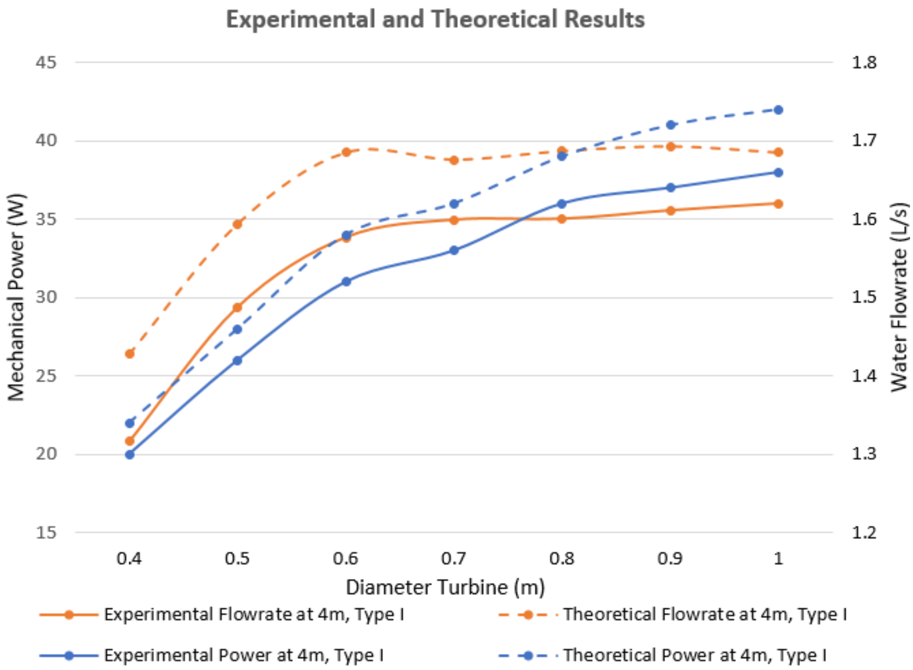


**Fig. 5.** Mechanical power and water flowrate at 4 m operating head for Ø0.019m: 0.75inch with various turbine length

## 4. Conclusions

Analytical and empirical contexts were utilised to design, develop, test, and analyse the performance parameters of a unique pico-hydro system with a Z-Blade reaction type water turbine. These sorts of turbines have proven increased cost and technical performance, particularly under situations of low water head and low water flow rate, which is one of the most significant findings and a basic strength of our work. Various key physical criteria, such as the water head, turbine diameter, pipe diameter, and nozzle exit area, have been applied to all of the under consideration turbine types. It has been proved that this novel and updated outward-flow reaction turbine is more cost-effective than previous types of similar turbines due to the ease of the fabrication process, which reduces the amount of time necessary for turbine production, hence reducing the overall cost. In addition, because of the simplicity of its overall layout, it is easy to construct and does not require the services of trained professionals in this field. In addition to this, it has a low cost of production due to the fact that it is developed utilising widely available off-the-shelf components, such as regular plumbing pipes and PVC pipe fittings, amongst other examples. Experimentation has shown that it is capable of reaching high rotational speeds (up to 130 rpm) with extremely low mass flow rates (about 1.77 L/s), high mechanical power among other things (roughly 55.1 W), and even high head water conditions even when the head water pressure is low (5m).

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