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Pico-Hydro Generation System: Empirical Investigation on a Novel Z-Blade Low-Head Low-Flow Water Turbine

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Abstract- This article provides a parametric study of the turbine style output flow reaction, known as low-head Z-Blade turbine. A nomogram was developed to analyze the theoretical performance requirements of Z-Blade turbine by implementing the concepts of mass preservation, motion and energy for ideal condition. These principles relies on several assumptions, by inconsideration for any losses related to fluid from the water tank, mechanical losses and any frictional losses. The mathematical model and governance formulas and analytical results have proved that the dynamic response rate, angular velocity, central fugitive head, energy production and efficiency to the water head, rotor length, pipeline size and pipe exit are dynamically determined. A turbine with a diameter of 1” gives a higher performance compared to a diameter of ½” and, when energy is provided, it certainly improves the performance of both pipe sizes. The maximum turning rate at this inventive turbine is at an ideal turbine diameter and is preceded by a point at which the water flow rate has suddenly decreased, when the water flow rate previously increased very high. The turbine Z-Blade was investigated and demonstrated high potential of low-head conditions (3m, 4m and 5m) as well as low-flow conditions (only about 2.5 L/sec). Compared with the CPT and SRT that been studied, ZBT is considered to have the simplest geometrical design with most straightforward fabricating process and low cost as per discuss in this study.

Keywords Low-flow, low-head, parametric, reaction turbine, Z-blade.

1. Introduction

Many countries have managed experienced water flow rate fluctuations, where the water flow rate and the water head were affected because of dry conditions. It is a period of limited power output, and a big issue for a pico-hydro power plant is to sustain consistently the performance of its generation system. The constrained source of energy is primarily "running rivers," so there is no need for a dam system but a restricted obstacle known as a small lake can be configured to enforce and sustain river flow. Pico hydropower provides alternative energy sources with efficient, reliable and cost-effective power. Furthermore, the availability for the pico hydroelectric system on the market showcases that it is the best and cheapest choice in emerging economies for rural or remote electrification [1]. The head and flow are two important characteristics in this specific method. The head component depends on the water pressure determining the vertical drop in the volume. The flow of water and the rotor both have a height [2-4]. Many other turbine generators that have so far been investigated and marketed only work in high flow, low-flow and low-flow conditions under high-head [2, 5] circumstances. The shortage of hydro technology [7] is the source of several low-flow areas not used to power generation [6]. In this study, the prelude in this field, often underrate and disregarded by many is an emerging reaction type turbine called a Z-blade turbine.

This study was based on the cross-pipe turbine (CPT) and Split Reaction Water Turbine (SRT), which classify both turbines as single reaction turbines. CPT and SRT are the findings of progress taken in an area that is not extensively covered and investigated to seize the opportunities available. Date et al. [8-11] addressed in detail CPT, built using standard iron (GI) pipe fittings. It was important to note that the SRT was created after testing by its inventor and that the CPT was not appropriate for low-head hydro implementations. In comparison to other hydraulic reaction turbines the SRT becomes less complicated in its structural pattern. The SRT has shown itself to be capable of performing in low head situations including its enhanced disk-shaped rotor structure. It is able to generate 150 Watt of electrical power at 40 kPa, with a turbine blade diameter of 0.122 m and a flow of water rate of approximately 20 L / sec [8-10]. The downside is that, while it can be worked in low-head water conditions, the SRT demands a high water flow rate.

This project presented that outer flow reaction turbine strongly resembles the CPT in its geometric nature, but has been updated and improved. This paper has examined the Z-blade rotor at low-head (3 to 5 m) and exceptionally low mass flow levels (averaging 2.5 kg / sec). The experimental phase will focus mainly on laboratory testing which will discuss in next section. The turbine uses a principle close to that of the sprinkler. Due to its uncomplex design, it can easily be manufactured and does not require high tech production machinery or professional laborers. The rotor blades are produced by means of standard PVC piping systems to make it an affordable reaction machine. The turbine is designed on the basis of tests and parametric SRT and CPT analyses as confirmed by [8-12].

This article provides an integrated Z-blade turbine that mostly highlights low-head low-flow water resources operational challenges. On the basis of parametric evaluation carried out through the regulatory equations, the working principles of the Z-blading turbine were examined using the concepts of mass conservation, momentum and energies. This paper also includes a nomograph designed to show that the performance parameters of a turbine are related. In addition, with only one parameter, the nomogram will automatically determine the overall turbine system. The comportment of this hydro system on the basis of observations must be determined by five parameters. The variables for different operating waterheads and multiple PVC pipe sizes were investigated in prevalence, such as the angle speed, volume flow rate, and best possible rotor diameter and nozzle exit area.

2. Experimental test rig

The Z-blade turbine was tested by feeding water from the top of the blade, while the generator was installed at the bottom of the Z-blade turbine. With this arrangement, as shown in Fig. 1, it was able to benefit fully from the gravitational potential energy supplied by the water in the tank. The test rig was able to provide a water head of up to 5 m and a mass water flow rate of up to 3 L/sec. The water test rig shown in Fig. 1 depicts the method used in real time hydro sites. In any real application, the pico-hydro power generation system to be implemented is similar to the water test rig shown in Fig. 1.

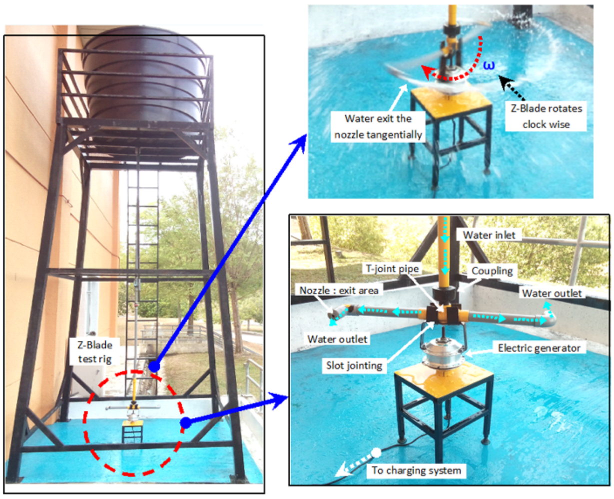

Fig. 1. Z-blade Turbine Experimental Test Rig

The Z-blade water turbine was developed using standard grey plumbing PVC pipes and the fittings of two pipe sizes, namely 1/2” (nominal diameter of 15 mm) and 1” (nominal diameter of 25 mm). PVC pipes have special features in terms of their robustness, easy handling, low cost and portability due to their light weight. Furthermore, this innovative turbine has a simple geometrical design and is easy to build, requiring no expertise.

3. Parametric Study of the Z-blade Turbine

This article seeks to present the best criteria for the determination of the maximum turbine output consistent with the theoretical similarities and empirical setup. Furthermore, this fact implies that the revolutionary turbine has a high potential for the application of a garden sprinkler for pico-hydro systems, particularly for low-head and low flow water supplies.

The Z-blade discussed in this paper uses the same principle as a sprinkler system, using the locally available material, an example of a waterproof reaction system commonly used today. Also this turbine require two exit nozzles separated at 180º angle. This Z-blade also applies to the same principle as previous work [2, 4, 7-12] as with other reaction turbines. The reaction style turbine typically operates with compressed water that enters the rotor uniformly and exits tenuously. Although in the review [8-12] certain observations must be made. The arguments presented would be that the power cannot be subsided by thermal conductivity, that there is no friction because it is a centrifugal pump, however because of its uniform volume, the water is incompressible, unlike the air that can be compressed. The other problems that are overlooked are the structural losses, particularly frictional losses in bearings and losses of windage during speed of rotation.

Fig 2 below shows the parameters involved in the Ideal Condition Analysis for evaluating the performance of the Z-blade turbine. These parameters are similar to the parameters that have been used for investigating the performance of SRT and CPT under specified conditions [8-11]. The red boxes are the parameters that are varied in order to investigate their effect on the parameters in the yellow boxes. Meanwhile, the green boxes are the fixed parameters based on the assumptions that there are no changes to the acceleration due to gravity and no changes in water density due to stable temperature.

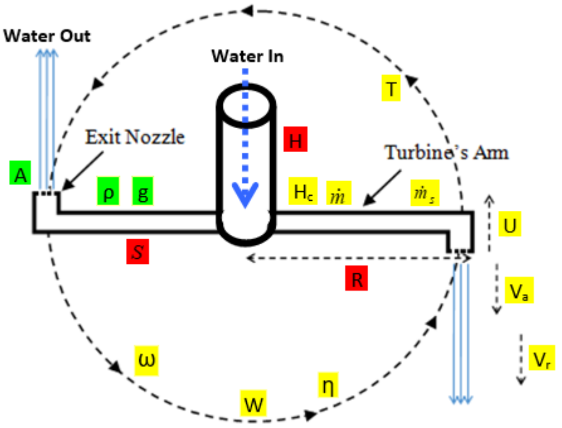

Fig. 2. Turbine equilibrium frame of view

The behavior of Z-Blade reaction water turbine under the incompressible water condition can be described using the principle of conservation of mass, momentum and energy. The governing equations for an ideal case where no frictional losses occur have been derived by [7, 11] with reference to Fig 2.

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

$$V_a = V_r - R\omega \tag{2}$$

If the turbine stays stationary (ω≠0), the centrifugal head (H_c) is given,

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

From (3), it gives the relative velocity,

$$V_r = \sqrt{2gH + R^2\omega^2} \tag{4}$$

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

$$\dot{m} = \rho A\sqrt{2gH + R^2\omega^2} \tag{5}$$

It is possible to determine the rotor angular speed (ω) by interpreting Eq.(5)

$$\omega = \sqrt{\frac{\left(\frac{\dot{m}}{\rho A}\right)^2 - 2gH}{R^2}} \tag{6}$$

The efficiency of the system in converting potential energy to work can be written as

$$\eta = \frac{\dot{W}}{\dot{m}gH} \tag{7}$$

Using the theory of energy conservation, the total amount of hydraulic energy supplied at the inlet must be equal to the rate of mechanical work additionally generated plus the rate of kinetic energy loss that occur due to water flowing out at the outlet water jet [10-11].

$$\dot{W} = \dot{m}gH - \frac{1}{2}\dot{m}V_a{}^2 \tag{8}$$

The criteria that can be gathered in the exploratory studies are water head (H), blade length (R), pipe size (S), nozzle exit area (A), mass flow rate (m) and rotor angular velocity (m) which focused on the ideal case. In the meantime, the other characteristics of the turbine reaction can be calculated using the Eq. (1) to Eq. (8).

4. Conceptual Study of Results

The blade radius (R) ranged from 0.3 m to 2.0 m, with the water head (H) ranged from 3 m to 5 m. The width of the nozzle exits area (ÿ) was measured at 3 x 10-3 m, 4 x 10-3 m, and 5 x 10-3 m, whereas the actual diameter of the PVC pipe was set at ½ "and 1". Parameters were set as follows is because the study was conducted based on comparison with SRT and CPT turbines [8]. Those are the variables used for the mathematical model to examine the turbine 's output and to compare it with the data obtained from the experiment under defined conditions. The empirical analysis was conducted out based on the spectrum of each parameter, using the algorithms mentioned in Section 3.

Controlled variables such as R, ṁ, H, S and ω, were regarded as the prominent factor influencing device performance. The nomograms, as shown in Fig 3 and 4, are determined by the other control factors, were designed to demonstrate the relation between those variables and device efficiency. Nomograms demonstrates the Z-blade turbine characteristic curve below 3 m and waterhead 5 m, respectively.

Fig 3 shows the relationship between the turbine diameter, relative velocity (V_r), angular speed (ω) and mass flow rate (ṁ). Initially, the increased rate in the V_r was considerably high with the increased length of the turbine blade. Once the angular speed of the turbine reached the maximum value at the optimum turbine diameter, it was immediately apparent that there was a drastic drop in the rate of increase of V_r and a simultaneous slowing down in the rotation of the turbine. It could be seen that after the Z-blade turbine reached the maximum speed, not much increase in the mass flow rate was observed, which was very different compared to the initial state. The efficiency rapidly increased with small changes in the mass flow rate, specifically for the small sized pipe (0.5") due to the rapid increase in the angular speed of the rotor. As the mass flow rate increased at a constant waterhead, the efficiency of the different sized pipes rose as they approached each other. It could also be seen that this simple turbine only required an ultra-low flow rate of water (less than 2 L/sec) in order for the system to achieve an efficiency that was higher than 80%.

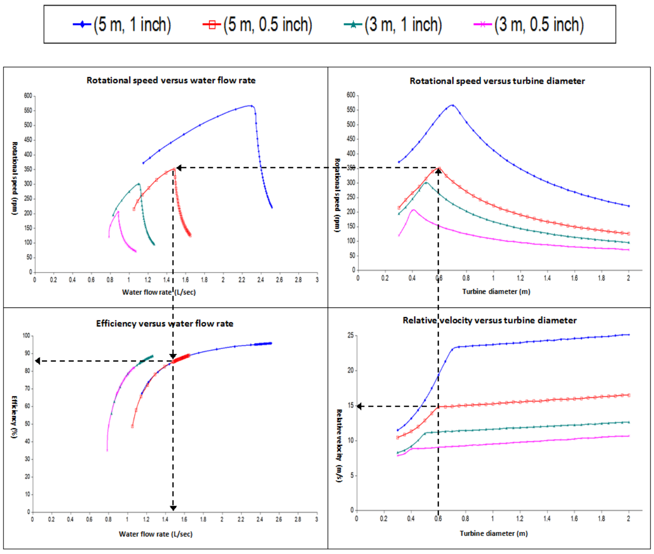

Fig. 3. Namogram 1

Fig. 4 shows that the curve patterns for the relative velocity V_r and tangential velocity U were similar. Conversely, the absolute velocity had the opposite pattern. With reference to Equations (1), (2) and (6) and Fig. 5, at the short turbine diameter, the relative velocity (V_r) was slightly greater than the absolute velocity (V_a). On approaching the highest point of the rotational speed of the turbine, the value of the absolute velocity (V_a) became smaller as a result of an increase in the tangential velocity (U) which had been affected by the high rate of increase in the rotational speed. The relative and tangential velocities, which had initially increased dramatically, experienced a slow increment after the maximum speed was reached, and eventually led to a consistent value. Since, the rate of increase in the relative velocity (V_r) and the tangential velocity (U) was very slow, it caused the absolute velocity (V_a) to decrease at a very slow rate and gradually subside towards the long blades.

As can be seen for all three parameters, initially, the increase in the rate of V_r and U was very high but then after the optimum turbine diameter, these two parameters experienced a slow increase in the rate as the turbine diameter further increased, approaching asymptotically twice the starting value. Meanwhile, the V_a had an opposing trend compared to the V_r and U, where it dropped further as the turbine diameter increased, approaching asymptotically half the starting value.

With regard to Eq. 7, by fixing the density of the water and the nozzle exit area, the behaviour of the mass flow rate was similar to the pattern for the relative velocity. According to the principle of conservation of energy, as shown in Eq. (15), and with reference to Figures 3 and 5, the mechanical work produced by this turbine increased consistently since the loss in kinetic energy, corresponding to the absolute velocity of the exiting water jet, remained low as the turbine diameter increased in length. Indirectly, this shows that the Z-blade turbine is a simple reaction machine with higher efficiency.

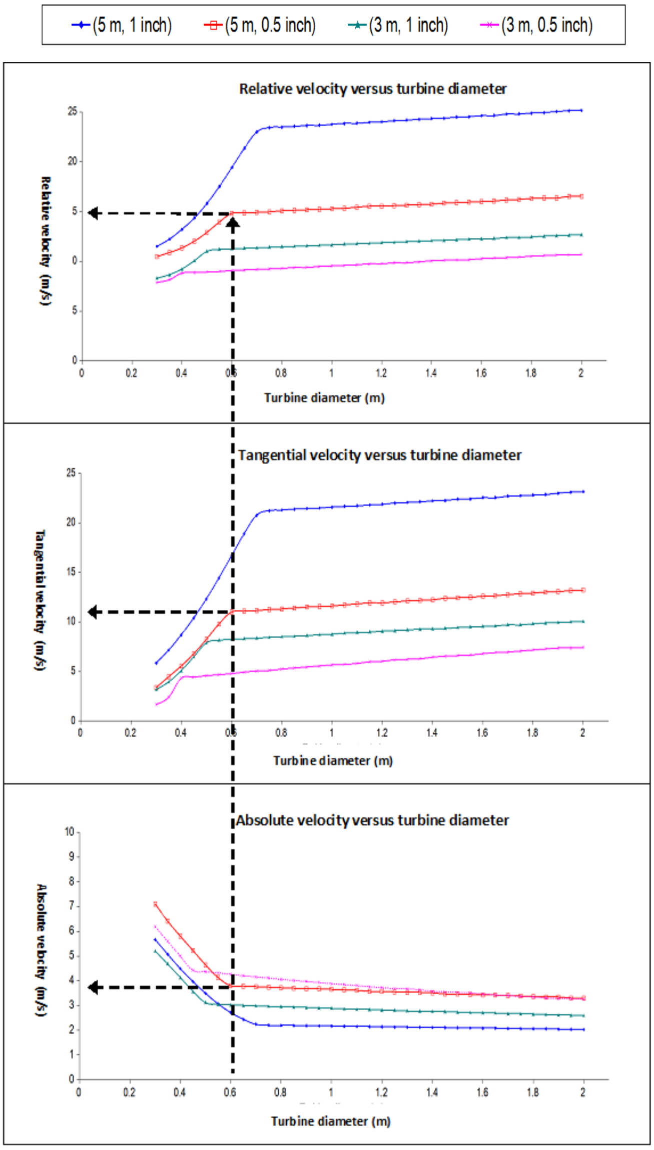

Fig. 4. Absolute, relative and tangential velocities versus turbine diameter

5. Observational output features

Investigated systematically and extremely accurate data have been achieved throughout the testing investigation by sustaining exploratory processes and equipment. In the conceptual parametric studies, the empirical results of the Z-blade turbine was found to be identical. The optimal parameters, which mainly affect the overall performance of the turbine, were apparently defined and discussed based on the actual and projected results.

5.1 Resemblance among rpm, diameter of the turbine and water flow

Fig. 5 represents the initial and empirical curves in various waterheads ranging from 3 m to 5 m for the rotor-dimensional Z-blade reaction water turbine. The Z-blade rotor also had nozzle with a diameter of 0.008 m with each blade handle. The turbines were built with 1 "(fractional diameter = 0.025 m), 1/2" (fractional diameter= 0.015 m) and grey PVC pipes.

With reference to Equations (1), (2) and (6) and Fig. 4, at the short turbine diameter, the relative velocity (V_r) was slightly greater than the absolute velocity (V_a). On approaching the highest point of the rotational speed of the turbine, the value of the absolute velocity (V_a) became smaller as a result of an increase in the tangential velocity (U) which had been affected by the high rate of increase in the rotational speed. The relative and tangential velocities, which had initially increased dramatically, experienced a slow increment after the maximum speed was reached, and eventually led to a consistent value. Since, the rate of increase in the relative velocity (V_r) and the tangential velocity (U) was very slow, it caused the absolute velocity (V_a) to decrease at a very slow rate and gradually subside towards the long blades.

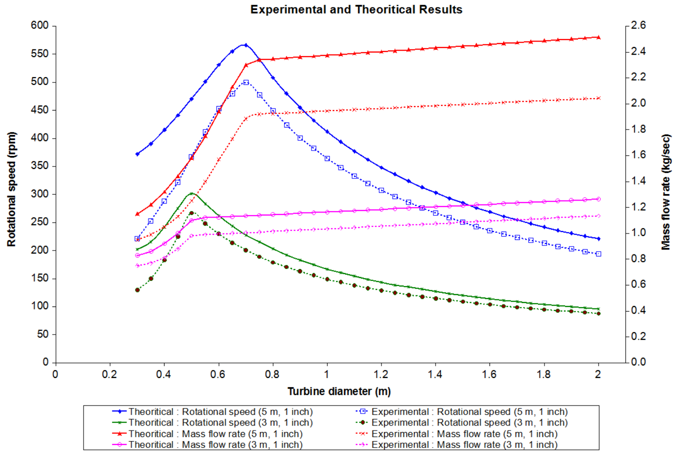

Fig. 5. Analytical and empirical evidence for 1” pipe

The rise in the water flow rate through the turbine began to be extremely poor, despite the fact that the diameter of the z-blade had dramatically increased, unlikes at the first stage, when the mass flow rate had increased significantly, as can be seen in Fig. 3. It should be noted that the curve pattern of the mass flow rate was reflected by the relative velocity. Since $\dot{m}$ is a function V_r, as expressed in Eq. (7), the mass flow rate is highly dependent on the relative velocity component ($\sqrt{2gH + R^2\omega^2}$) and the tangential velocity component (Rω), provided that the density of water (ρ), height of water (H) and total exit nozzle area (A) remain unchanged.

The measured result shown in Fig. 5, at 5 m, the top rotational speed was 500 rpm only by a requirement of water flow rate 1.89 L / sec. The rate was slightly different from the actual approximation by about 11.7 percent, with the maximum calculated speed of 566 rpm.

5.2. Effect of pipe sizes on turbine performance

The line pointed in the Fig. 6 shows the empirical data obtained from the experimental study, which is close to the theoretical research but reduces significantly in magnitude. It was found that, for both tube sizes, the performance of the calculated output curves was similar, but the overall performance of the 1 "blade was better than the 0.5" blade. Owing to the higher relative velocity (Vr) and tangential velocity (U) the mass flow rate for the 1 "blade was higher than for the 0.5" blade. This caused the torque and mechanical output of the 1 "pipe, as expressed in equations (2), (11) and (12), to be greater than that of the 0.5" pipe because of the differential in the speed of the water leaving a pipe as opposed to a stational object called the absolute speed.

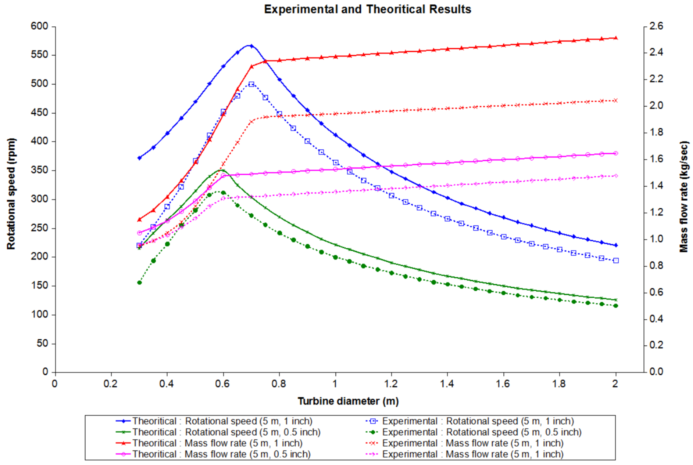

Fig. 6. Experimental and theoretical results for various pipe sizes at 5 m water head

The scale (fractional radius) of the PVC pipe had no massive impact on mass flow, especially in case of the short turbine diameter, so long as the total exit nozzle and waterhead were constant. The rotor velocity, in general when the turbine was short, seemed greatly affected by the pipe size, but less by a large turbine diameter where the ideal and the experimental flow rate surpassed one another. The rate of water flow through the rotor blade can be seen as the size of the pipe increases continuously. Nevertheless, the rise in the rate of water flow for both tube sizes fell after the maximum diameter was reached. The angular velocity of the Z-blade turbine dropped, and this continued despite the extension of the turbine blade.

During the laboratory investigation, the 0.5" pipe-sized Z-blade turbine was faster than the 1" blade than the peak rotating speed. At water head 5 m, the 0.5” pipe-sized had an optimum rotor diameter of 0.6 m. This was the moment whre the turbine rotated at the maximum rotational speed due to the static head, together with the pressure exerted by the centrifugal pumping effect. The optimum diameter is defined as the length (diameter) corresponding to the maximum rotational speed for agiven water head. At 0.6 m turbine diameter and a water flow rate of 1.31 l / sec the 0.5" blade achieved the highest speed of 312 rpm. In the meantime, a maximum velocity of 500 rpm was achieved for the 1" blade at a diameter of 0.7 m and a rates of water flow of 1.89 L/sec. This indicates that the 0.5 "blade 's peak rotary velocity was roughly 37.6% less than the reported maximum 1" blade velocity.

6. Conclusion

Nomograms and graphs have been shown to provide the output properties of a basic reaction Turbine known as a Z-blade turbine. The turbine Z-Blade was tested and demonstrated its strong ability for use in low waterhead (3 m, 4 m, 5 m) and less than 2.5 L / sec. at low flow rate.

Previously, at a smaller turbine width, the rate of rotation increased quickly due to the mass flow rate ($\dot{m}$) and the centrifugal pumping action, with increases in turbine diameter. When the rotor achieved the desired velocity, the amount of water flow increases by the turbine toward the higher z-blade turbine diameter. The water flow is strongly influenced by the relative speed parameters ($\sqrt{2gH + R^2\omega^2}$) and the tangential speed components (Rω), given there are no changes in water density (p) and water height (H) and the exit area of the total nozzle (A).

The water flow rate through the turbine blade increases consistently when the size of the PVC pipe is increased. Hence, the angular speed also becomes high, provided that the water head, radius of the rotor and nozzle exit area, remain constant. In contrast, when the turbine is at its optimum diameter, the change in the PVC pipe size has a significant effect on the rotational speed. However, the rate of increase in the water flow for both PVC pipe sizes drops after the optimum diameter is reached. This causes the angular speed of the Z-blade turbine to decrease and this situation will persist even if the turbine blade is extended.

According to the actual performance curves and nomograms designed in this paper, it proves that the mass flow rate, angular speed, centrifugal head, relative velocity, power output and efficiency respond dynamically to the water head, radius of the rotor, size of the PVC pipes and the nozzle exit area. Furthermore, the turbine diameter, mass flow rate, and water head are the optimal parameters in determining the best performance of Z-Blade turbine. From the nomogram state that with the turbine diameter 0.6 m can give the optimal result at rotational speed maximum 550 rpm with size of diameter pipe at 1" and 312 rpm for 0.5" pipe diameter with water head 5 m.

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