International Journal of Applied Engineering Research ISSN 0973-4562 Volume 10, Number 24 (2015) pp 44489-44492
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The Effect of Viscous Losses Factor on a Simple Pico-Hydro Reaction Type Turbine

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Abstract

To date, there have been eight types of simple reaction hydraulic turbines. One of these is the Z-Blade turbine, which is capable of being used for pico-hydro applications. This paper also explores the effect of k-factor on the performance of a Z-Blade turbine for ideal and practical cases. The viscous losses factor represents the power loss associated with the fluid flow through the turbine, which definitely occurs during real operating conditions. By using the governing equation, which has been derived from the conservation of energy principle, the k-factor is simulated and investigated. Furthermore, this paper also proves that, with a one percent difference in the magnitude of rotational speed and mass flow rate, a large variation in k-factor is presented.

Keywords: K-Factor, Pico-Hydro, Simple Reaction Turbine, Viscous Losses.

Introduction

For hundreds of years, before the use of advanced fossil fuel-based generation technologies, mankind has relied on hydro power for the generation of electricity [1-3]. In these modern times, hydro power is classified as large or small hydro power; according to the system's ability to generate hydro-electric power [4-6]. Pico-hydro power, is an example of small-hydro power with a higher potential for future power generation applications [1, 4, 7].

In this paper, a simple hydraulic reaction type turbine, known as the Z-Blade turbine, is explored. Next, by taking into account the effect of the k-factor, the performance of this innovative turbine is discussed.

Pico Hydro

Pico-hydropower plants provide alternative ways to generate electricity without causing damage to the environment. Figure 1 shows the classification of hydropower with reference to the power output [1]. Pico-hydropower is defined as a small-scale green energy generation with a capacity of less than 5 kW without relying on any sources of non-renewable energy [1, 5].

Pico-hydro technology is typically implemented by means of the run-of-river approach and the plant is built on a small area of land. It is generally considered to be an affordable technology for the generation of electrical power for rural communities [2, 3].

In the majority of the less developed countries, more than 75% of the people in rural areas have no access to electricity, while the other 25% of these rural communities are supplied with electricity through extensions of the local contribution grids [8]. However, the expenses involved in the delivery of electricity by means of transmission lines are costly [9] and, as a result, it is not a popular alternative for supplying electricity to small isolated areas [7].

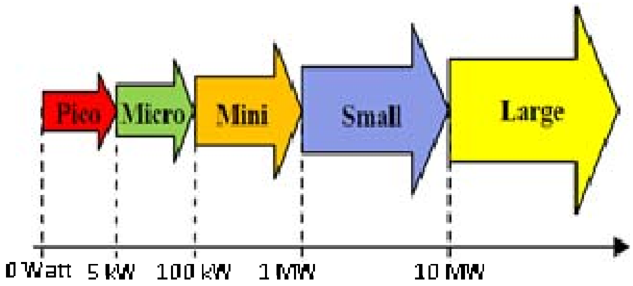

Fig. 1. Classification of hydro power [1]

As a solution, pico-hydropower is an attractive prospect for satisfying the basic electricity needs of remote communities [1, 2, 7]. Pico-hydropower is a smart alternative because the generated power is transmitted by means of a simple wiring system and can be stored in a low DC voltage battery. The battery will then be connected to an inverter system that suits the requirements of the electrical appliances. The cost for transmitting and converting the electrical power by this scheme is extremely low.

Simple Reaction Type Turbine

Water turbines can be divided into two main categories, namely impulse turbines and reaction turbines, depending on their working principles [9].

The garden water sprinkler is the most common example of a reaction water turbine. In a pure reaction hydraulic turbine, the water stream is pressurized and flows through the guiding mechanism to rotate the moving blades or moving nozzle [10]. As the water glides through the moving blades, the pressure is reduced, and the velocity of the water stream relative to the moving parts is increased.

In terms of simple reaction water turbines, there are eight types, namely Hero's turbine, Barker's mill, Pupil's turbine, Whitlaw's mill, Quek's turbine, the Cross Pipe Turbine (CPT), Split Reaction Turbine (SRT), and the Z-Blade turbine [10-15]. However, only split reaction turbines, as in [13-15], and Z-Blade turbine as in [12, 16, 17], are suitable for pico-hydro range for low-head and low flow applications. Both turbines have a simple fabrication method and use locally available materials [12-15].

The Z-Blade turbine, which was developed by Farriz in 2014 [16], is the latest version of a simple reaction turbine. Compared to the other seven turbines (listed above), this innovative turbine is considered to have the simplest geometrical design and fabricating process of all [4, 16]. As such, this turbine is inexpensive, user friendly, and easy to install and maintain. As shown in Figure 2, standard PVC pipe fittings were used to develop the Z-Blade turbine.

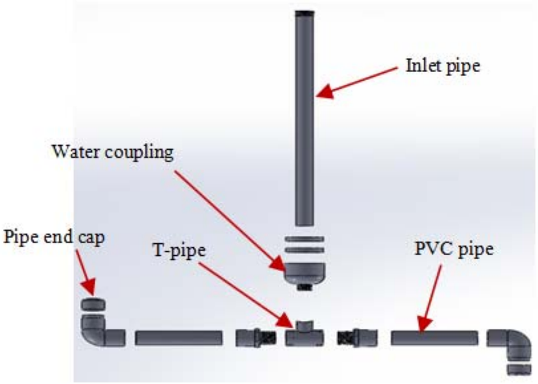

Fig. 2. Z-Blade turbine

In this paper, the parametric analysis of the simple reaction water turbine performance as in [10-15] is revisited. Reference [10, 11] provides governing equations for the prediction of simple reaction water turbine performance. These equations are used for the parametric study of simple reaction water turbine [11].

Factor for Viscous Losses

The k-factor, also known as factor for viscous losses, has been analyzed in several journals, including: [11], [15], [13] and [10]; the most comprehensive being the latter. The k-factor is simulated and investigated for ideal and practical situations using the governing equation; which was derived from the principle of conservation of mass, momentum and energy [10, 11, 13-15].

Referring to the governing equation established in [10, 11, 13], the tangential velocity of the nozzles, U is equal to

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

where R is the radius of the turbine and ω is the angular speed of the rotor. The relationship between absolute velocity, V_a and relative velocity of water, V_r is,

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

The combined effect of two components of pressure; from centrifugal pumping effect, H_c and from head, H in reservoir,

$$\frac{1}{2}\rho V_r^{\,2} = \rho g\,(H + H_c) \tag{3}$$

The mass flow rate of water is the product of relative velocity, density of water, ρ and total nozzle exit area, A;

$$\dot{m} = \rho A V_r \tag{4}$$

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

By rewriting (5), the angular speed of the rotor can be calculated by

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

The turbine efficiency is

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

With conservation of momentum, torque is

$$T = \dot{m}V_a R \tag{8}$$

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

$$\dot{W} = T\omega \tag{9}$$

Using the principle of conservation of energy, the gravitational potential energy supplied at the inlet must be equal to the rate of mechanical work produced. It is then added to the rate of kinetic energy loss due to the water flowing out that appears at the exiting water jet [10, 11, 13-15].

$$\dot{m}gH = \dot{W} + \frac{1}{2}\dot{m}V_a^{\,2} \tag{10}$$

In order to adapt to a real operating situation, there is the existence of another power loss due to the k-factor. Hence, (10) become as follows;

$$\dot{W} = \dot{m}gH - \frac{1}{2}\dot{m}V_a^{\,2} - \frac{1}{2}\dot{m}kV_r^{\,2} \tag{11}$$

Combining (1), (2), (8), (9) and (11), we then have

$$V_{r(k\neq 0)} = \sqrt{\frac{1}{(1+k)}}\sqrt{2gH+R^2\omega^2} \tag{12}$$

Combining (4) and (12), we then have

$$\dot{m}_{(k\neq 0)} = (\rho A)\left(\sqrt{\frac{1}{(1+k)}}\right)\left(\sqrt{2gH+R^2\omega^2}\right) \tag{13}$$

The k-factor can be calculated by rearranging (13) as follows,

$$k = \frac{2gH + R^2\omega^2}{\left(\frac{\dot{m}}{\rho A}\right)^2} - 1 \tag{14}$$

As described by [13, 15], all of the parameters in (14) can be gathered in experimental work to determine the value of the practical k-factor. Furthermore, the other ideal parameters (V_r,

$\dot{m}$ and ω) during k-factor = 0, can be determined by using the value of the k-factor and the V_r obtained from the experimental work. The ideal k-factor occurs when no frictional losses have occurred.

In addition, some assumptions have to be made in the analysis [10-15]. The assumptions made are that the energy cannot be dissipated through viscosity. The water is incompressible due to its constant density. The other matters that are neglected are the mechanical losses, including frictional losses in the bearings during the rotation of the rotor.

Simple reaction turbines, such as the Z-Blade turbine, face a considerable amount of kinetic energy and fluid frictional losses [17]. On average, for the 3 m to 5 m water head with the nominal diameter of PVC pipe at Ø25MM (1”), the Z-Blade turbine experiences an increase in fluid frictional loss (k-factor) up to 0.25 [17]. Meanwhile, for the 3 m to 5 m water head with the nominal diameter of PVC pipe at Ø15MM (0.5”), the Z-Blade turbine experiences a fluid frictional loss (k-factor) up to 0.2 [17].

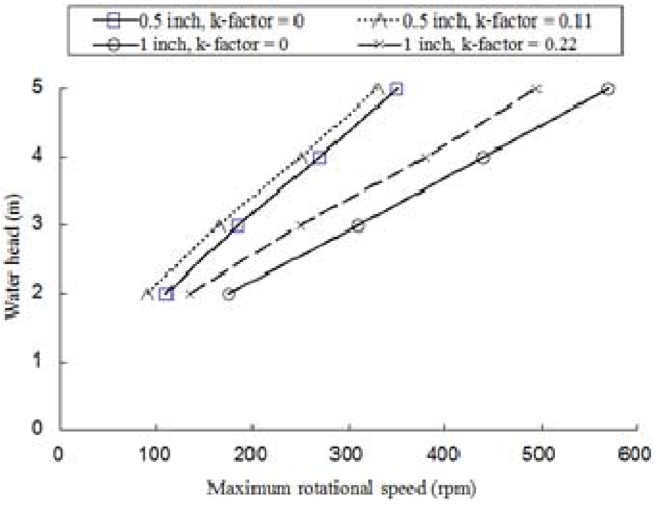

Fig. 3. Rotational speed at different operating water heads

Figure 3 shows the maximum angular speed for any given water head with various k-factors. The turbine is in an ideal condition when the k-factor is equal to 0. In other words, the turbine only faces the kinetic energy loss corresponding to the absolute velocity of the exiting water jet. No energy loss is associated with the friction of fluid flow through the turbine [10, 11, 13-15].

Using either 1” or 1/2” pipe, it is observed that the linear line of rotational speed for an ideal condition (i.e., k-factor equal to 0) is found to be located in the rightmost part of the graph, compared to the k-factor linear lines for the experimental condition. The higher the value of k-factor, the farther its linear line of experimental condition with the line of ideal conditions.This is due to the reduction in mass flow rate and angular speed of the rotor.

Tables 1 and 2 show several experimental case scenarios to investigate the variation of k-factor for two sizes of nominal diameter PVC pipe. There is a large variation in the value of k-factor; when the values of rotational speed and mass flow rate are varied by 1%. It is worth noting that, a small error in reading the rotational speed and mass flow rate can cause the calculated k-factor value to be imprecise.

TABLE.1. Variation of K-Factor for Ø25MM (1”) PVC Pipe

	Rotational speed, ω (rpm)	**Mass flow rate, $\dot{m}$ (kg/s)**	**k-factor**
	379.00^a	1.38^a	0.16^a
Case 1 : ω reduced 1%, $\dot{m}$ increased 1%	375.21	1.39	0.13
Case 2 : ω reduced 1%, $\dot{m}$ unchanged	375.21	1.38	0.14
Case 3 : ω unchanged, $\dot{m}$ increased 1%	379.00	1.39	0.14
Case 4 : ω increased 1%, $\dot{m}$ increased 1%	382.79	1.39	0.15
Case 5 : ω reduced 1%, $\dot{m}$ reduced 1%	375.21	1.37	0.16
Case 6 : ω increased 1%, $\dot{m}$ unchanged	382.79	1.38	0.17
Case 7 : ω unchanged, $\dot{m}$ reduced 1%	379.00	1.37	0.17
Case 8 : ω increased 1%, $\dot{m}$ reduced 1%	382.79	1.37	0.19

a = Data from experimental result.

TABLE.2. Variation of K-Factor for Ø15MM (1/2”) PVC Pipe

	Rotational speed, ω (rpm)	**Mass flow rate, $\dot{m}$ (kg/s)**	**k-factor**
	236.00^b	1.03^b	0.1^b
Case 1 : ω reduced 1%, $\dot{m}$ increased 1%	233.64	1.04	0.07
Case 2 : ω reduced 1%, $\dot{m}$ unchanged	233.64	1.03	0.09
Case 3 : ω unchanged, $\dot{m}$ increased 1%	236.00	1.04	0.08
Case 4 : ω increased 1%, $\dot{m}$ increased 1%	238.36	1.04	0.09
Case 5 : ω reduced 1%, $\dot{m}$ reduced 1%	233.64	1.02	0.11
Case 6 : ω increased 1%, $\dot{m}$ unchanged	238.36	1.03	0.11
Case 7 : ω unchanged, $\dot{m}$ reduced 1%	236.00	1.02	0.12
Case 8 : ω increased 1%, $\dot{m}$ reduced 1%	238.36	1.02	0.13

b = Data from experimental result.

Power Loss

Based on (11), the k-factor has a significant impact on the power loss and mechanical power generated. Meanwhile, a high value of k-factor should be avoided, because it reduces the rate of mechanical output power that can be produced due to power loss. Over most of the range of the k-factor, after the maximum rotational speed is achieved, the effect of k-factor is insignificant.

Conclusion

According to the experimental results, for a constant water head, the larger the value of k-factor, the farther its overall performance moves away from the ideal conditions. With a higher k-factor, the Z-Blade turbine experiences higher power loss. Further efforts were made to prove that a change of 1% in the values of rotational speed and mass flow rate will cause large variations in the value of k-factor.

Acknowledgment

The authors would like to thank the Ministry of Higher Education, Malaysia for funding this research (PRGS/1/2014/TK06/FTK/02/T00011), and Universiti Teknikal Malaysia Melaka and Universiti Kebangsaan Malaysia for providing the laboratory facilities and technical support.

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