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Design and Testing of Screw Turbines for Flat Flow with Uneven Blade Distances

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Abstract: It is an innovative thing to design turbines that are compatible with flat-flow water energy. The turbine that was chosen is a turbine screw model with a non-uniform blade slope. The turbine made with a stator consists of a collector pipe and a quick pipe as a nozzle and a screw-shaped rotor with varying blade spacing. The results of the design are two screw parallel with each consisting of five blades which are installed at 45°, 55°, 65°, 75° and 80° angles. The research methodology used is experimental through theoretical design and practical testing. Tests are carried out in uniform blade angles and compared with combination blade angles. The test results show that the turbine with a combination blade angle has a rotational speed lower than the maximum rotational speed (i.e., at 60° blade angle) but has better rotational stability against load changes. Turbines still have good efficiency even though the rotating speed drops to 60% due to loading.

Keywords: Turbine Screw, Uneven Blade, Partial Blade, Flat Flow, Micro-Hydro

Introduction

The use of fossil fuels is increasingly expensive and causes pollution so that in the long run it is no longer a good alternative (Figdor *et al*., 2009). Renewable energy development use bio is also damage the environment, especially due to the application of pesticides that are not according to the rules or are still being used incorrectly (Fritsche *et al*., 2010). Seems smaller result in environmental degradation is the use of energy earth heat, the sun, the wind and plunge water. This energy use must also be designed properly to minimize environmental damage. Consideration in the use of environmentally friendly energy is the availability and technology used. The availability of large and small scale waterfall energy is quite large. What is still a lot of untapped is the energy of plunging water on flat flow, its availability along the river with a low slope but having a large discharge. In energy use plunging water needs to consider the distribution of water volume to use for irrigation. A thing that is beneficial if the use of waterfall energy is designed so as not to interfere with irrigation needs or others. For this purpose, turbines need to be designed and made with characteristics that are compatible with river flow conditions.

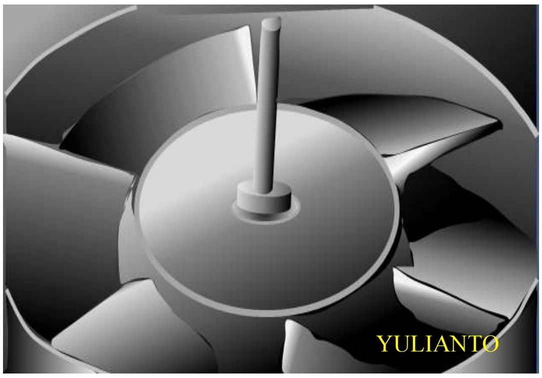

Fig. 1: A turbine for flat flow (EMRC, 2018; Schleicher *et al*., 2014)

The following are some types of turbines that are often used in micro hydro, one of which is a turbine that uses kinetic energy/water potential to produce power on a turbine shaft. Kinetic energy from the flow of water flowing into the turbine directly moves the blades to rotate and so the rotational speed is obtained on the turbine shaft. Many kinds of turbines are designed to be operated in rivers with flat flow. In Fig. 1, an example of a turbine with a blade is designed for flat flow.

Archimedes screw turbine models are also being developed. The threaded turbine model is also intended for low elevation flow, screw turbine models are installed with a certain height so that the flow of water in the turbine will also form an elevation in accordance with the elevation of the turbine. The maximum efficiency is 72% and is not affected by the selected rotation rate; however, the rotation rate changes the flow rate at the best efficiency position (Schleicher *et al*., 2014). In Fig. 2 and 3, each shows a threaded turbine model (Rorres, 2000) and a screw model is displayed (Yulianto *et al*., 2017).

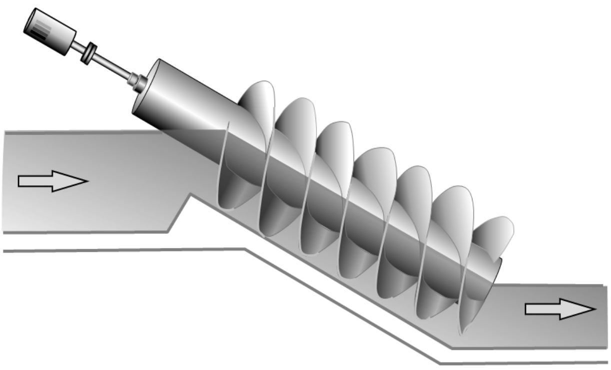

Fig. 2: Sketch of threaded turbines

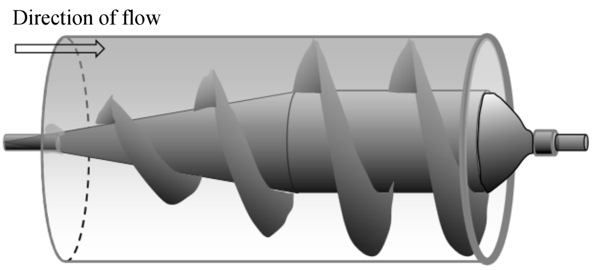

Fig. 3: Sketch of Screw Turbine

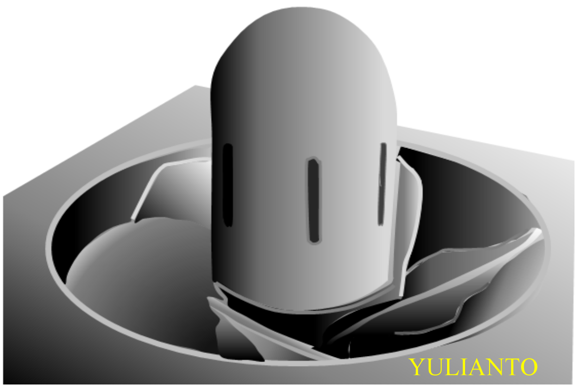

Fig. 4: Sketch of vortex turbine (Donihue, 2018; Yaakoba *et al*., 2014)

A turbine with a blade resembling a Pelton turbine has been developed and is specifically for vertical flow, which is known as a vortex turbine. This turbine is suitable for use in the water discharge of 1-8 m^3/s with a height between 1.5-3 m, which can produce power up to 15 kw. In Fig. 4, shown a vortex turbine (Donihue, 2018; Yaakoba *et al*., 2014).

The turbine model still needs to be developed. One of the results of its development is a turbine model named screw turbine with a combination of partial blade angles. This turbine is developed from Archimedes turbines, is expected to have better efficiency at various waterfall heights. This can happen because the entire flow of water is flowed to the turbine and one of the slopes of the blade corresponds to the height of the waterfall.

In the theory of windmill or water wheel turbines, the blade diameter is related to torque while the blade angle is related to the rotational speed produced. The design of the diameter and angle of the blade must involve the characteristics and availability of energy (Sarkar and Behera, 2012; Saroinsong *et al*., 2016). In some previous tests, for certain flow capacities, optimal energy was obtained at the blade angle between 60° to 70° (Yulianto *et al*., 2017). The flow is not always very flat, there are variations in altitude plunging water that is made intentionally or original as is. Because the entire flow of water is passed through a turbine, there is a possibility of excess water volume when the turbine turns down. Excessive volume of water can add water levels. Small variations in waterfall height can be used as feedback to get rotational speed stability and to obtain optimal power. For this requirement a screw turbine is designed with the blade arranged close together at an angle range between 45° and 80°, with the hope that there is a blade angle that is right at the waterfall level that changes. The resulting effect also considers the flow of water in the turbine which tends to change from the direction of straight motion to rotating following the turbine blades.

Theoretical Analysis

A. Flow, Pressure and Power Theory

Bernoulli's principle states that increasing the velocity of fluid flow can cause a decrease in pressure in the flow. This principle is a simplification stating that the amount of energy at a point in a closed flow is equal to the amount of energy at another point in the same flow path. Some assumptions in the implementation of Bernoulli law: (1) Incompressible and nonviscous, (2) no energy loss due to friction, (3) no heat energy is transferred across the pipe boundaries, (4) there are no pumps in the pipe section and (5) laminar fluid flow. If P is pressure (Pascal), v is speed (m/s), ρ is fluid density (kg/m^3), h is height (m) and g is gravitational acceleration (9,8 m/s^2), then, the Bernoulli Law formula (OpenStax College, 2018;

https://courses.lumenlearning.com/boundless-physics/chapter/bernoullis-equation/) is stated in Equation (1):

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2 \quad (1)$$

The Bernoulli equation can be used to calculate the velocity of the flow of liquid coming out of the bottom of a water reservoir. If the velocity of the liquid on the surface of the water reservoir is considered zero ($v_1 = 0$) the pressure on the surface of the water reservoir and the surface of the open hole are equal to atmospheric pressure ($P_1 = P_2$). Then the Bernoulli equation for this case is expressed in Equation (2) (OpenStax College, 2018; https://courses.lumenlearning.com/boundless-physics/chapter/bernoullis-equation/):

$$\rho g h_1 = \frac{1}{2}\rho v_2^2 + \rho g h_2 \quad (2)$$

The flow velocity at the bottom of a container can be calculated by Equation (2), if $h = h_1$-h_2, then, so that Equation (3) is known as the Torricceli Theorem (https://courses.lumenlearning.com/boundless-physics/chapter/bernoullis-equation/):

$$v_2 = \sqrt{2gh} \quad (3)$$

The Bernoulli equation can also be applied to the fluid flow in a pipe that has a small height difference. Flow in the fast pipe with a significant diameter compared to the waterfall height causes the flow velocity to be different at each point. Bernoulli's law above is no longer accurate. The flow on the upper side is faster than the bottom side. But this condition is different after the inside of the pipe is inserted a rotor with a certain blade position which can cause the flow velocity to be more even. Blade arrangement and approximate pattern of water flow in a two-dimensional image are shown in Fig. 5.

If the blade angle is low (approaching the direction of water flow) then a lot of water energy is not converted into mechanical energy on the turbine shaft. Water flows smoothly towards the straight direction. Conversely, if the blade is made close to perpendicular to the direction of water flow, precisely these blades become a barrier to the flow of water thus reducing the water discharge. In this event, the conversion process of mechanical energy to rotate the turbine shaft occurs. not optimal. The slope of a particular blade angle has the most optimal energy conversion power which is then called the optimal blade angle value (optimal angle). The slope of a particular blade angle causes the thread length per thread turn to be not free and results in empty spaces without blades. To anticipate this can be made parallel blades. The optimal angle is not a fixed value, but follows the amount of hydrostatic pressure available. The greater the availability of hydrostatic pressure, the greater the optimal angle required. It is very difficult to make turbines that can change automatically at optimum angles to keep up with changes in hydrostatic pressure caused by rising and falling water levels. To overcome this can be done by making a different optimal angle on a circle of blades that is between 45^o and 75^o. The thread density which consists of rows of blades or blade angles is getting closer and closer together, or in other words, the more to the back side the angle of the blade is getting bigger and the screw distance is getting closer as shown in Fig. 6. With the hope that at every level of water will find the optimal blade angle value. But at the blade angle that is larger than the optimal angle causes the turbine's rotating speed to decrease, to overcome this is to raise a high level of waterfall so that the optimal point shift occurs. The advantage of such construction is that the direction of the flow of water forms a circle resembling a sepiral which is more tenuous on the front side and getting closer on the back side. The collision of the water flow to the blades as shown in Fig. 6 seems to be more optimal. This event can increase efficiency in energy conversion.

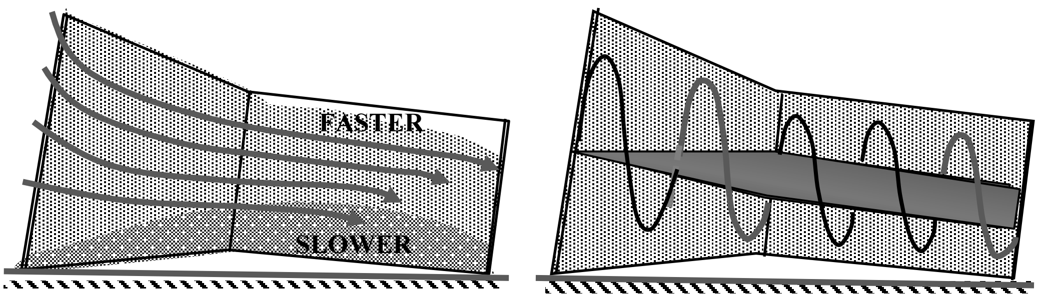

Fig. 5: Pattern of water flow in the turbine

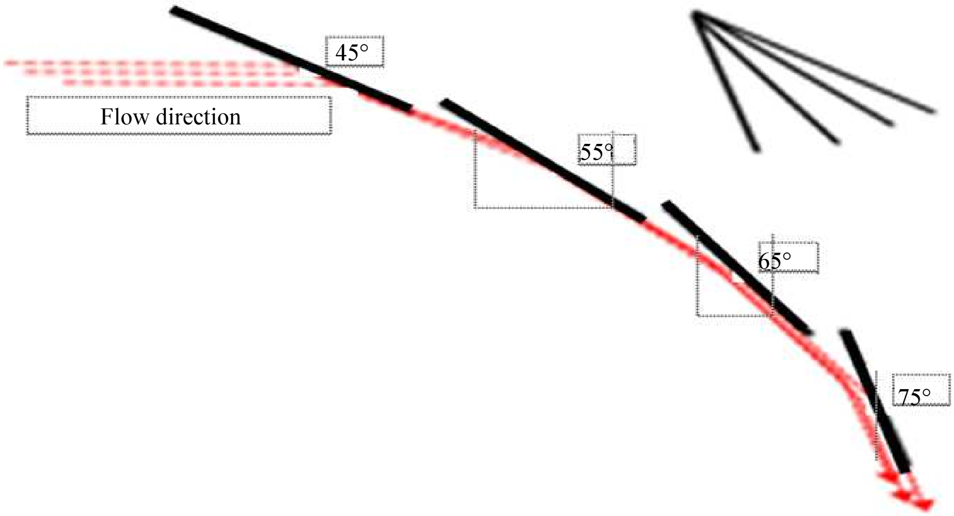

Fig. 6: Structure of the blades and forecast of water flow

In the analysis of the water flow velocity in the pipe for Fig. 5, after being equipped with a blade with the arrangement as shown in Fig. 6, Equation 1 can be used. But for the approach and simplifying the flow velocity calculation we can use Equations (3) (OpenStax College, 2018).

If the waterfall level at the front side is higher than the vertical diameter of the front funnel, then the speed of the maximum water flow (v) that enters the turbine applies Equation (3). Whereas the output side of the turbine can be calculated by Equation (4):

$$V_1 = \sqrt{\frac{2gh}{\left(\frac{A_1}{A_2}\right)^2 - 1}} \tag{4}$$

To calculate the availability of power, it can be derived from the hydrosatatis pressure at the bottom of the water. Hydrostatic pressure caused by water with height h is: $P_h = \rho.g.h$, for a rough approach, the values of ρ = 1000 kg/m^3 and g = 9.8 m/s^2. While the potential power (P_a) generated by the discharge (Q) and the high level of the water flow is expressed by Equation (5) (Forinash, 2010; Lajqi *et al*., 2016):

$$P_a = \rho.Q.g.h \tag{5}$$

The power in Equation (5) will be transferred to the rotating power on the turbine shaft (PM), which is then converted to electrical power by a generator coupled to the turbine shaft. If τ is the torque and N is the rotating speed per minute, then the power that occurs on the turbine shaft can be expressed as Equation (6):

$$PM = N.\tau / 9545(kW) \tag{6}$$

Table 1: Design result turbine specifications

Item		Size
Front funnel diameter	:	40 cm
Rear funnel diameter	:	30 cm
Rotor diameter	:	15 cm
Rotor length	:	47 cm
Front funnel	:	35 cm
Number of blades	:	2×5 seeds
Blade angle	:	45°, 55°, 75°, 80°
Blade composition	:	Parallel, 2 circles
Thread length of one circle (L_u)	:	20 cm (average)

B. Analysis and Synthesis of the Speed

The turbine has been designed and made with physical size as shown in Table 1. The fast pipe is made of transparent acrylic and rotor from stainless steel. The generator is coupled directly to the rear side of the turbine using a "V belt" and pulley with a diameter ratio of 1/5.

With reference to Table 1, intake diameter = 0.4 m or A_1 = 0.1236 m^2, outtake diameter 0.3 m (or 0.071 m^2) and rotor diameter 0.15 m (or 0.0153 m^2) so A_2 = 0.0554 m^2. For h = 0.5 m, the linear flow velocity in the rotor is:

$$V_2 = \sqrt{2gh} = \sqrt{2 \times 9{,}8 \times 0{,}5} = 3.1305 m/s$$

$$V_1 = \sqrt{\frac{2gh}{\left(\frac{A_1}{A_2}\right)^2 - 1}} = \sqrt{\frac{2 \times 9.8 \times 0{,}5}{\left(\frac{0.1236}{0.0554}\right)^2 - 1}} = 0.7869 m/s$$

Because the velocity of the water flow is 3.13 m/s, the ideal speed of the maximum rotation is the flow velocity divided by thread length, v_2/L_u = 313/20 = 15.65 rps or equal to 940 rpm. This rotational speed value is not the actual value, because in reality there is a slip, or the water flow is not straight but rotates according to the pattern of turbine blades. The slip value needs to be assumed with consideration, if the 0° turbine blade angle does not rotate because the slip is 100%, so if the blade angle is 90°, the turbine does not rotate, it means the slip is also 100%. The lowest slip is located at one vertex between 0° to 90°. In the previous test results it was shown that at an angle of 45° and 80° it also had a considerable slip (Yulianto *et al*., 2017). Based on (Yassen, 2014) states that the highest efficiency on the screw turbine is at an angle of 60-70°, this also means the slip that occurs is the lowest. For this reason, it is assumed in the design that the slip that occurs is 65%, so that the distance of the water flow for one round is 0.4 m and the rotation is only 470 rpm. For real conditions shown in the test results. If the pulley ratio used is 1/5, then the maximum ideal rotational speed is 4700 rpm, the rotating speed with a 65% slip is 3055 rpm. This is in the desired rotation range of 3000 rpm. Of course this rotational speed will drop when given a load.

Machine Testing and Data Analysis

A. Machine Testing/Methodology

Designed and made of four kinds of screw turbines each have a rotor with different blade angles, namely: (1) 45°, (2) 60°, (3) 75° and (4) blade with combination angle range of 45° to 75°. The fourth turbine is the turbine under study, while the other three turbines are used as comparison and initial research in obtaining blade angle range. All turbines are tested directly on a flat river flow with a waterfall of 0.5 m dan the same water discharge. The turbine is coupled with a 750 watt/ 3000 rpm generator via a belt and pulley with a 8/3 or/and 5/1 ratio. In Fig. 7 the testing process is shown. Then several stages of testing are performed including:

1) Observation of flow in the condition that the rotor is maintained does not rotate and in rotating conditions. Observation results are shown in Fig. 7
2) No-load testing, measuring turbine rotational speed, torque and voltage generated in the condition of a generator without load
3) Load testing, measuring turbine rotational speed, voltage and current generated at various resistive loading conditions on the generator
4) To carry out the turbine characteristic test, this time the data used does not take into account the efficiency of the turbine and generator. This is intentional because the analysis carried out is to determine the behavior of the turbine. The efficiency constants of turbines and generators may change because they are very dependent on the use of bearings, blade size precision and the use of generator brands

Table 2 shows the test result data on the turbine generator with belt/pulley with ratio 8/3 and blade angle of each 45°, 60° and 75°. In the table, the value of the power (watt) is not the result of measurement but the result of the calculation of the multiplication between the direct current (Ampere) and the voltage (volt) measured. Retrieval of data at a fixed blade angle of 45° is not continued because the no-load test has shown unfavorable results and the blade angle value is not an option.

Fig. 7: Turbine testing process

Table 2: Data for turbines with different blade angles, 8/3 belt-pulley ratios

Blade Angle	Testing type	Turbine (N:rpm)	Generator (N:rpm)	Voltage Output (v)	Current Output (A)	Power (Watt)
45°	No Load	95	253	-	-	-
60°	No Load	225	600	10	0	0
60°	With Load	169	450	6.0	1.2	7.2
		130	346	4.0	1.5	6.0
		105	281	4.0	1.4	5.6
		106	282	3.0	1.6	4.8
		78	209	2.0	1.8	3.6
		78	208	1.0	1.9	1.9
75°	No Load	121.72	325	7.0	-	-
75°	With Load	97.08	261.6	5.0	1.1	5.5
		78.65	210	3.0	0.9	2.7
		72.66	194	3.0	1.0	3.0
		67.41	180	2.0	1.2	2.4
		52.43	140	1.5	1.6	2.4
		50.56	135	1.0	2.1	2.1

N: Rotary speed

Table 3: Data for uneven angles blade, 5/1 belt-pulley ratio

Testing Type	Turbine (N:rpm)	Generator (N:rpm)	Voltage Output (v)	Current Output (A)	Power (Watt)
Without Generator	130-165	-	-	-	-
Generator Installed	106-148	530-740	16.5-17.0	-	-
With Load	93-120	465-600	14.5	1.18	17.11
	78	390	14.1	1.15	16.22
			11.4	1.22	13.91
	62	310	11.2	1.21	13.55
			11.1	1.20	13.32
	58	290	9.8	1.14	11.17
			9.5	0.80	7.6
			9.0	0.76	6.84
	50	250	7.7	0.67	5.16
			5.9	0.56	3.30
			5.3	0.52	2.76
Short Circuit	8-15	38-75	0	0.50-0.95	0

N: Rotary speed

While, Table 3 shows the test results data for turbines with combined blade angles and 5/1 belt-pulley ratios. All values that have been manipulated from the repeatability and theoretical counts to facilitate analysis. Changes in the use of belt-pulley ratios are intended to increase the rotating speed of the generator based on previous research using a comparison of 8/3. But in reality this effort cannot be achieved because it becomes an excessive turbine load. Of course this incident will be different if the height of the waterfall available is quite large.

B. Data Analysis

Flow velocity in the turbine is very difficult to observe. Different blade angles cause the linear velocity of the water flow to be expected to be different at each point. At the smallest angle 45^{o} has a linear speed (the actual speed that is converted to linear direction) that is faster than the larger angle. The leading blade will deflect the direction of the flow of water in the direction that has a tendency to rotate, getting closer to the back end, the flow velocity is getting higher but the linear speed is getting lower. This event is the influence of the angle of the blade that is closer and the fast pipe that is conical. Then this effect is compared to a turbine that uses a uniform blade angle.

Testing on a uniform blade angle of 45°, gives an indication that the turbine rotating speed is 95 rpm at the same location (same turbine elevation and same discharge). At a uniform angle of 45° it turns out that the level of water flowing in the turbine is only half of the height of the turbine, the discharge provided cannot fulfill (60% of the height) the turbine. This shows that at the same discharge, the water flows quickly without being offset by an increase in torque so that it can be said that many energies are not converted into mechanical energy on the turbine shaft. The rotational speed and torque produced are too low, so it is not feasible to rotate the generator.

At a uniform blade angle of 60°, no-load test results show that the turbine rotation results obtained have been folded to around 225 rpm. Changes in angle from

45° to 60° can increase the rotation from 95 rpm to 225 rpm. This is a special event. The flow rate of water becomes lower which can be proven from the increase in water level to 75% from the height of the turbine, but the turbine rotation becomes higher. This proves that there is an increase in efficiency in the conversion of waterfall energy into a spin energy on the turbine shaft. Also supported by literature studies show that thread turbines with blade angles between 60° and 70° have the highest efficiency. This also applies to screw turbines tested in this study.

The 75° blade angle setting has a symmetry case with a 45° blade angle. But the turbine rotational speed is slightly faster than the 45° blade angle, which is 122 rpm. If at the angle of the 45° blade, the water flow is passed just like that with a low energy conversion, in contrast to the 75° blade angle, the flow of water is restrained so as to produce low rotation with low torque, so that the total power is lower than the angle of the blade 60° or about 76%. Figure 8 shows the turbine behavior curves with blade angles of 60° and 75°. The vertical axis states the output power and vertical axis indicate the change in turbine rotational speed. At each change the angle of the uniform blade should be followed by a change in the height of the waterfall. The greater the angle of the uniform blade required the greater the height of the waterfall. In Fig. 9 a turbine response curve is shown which states the power to the turbine rotation speed with a blade angle of 60° and 75°. Unfortunately, in this type of turbine, the heavier the load that is installed is precisely the turbine's output power decreases and weakens, the turbine turns and the water discharge through the turbine also decreases. The decrease in water discharge through the turbine causes the water reservoir to become larger and can increase the waterfall level. Because of that the large water reservoir must be designed according to the speed of change in the level of the waterfall caused by the turbine turn down. This feedback can improve the turbine response to the load.

What has not been understood and becomes a question is why both curves in Fig. 8 have almost the same curved patterns. This pattern indicates a unique behavior and is not a mistake in the trial. The different of both curve is the speed of the fall of the output power which indicates that it occurs faster at the angle blade of the 75°.

This initial test provides inspiration for making turbines with blade angles that are not uniform, but made more and more tightly backward. Uneven blade angle is expected to be one corner blade has a high efficiency in accordance with the high availability of the waterfall. It is hoped that one side of the blade with a larger angle will not have a negative impact on the energy conversion process, because the water flow does not become linear anymore, but rather rotates following the direction of the previous blade. It is as if the entire angle of the blade is 60° relative to the water flow.

In Fig. 9 the turbine response curve is shown with the blade angle changing closer from 45° to 80°. The test results show the effect of turbine speed. The blade angle is too large or vice versa the blade angle is too small, both can reduce the rotational speed, so that the average blade angle calculation cannot be used. This is evident in the results of the test, namely the decreasing speed or lower than the uniform blade angle of 60°. But the decrease in rotational speed is not as low as in the turbine with a blade angle of 45° or 65°, because the load-free rotation is still around 147 rpm. Maybe the results will be clearer in testing with a higher water level.

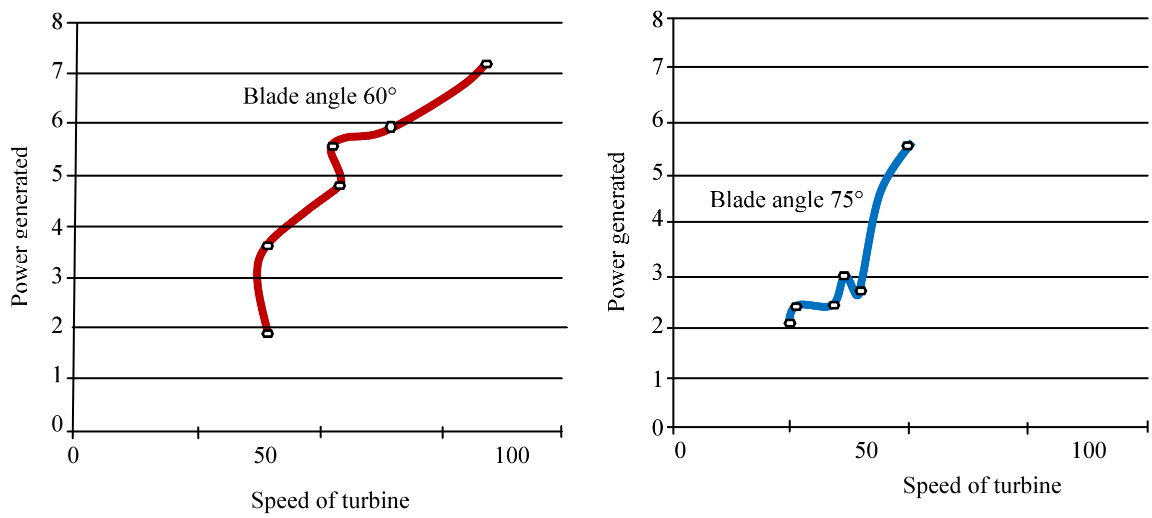

Fig. 8: Power generated Vs. rotational speed curve of the 60° and 75° angles blade turbine

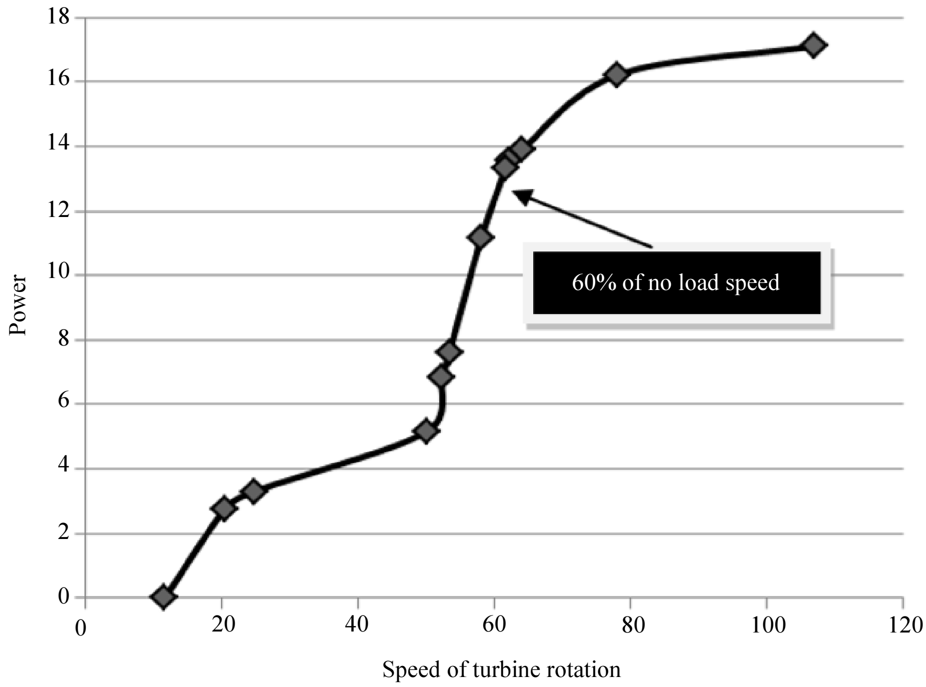

Fig. 9: Power Vs. rotating speed curve of the combining angles blade turbine

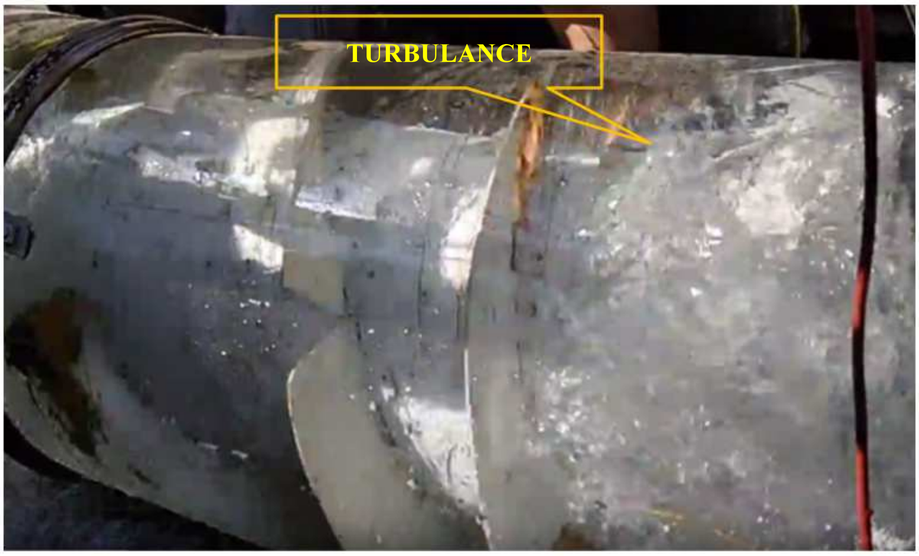

Fig. 10: Turbulence due to shifting blade angle from 85° to 80°

The new question obtained from this test, which is why the change in the belt-pulley ratio from 8/3 to 5/1 cannot change the rotating speed of the generator, but instead it decreases the rotating speed of the turbine. This unanswered question will be tested on different occasions.

As with the turbine with a uniform blade angle, loading on the turbine with the blade angle also causes a fall in the output power of the turbine, but not as drastic as the uniform blade angle of 45° or 75°. This tendency is owned by a turbine with the angle of the blade is getting closer. The output power is still in good condition provided that the rotation speed does not fall above 60% of the load speed without load.

In designing the turbine blade, 5 pieces are made, each of which is mounted on the blade angle of 45°, 55°, 65°, 75° and 80°. Note that the last blade should be installed at the angle of the 85° blade, but a 5° shift to 80° is carried out with the hope of reducing turbulence of the water flow at the end of the turbine. The results obtained show that turbulence is still very large. Photographs of turbulence are shown in Fig. 10.

Conclusion and Suggestion

In this work the machine has the ability to collect the entire flow of water to enter the turbine. So that all water energy can be converted into mechanical energy on the turbine shaft. With a non-uniform but regular thread design, one point or static corner of the blade can adjust to the level of the waterfall so it becomes compatible for all waterfall heights and can maintain good rotating speed for any load and any elevation of water. If the input side is equipped with a simple weir, it can provide natural feedback which can increase the stability of the turbine's rotating speed. Although the ideal characteristics cannot be achieved perfectly, the improvement in performance has been better.

A. Conclusions

In a turbine with a uniform blade angle it has the best output power at a 60° blade angle. Adding excessive loads can cause a decrease in power or failure in energy conversion in turning the turbine shaft. The fall of rotating speed occurs very drastically at the angle of blade 45° and 75°. To increase the rotational speed on load conditions can be done by increasing the waterfall height. To get a good turbine performance, a turbine with a non-uniform blade angle that is between 45° to 80° can be selected, which has characteristics similar to the uniform blade angle 60°, at certain water level plunge levels. But on a turbine with a non-uniform blade angle, the rotational speed is almost constant with respect to changes in altitude plunging water and efficiency can be maintained against changes in height of waterfall and changes in load. The same characteristics between turbines with 60° uniform blade angle with turbines with a combination angle of 45° to 80°, both of which are still quite efficient if the rotation speed decreases not more than 60% from the no-load rotating speed.

B. Suggestions

To increase the stability of rotational speed and torque can be done by designing the right reservoir size taking into account the availability of water discharge to have a high speed increase in waterfall. If the load increases, the turbine rotation decreases causing the water debit to also decrease. The decrease in water discharge must quickly increase the waterfall height to increase hydrostatic pressure so that feedback can be obtained to improve round stability.

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Authors' Contributions

Yulianto: Organized the study, author of paper, design, testing and analysis.

Bambang Priyadi: Assist in paper writers, image design and mechanical testing.

Fathoni: Assemble the system, data collection and analysis concept making.

Hari Sucipto: Designing, assembling electrical installations and making analytical concepts

Ethics

This article is an original research paper. There are no ethical issues that may arise after the publication of this manuscript.

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