Effect of Variation in the Number of Inclined Type Blades and Flow Discharge on the Performance of a Vortex Turbine Using a Cylindrical Type Basin

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Abstract- One of the challenges in the mandate of the National Energy General Plan in Indonesia is to increase the national energy mix to 23% in 2025 and 31% in 2050. This regulation is one of the driving forces for researchers to be able to provide solutions in the utilization of renewable energy. Indonesia has many renewable energy sources, from water, geothermal, bioenergy, wind, and solar. Of all these sources, one that can provide a significant contribution technologically is water energy. Even though it is very promising, the development of water energy still requires a very large investment, and its position is generally in mountainous areas. One of the potentials of water energy rarely used in Indonesia is water energy with a low head. Energy sources like this, with heads between 1 and 3 m, are very easy to find in almost all parts of Indonesia. One type of turbine used at low heads is the Gravitational Water Vortex Turbine (GWVT). This study aimed to obtain the performance of a vortex turbine that uses a cylindrical shape basin by varying the number of inclined blades and the flow rate. A test tool has been built that is equipped with a data acquisition system to carry out this experiment. The results show that the vortex turbine efficiently produces electrical energy from low-head water flow.

Keywords Micro hydro, vortex turbine, performance, experimental.

1. Introduction

A micro-hydro power plant is a power plant that utilizes water power as a working fluid to drive a turbine connected to an electric generator [1]. Micro hydropower has the advantages of having low maintenance costs, does not use fuel, having simple construction, making it easy to operate, especially in remote areas, and being environmentally friendly [2]. The turbine is the essential component in a power plant that converts the potential energy of water into mechanical energy. The mechanical energy rotates the generator to produce electrical energy. Water turbines generally have two main components: the stator, which consists of a casing and fixed blades, and the rotor, which consists of a shaft, moving blades, and bearings [3,4]. In general, turbines are grouped into two parts: impulse turbines and reaction turbines. Impulse turbines convert the potential energy of water into kinetic energy by using a nozzle where water coming out of the nozzle at a relatively high speed will hit the side of the turbine blades. Then the turbine blade that hits the direction of flow velocity changes, and there is a change in momentum so that the turbine blade can move. Impulse turbines are divided based on high head, medium head, and low head, such as Pelton, Turgo, Multi-jet, and Crossflow [5]. At the same time, the reaction turbine is only for the medium and low heads, such as Francis, Propeller, Kaplan, and vortex [6–8]. In addition to the working fluid of water, vortex turbines as wind turbines are also widely developed in coastal areas and at high altitudes because they are considered very effective as power generators [9]. A *gravity whirlpool power plant* is a micro-scale hydropower generation technology that operates at low-altitude water flows [10–12]. Therefore, this type of generator is very suitable to be applied at low heads such as rivers [13–15]. This power plant is very environmentally friendly, with zero greenhouse emissions. It can also improve water quality by lowering water temperature to be good for aquatic life [16]. Using water energy with this technology is one form of maximizing the use of renewable energy to overcome the current energy crisis [17]. One type of turbine that utilizes a whirlpool to drive the road blades on the turbine is a vortex turbine [18]. Because every flow of water contains potential and kinetic energy, the vortex turbine utilizes potential and kinetic energy as a whirlpool [19]. The water flow will be directed toward a cylindrical cross-section to form eddies, where this cylindrical cross-section is called a basin [20]. An outlet at the bottom of the basin will allow the flow to fall due to gravity. The whirlpool is formed due to the balance between the tangential and axial forces of water passing through the basin so that a free surface will be formed centered on the axis of the outlet hole. The height of the waterfall will be one of the variables that affect the energy of the water and is assumed to be the height of the basin [2]. The kinetic energy in the form of a whirlpool is used to drive the turbine blades, which are placed in the middle of the two whirlpools [21]. Because the water moves radially, the turbine will be centered on the vertical axis. Then the turbine's mechanical energy in the form of shaft rotation will be converted to electrical energy using a generator [22]. The input energy in the form of hydraulic water energy will have a different value from the output power of the generator, depending on the efficiency of the system, including the efficiency of the turbine and generator. Based on several previous studies, the efficiency of vortex turbines ranges from 35 – 40% [23].

The gravity whirlpool turbine generator was first patented by Franz Zotloterer [24], a scientist from Austria looking for a vortex phenomenon without any external force causing it. In other words, naturally occurring eddies [25]. This investigation resulted in an idea to generate a vortex in a cylindrical container with an outlet at the bottom [26]. From that time [20], vortex turbines as generators have become a concern for scientists to develop and improve their efficiency.

Saleem et al. [20] analyzed the performance of a single-level gravity whirlpool power plant with a cylindrical basin type. By using mathematical and experimental calculations, analyze the effect of vortex height, blade position, percentage of blade submersion, blade slope, and straight or conical tipped blades on the performance of the vortex turbine. From the results of the analysis, it was found that the more water discharge that enters the basin, the more vortex height will increase [27]. Another researcher [2] tried to investigate a multistage vortex turbine to find the energy potential in a conical basin-type whirlpool. Ullah et al. performed an analytical and experimental analysis by installing three blades in a conical basin. Some parameters analyzed include shaft rotation, torque, efficiency, and power produced with different loads. It was found in this study that the blades cause a vortex distortion at the upper level, which also affects the blades at the lower level.

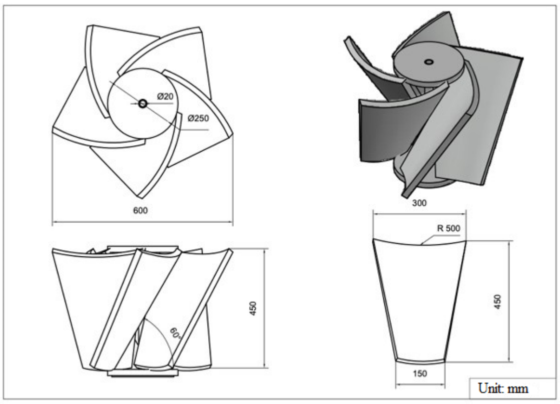
On the other hand, an analysis of the whirlpool-free surface was carried out by researchers [28]. They want to analyze changes in whirlpools in the form of vortex diameter, discharge, and circulation that occur with variations in the height of water entering a basin. An analytical model is used to determine the correlation of the research variables determined by experimental validation. The results showed a significant influence of the water level in the basin on the output parameters such as eddy diameter, discharge, and circulation. Nishi et al. [29] analyzed the axial flow field of a hydraulic turbine on an open channel. The aim is to characterize the flow, especially the slipstream, that occurs when the flow is axially passing through an impeller. As a result of this study, it was found that there is a slipstream that produces a free surface in the form of eddies on the downstream side. Based on the studies, there have not been any studies regarding the performance of vortex turbines using variations in the number of tilted blades and flow discharge in detail. The purpose of this study was to obtain the performance of a vortex turbine by varying the number of tilted blades and the flow rate using a cylindrical basin. Performance investigation is also carried out by testing the resulting torque, power, and blade rotation. This study under a lab scale shows that increasing the number of inclined blade-type blades in vortex turbines in the cylindrical basin also affects the increase in turbine power and efficiency. This condition is also supported by research conducted by [30] that efficiency increases with an increase in the number of turbine blades. He also stated that further studies were needed to determine the optimal number of blades for turbine performance.

So for further research, considerations in reducing or increasing the number of blades will affect the power and efficiency of the turbine. The expected results of this study will provide important information in designing a vortex turbine with better efficiency.

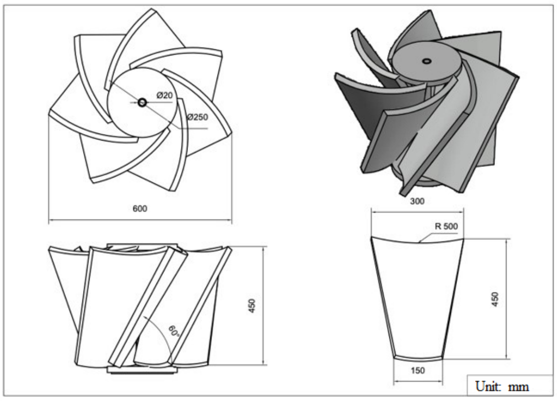
2. Methodology and Experimentation

2.1. Experimentation

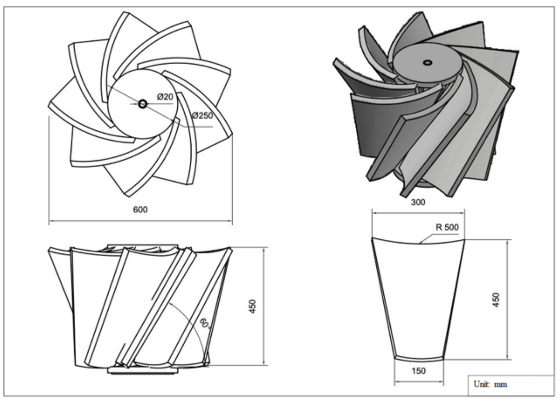
Topological conditions and water flow for the type of turbine that is made can be briefly described as follows. The research was conducted at the Mechanical Engineering Laboratory, Universitas Sumatera Utara, and the Workshop at Politeknik Negeri Medan. The test location in Medan city which has an area of 265 km^2 with an altitude ranging from 2.5 to 37.5 meters above sea level and rainfall ranging from 985 mm yearly. The turbine requires a head ranging from 1 - 3 meters with a flow capacity of 0.01 - 0.0225 m^3/s and a flow velocity ranging from 2 - 2.5 m/s. The main equipment is the inclined-type turbine blade (Fig.1) and the basin-intake tunnel (Fig.2). The turbine blade has a slant-type specification, a head diameter of 25 cm, an outer diameter of 60 cm, a radius of curvature of the blade R500 and an angle of inclination of 60°. Meanwhile, the basin used is cylindrical.



(a)



(b)



(c)

Fig. 1. Design of vortex turbine blades
(a) 5 blades (b) 7 blades (c) 9 blades.

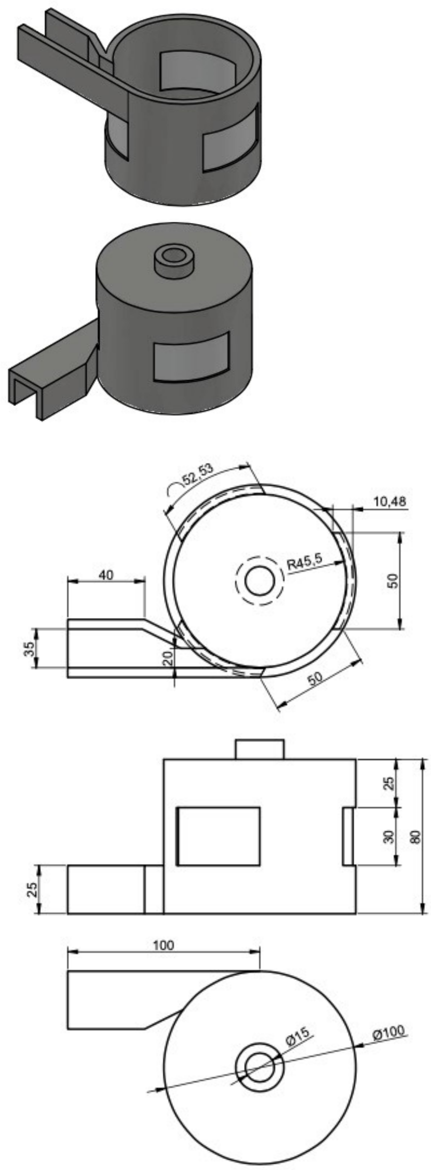


Fig. 2. Design of basin and intake tunnel.

The experimental scheme for the research is shown in Fig.3. The gravity whirlpool power plant was built on a laboratory scale with a basin diameter of 1 m and a basin height of 0.8 m. This dimension has followed a ratio from previous studies, which stated that for the best performance, the ratio of basin diameter and basin height is between 0.5 - 1.5 [23]. In the basin, three transparent windows of acrylic material have been designed, which make it easy to observe the flow in the basin. There is a hole at the inlet bottom with 0.15 m; the value suggested is 0.14 - 0.18 of the basin diameter. An inlet is a ditch at the basin top with a size of 0.3 m x 0.25 m where there is a slope where it touches the basin's edge with a notch angle of 27°. A water supply tank 1 m high with an outlet at the bottom is arranged parallel to the inlet. Water will continuously be pumped to the supply tank from the reservoir under the basin when in operation. In this test, two pumps with a capacity of 800 L/minute were used to pump water into the supply tank and maintain the water level in the tank.

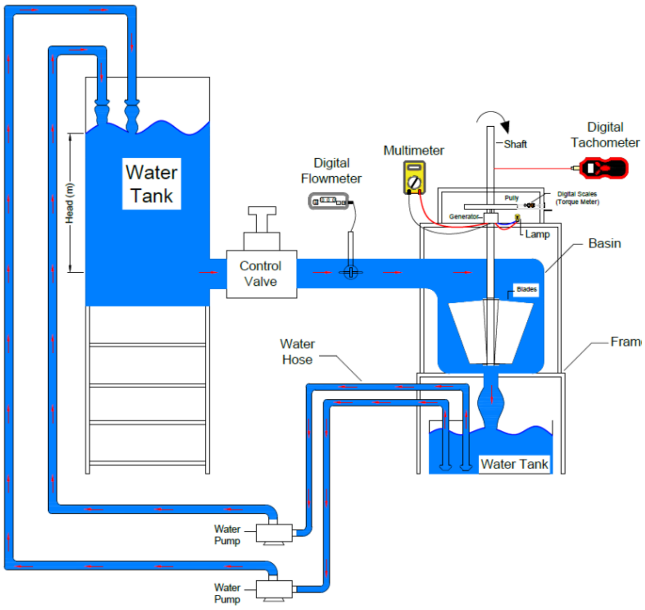


Fig. 3. Experimental scheme.

The water from the reservoir is controlled by a JIS 10K type gate valve with a diameter of 6 inches directly connected to the inlet of the basin. Variations of valve openings carried out are 50%, 40%, and 30% openings. The water level in the supply tank is kept constant and ensures that the two pumps operate correctly. The type of blade used is inclined with a slope of 60^o. This blade type is expected to provide the best performance because the inclined type utilizes the axial force and the tangential force from the water to rotate. The blade has a diameter of 0.5 m, where this value is suggested to be half the diameter of the basin. The blades are made of acrylic material with variations in the number of blades 5, 7, and 9, and the blade height is 0.45 m. The blade is placed with a vertical axis as far as 0.1 m from the output hole, as shown in Fig.4a. The water discharge entering the basin is calculated by multiplying the open cross-sectional area of the valve by the velocity of water leaving the valve. The speed of the water is measured using a flowmeter placed on the flowing water. Another parameter that is measured when the vortex turbine is operated is the rotation of the shaft due to the whirlpool that drives it using a digital tachometer (±0.05%). The torque parameter is an indicator of the power of the water absorbed by the turbine. This torque measuring technique uses a mass balance connected to a rope that rubs against the pulley, as shown in Fig.4b. Load on this measurement with each increase of 0.5 kg until the shaft stops rotating. All parameters are measured for each variation of valve opening and the number of turbine blades. A digital kWh meter is used with a working voltage of 6.5-200 VDC and a maximum power of 200A/1000 W to determine the power value, voltage (volts), and current (amperes). Digital scales are used to measure the load when testing a vortex turbine with a capacity of 5 kg/10 G. The velocity of water to the basin is measured using a streamlined digital flow meter. At the same time, the electric generator generates electricity due to turbine rotation that occurs with power specifications of 12V - 48V, 300 watts, and 500 rpm.

(a)

(b)

Fig. 4. (a) Blade (b) Torgue measurement.

The variables observed in this study consisted of independent variables and dependent variables. The independent variables consist of the number of turbine blades (5, 7, and 9 blades) and the inflow velocity variables, namely, 2 m/s, 2.2 m/s, and 2.5 m/s. At the same time, the dependent variable consists of shaft rotation speed, torque, power, and efficiency of the turbine. Figure 5 shows a photo of the installation of the test equipment used in this study.

Fig. 5. Photo of test equipment installation.

2.2. Performance Calculation

Factors that affect the turbine's power are torque and shaft rotation. So to know the performance of the whirlpool turbine, data is needed to calculate and analyze. The calculation source refers to a researcher [20] who examined experiments on whirlpool gravity turbines. The following parameters are required to determine the performance of the tested vortex turbine.

1. Torque

Torque is the rotating force generated by the turbine shaft or the turbine's ability to do work—torque measurement in experimental testing using a static torque meter.

$$\tau = F \; r_p \tag{1}$$

Where τ is torgue (Nm), F is force generated by the turbine shaft (N) and r_p is radius puly (m).

2. Angular Speed

Angular speed (ω) is the value of the circle angle formed by the trajectory of a point that moves in a circle per unit of time. Where the angular speed units are rad/second or rad/minute and n is shaft rotation in rotation per minute (rpm).

$$\omega = \frac{2 \; \pi \; n}{60} \tag{2}$$

3. Turbine power

Turbine power is the power generated by the turbine rotor due to obtaining energy from the flow of water. Turbine power is not the same as water power because turbine power is affected by the power coefficient. The power coefficient is the percentage of power contained in the water flow, which is converted into the form of mechanical energy.

$$P_{turbine} = \tau \; \omega \tag{3}$$

Where $P_{turbine}$ is turbine power in watt.

4. Water Power

Water power is the power generated by water per area, or water power is water moving per unit of time.

$$P_{water} = \rho \; Q \; g \; H \tag{4}$$

Where P_{water} is water power (watt), ρ is water density (kg/m^3), g is gravity (m/s^2) and H is head vortex (m).

The volume of water flowing per unit time (Q in m^3/s) that moves with speed v (m/s) and passes through an inlet surface area A (m^2) is:

$$Q = v \; A \tag{5}$$
$$A = \pi \; r^2 \tag{6}$$

Where r = radius inlet (m).

5. Turbine Efficiency

Turbine efficiency is the ability of the turbine to convert the potential energy contained in the water into mechanical energy to drive the generator.

$$\eta_{turbine} = \frac{P_{water}}{P_{turbine}} \; . \; 100\% \tag{7}$$

Tests were performed using the GWVT prototype setup, but the same can be done on a large scale. In this regard, scaling by considering the effect of turbine dimensions on performance parameters, such as rotational speed, flow rate, power, and efficiency, can be explored specifically for GWVT. To develop the relationship, one of the best references is provided by Moody and Zurowski [14], which is also followed by Thakker and Hourigan [22], for wave power generation. Assuming the geometric similarity of the original turbine and the scale turbine with negligible variations of the Reynolds number and surface roughness effects across the two turbines, the following relationship can be used to find the performance parameters of the scale turbine:

$$\frac{N_s}{N_o} = \left(\frac{D_o}{D_s}\right)\sqrt{\frac{H_s}{H_o}} \tag{8}$$

$$\frac{Q_s}{Q_o} = \left(\frac{N_o}{N_s}\right)\left(\frac{D_o}{D_s}\right)^3 \tag{9}$$

$$\frac{1-\eta_s}{1-\eta_o} = \left(\frac{D_o}{D_s}\right)^n \tag{10}$$

$$\frac{P_s}{P_o} = \left(\frac{N_s}{N_o}\right)^3\left(\frac{D_s}{D_o}\right)^5\frac{\eta_s}{\eta_o} \tag{11}$$

where Q and H are the flow rate and water head, respectively. Parameters N, P, n, and D are notations for rotational speed, power, efficiency, and turbine diameter, and the subscripts o and s refer to the original model and scale. Index n is in the range of 0.2 - 0.25. From comparing the scale unit field tests with the original model, Moody and Zowski concluded that the best value for n is around 0.2 [14].

3. Results and Discussions

As previously stated, this research is intended to obtain the performance of a vortex turbine. This study investigated the effect of the number of tilted blades and valve openings on each performance parameter. Each variation in the number of blades is operated for three valve opening sizes, resulting in a constant flow rate of 0.0225 m^3/s (water velocity 2.5 m/s), 0.0154 m^3/s (water velocity 2.2 m/s), 0.01 m^3/s (water velocity 2 m/s) while maintaining a water level in the reservoir of 1 m. The total weight of the water-driven components, including the weight of the blade, pulley, and shaft, is 9.8 kg. When measuring torque, a load variation is carried out on the pulley, which affects the number of shaft rotations until it finally stops.

Figure 6 shows the test data with variations in shaft rotation and load on the turbine. The data shows that the water velocity at the inlet of the basin is 2.5 m/s resulting in a maximum discharge of 0.0225 m^3/s. When testing using five blades, the maximum shaft rotation speed occurs without loading, which is 98 rpm. Meanwhile, with loading, the maximum turbine power occurs at a loading of 4.5 kg for a torque value of 8.82 Nm and a turbine efficiency of 40.31%. For the maximum flow rate, it produces maximum parameters for shaft rotation, torque, and turbine power.

Meanwhile, for a minimum discharge of 0.01 m^3/s, a maximum turbine efficiency of 38.24% is obtained. The resulting change in torque increases with increasing load on the turbine shaft while the shaft rotation gets smaller. A note that a large load will also require a large water force. Because the water discharge is assumed to be constant, the water power to rotate the turbine is not maximum, resulting in decreased turbine shaft rotation.

It shows that the generated turbine power has increased up to a certain point and will decrease with increasing torque. The maximum torque value occurs at a loading of 6.5 kg and a maximum discharge of 12.75 Nm. The efficiency value of the turbine using seven blades increased by 2.46% compared to that of the turbine using five blades. This condition happens because the absorption power of the turbine increases due to the increased cross-sectional area of the turbine. The test results show that the maximum turbine efficiency when using seven blades at a water velocity of 2.5 m/s is 42.77%. The turbine test produced the maximum efficiency when using nine blades, 43.11%. The increase in efficiency is supported by the increased sweep area of the turbine blades so that water power can be absorbed faster and more than when the turbine uses 5 and 7 blades. Table 1 also shows the turbine performance obtained from the test results with variations of 5, 7, and 9 blades. There is a clear approach regarding the effect of the number of blades on turbine performance based on the data that has been presented. The increasing velocity of water entering the basin will increase the tangential force of circulating water. The axial force of water can be maximized with a slanted blade design—the water's hydrostatic pressure increases as the waterfall height. Nevertheless, a large water discharge generally will increase the vortex turbine's performance because a large amount of water is needed to produce a strong vortex. Table 1 shows that turbine efficiency increases with increasing circulating water discharge. The efficiency of the turbine using five blades is the lowest, and the turbine with nine blades has the maximum efficiency. It shows that the more blades, the more turbine efficiency increases.

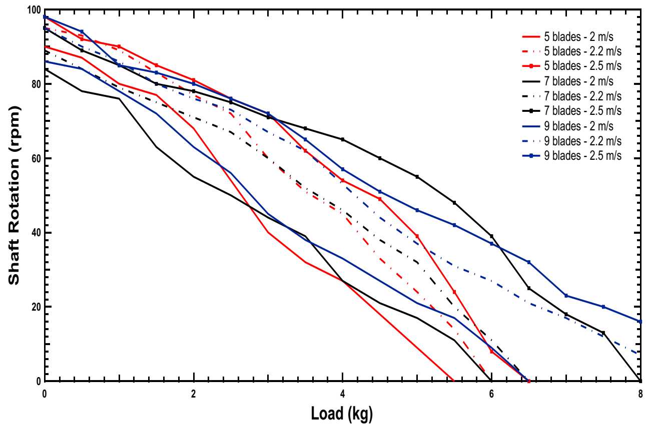


Fig. 6. Shaft rotation versus load for 5, 7, and 9 blades.

Table 1. Turbine performance test results with variations in the number of blades

Number of blades	Water Velocity (m/s)	Discharge (m^3/s)	Head (m)	Shaft Rotation (rpm)	Torque (Nm)	$P_{turbine}$ (Watt)	P_{water} (Watt)	η_t (%)
5	2	0.01	0.7	54	6.8	27.72	68.46	40.49
	2.2	0.0154	0.6	45	7.8	36.96	90.37	40.90
	2.5	0.0225	0.5	49	9.8	45.28	110.03	41.15
7	2	0.01	0.7	39	6.8	28.03	68.46	40.94
	2.2	0.0154	0.6	46	7.8	37.79	90.37	41.81
	2.5	0.0225	0.5	55	9.8	46.47	112.03	42.77
9	2	0.01	0.7	56	5.8	28.74	68.46	41.99
	2.2	0.0154	0.6	62	10.8	44.56	105.43	42.26
	2.5	0.0225	0.5	42	10.8	47.43	119.03	43.11

Figure 7 compares the torque and shaft rotation for the 5, 7, and 9 blades. When the turbine uses five blades, it will produce minimum torque, and when using nine blades, it produces maximum torque. The effect of the number of blades has a significant effect on the torque of the turbine being tested. Figure 8 shows the ratio of shaft rotation to turbine power, whereas the shaft rotation increases, the turbine power also increases. The maximum turbine power of 47.43 watts is generated when the turbine is tested using nine blades at 42 rpm. Figure 9 shows the ratio of shaft rotation to turbine efficiency, where the maximum efficiency of 43.11% occurs when the turbine uses nine blades.

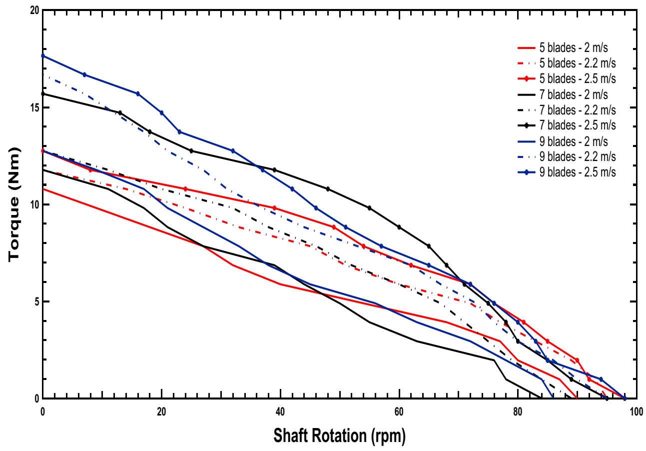


Fig. 7. Torque versus shaft rotation for 5, 7, and 9 blades.

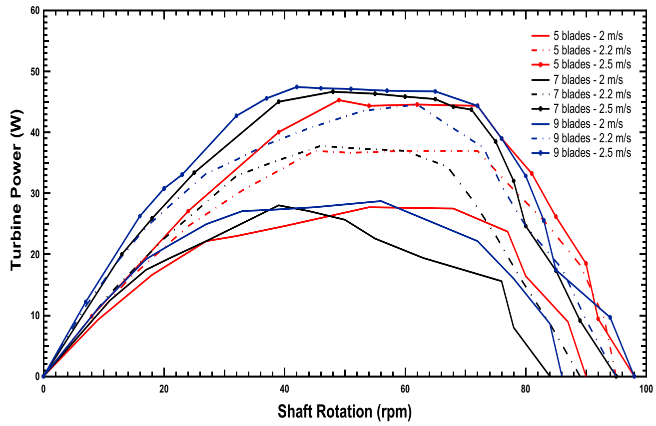


Fig. 8. Turbine power versus shaft rotation for 5, 7, and 9 blades.

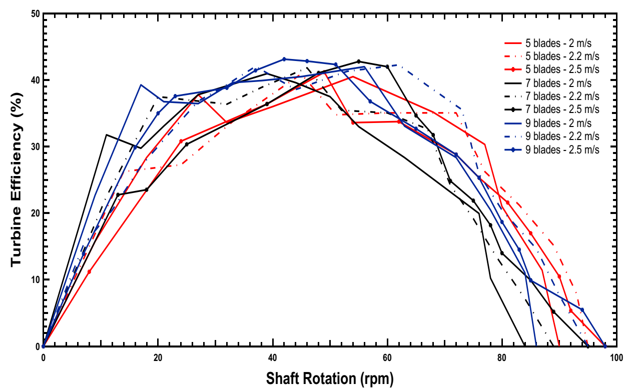


Fig. 9. Turbine efficiency versus shaft rotation for 5, 7, and 9 blades.

4. Conclusion

Research on the performance of vortex turbines with variations in the number of inclined blades and flow rates for cylindrical basins has been successfully carried out. Test data shows that increasing the number of inclined blade type blades in vortex turbines in the cylindrical basin also affects the increase in turbine power and efficiency. The performance of the laboratory scale vortex successfully built turbine can produce a maximum turbine power of 47.43 watts and a turbine efficiency of 43.11% when using nine blades. Please note that the material for the blade is acrylic, the basin is made of fiber resin, and the water tank is made of an iron plate. Adding the number of blades will affect the dimensions of the vortex turbine installation. The condition will also affect the economic aspects of the vortex turbine installation costs due to increased material and component production costs.

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