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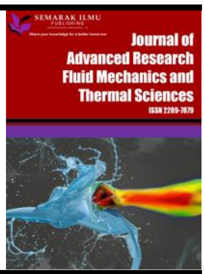

Semi Twisted Curve Blade Vortex Turbine Performance at Runner Rotation Speed Variation using CFD Simulation

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ABSTRACT

Utilization of renewable energy potential continues to be developed at this time. One of them is a hydroelectric power plant with turbulent vortex technology. One of the vortex turbine blade designs that has been developed is the semi twisted curve. The blades shape of the blades and the position of the runners affect the performance of the vortex turbine. This research uses CFD simulation by varying the rotational speed of the runner, which is between 80 to 120 rpm. The position of the upper end of the runner is placed at a depth of 4.5 cm from the total depth of the cone basin of 33 cm, the maximum water power is set at 28.66 Watt obtained from the mass flow rate of water of 6.21 kg/s. The simulation results show that as the runner's rotational speed increases, the torque decreases, as well as the torque decreases slightly. The highest turbine power and efficiency occurred at 90 rpm runner rotation, which was 4.044 Watt and 14.11% respectively. This is because the turbine power calculation is the result of the multiplication between torque and runner rotation which produces the highest value at 90 rpm.

1. Introduction

All countries around the world are encounter a problem for energy security. Therefore, they are expected to be independent of global energy share and increasing for renewable energy contribution [1]. The adverse effects of the use of fossil fuels and nuclear have affected the intensive development of renewable energy sources such as solar energy, micro hydropower, wind energy, biomass and geothermal [2]. In order to increase renewable energy application and reduce fossil fuel, for instance, rice husk as biomass has caloric value of 11.03 MJ/kg [3]. In Indonesia, until now, the main power plants still use fossil energy sources such as coal by 50%, natural gas 29%, and fuel oil at 7% [4]. Data shows that fossil energy sources are limited in number so efforts are needed to reduce the use of conventional energy sources to prevent an energy crisis. In addition, the combustion process produces pollutant containing carbon dioxide gas (CO_2) in the air which will absorb radiant heat from

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the sun and then emit the heat again to the earth so that global warming occurs [5]. Therefore, there is a need for new and renewable energy sources to prevent an energy crisis and global warming.

The biggest potential of Indonesia's renewable energy sources, especially compared to other renewable energy sources, is hydroelectric power, which is 94.3 GW [6]. Hydroelectric power plants convert the potential energy of water into mechanical energy in the form of a turbine rotation coupled with a generator to generate electrical energy. In selecting the appropriate type of turbine, it depends on the discharge and head of the water source that drives the turbine [7]. A Small-scale hydropower can be an economically viable source of supply, as micro-hydro can provide decentralized electricity supply in rural areas that have adequate hydroelectric technical potential [8]. A vortex turbine is a turbine that utilizes a vortex of water flow [9]. The whirlpool creates rotational energy to drive runners or a series of turbine blades to produce mechanical energy in the form of shaft rotation [10,11]. Then, the turbine shaft is coupled to the generator to generate electrical energy. A vertical axis turbine runner is installed in the center of the whirlpool in the turbine basin [12]. Hence, the vortex turbine harnesses the whirlpool energy into useful energy [13]. In addition, the twisted tape/blade increases the swirl of flow and the magnitude of the velocity [14]. Furthermore, viscous forces of the swirling flow affect the life level of microorganisms [15]. The main advantage of a vortex turbine is that it can operate at a very low water flow source head and friendly to aquatic creatures such as fish [16,17].

Computational fluid dynamics (CFD) will play a growing role in turbines optimization [18]. The 3D model gives closer pattern to the experimental photo than the 2D [19]. Flow regime identification is of huge importance for flow analyzing in a fluid machinery. One method can be using such as dynamic pressure signals to identify flow regime [20]. Output power of a wind turbine, which is similar to hydraulic turbine, can be maximized by increasing the wind velocity at its entrance through a diffuser shape at entrance of the wind turbine [21].

Given the many potential low-head water flows available, the appropriate type of turbine is a vortex turbine. The advantage of this type of turbine compared to other turbine types is that it is able to operate at a low water flow head, which is around 0.7m - 3m. Therefore, the vortex turbine generator system can be applied to irrigation water flows or downstream rivers [22]. Because the source of the driving energy is the flow of water at a low head, the resulting turbine rotation is also low. Vortex turbines produce between 80 and 180 rpm with relatively low power [23]. Based on the results of these studies, this research was carried out on variations in the rotational speed of the vortex turbine, namely 80, 90, 100, 110 and 120 rpm with a depth distance of the runner with the basin floor is 4.5 cm and the slope angle of the semi-twisted curve blade is 30°, then investigated the output power and efficiency. This research uses the CFD simulation method with ANSYS Fluent commercial software.

2. Methodology

2.1 Vortex Turbine Power

A vortex turbine is a water turbine that can transfer water energy on a vertical axis which causes a pressure difference around the axis by utilizing a whirlpool. This type of water turbine can operate in low head water flow because it utilizes gravity and vortex eddies [24]. The entry of water flow energy into the basin is in the form of kinetic energy. Kinetic energy itself is focused as a rotational energy at the center of the vortex flow. After that the energy from the rotation is connected through the blade shaft and produces torque and power. Then the power is transmitted to the generator and converted into electrical energy. The turbine power equation is

$$P_{shaft} = T\omega \quad (1)$$

where P_{shaft} is shaft power in Watt, T is torque in Newton-meter, and ω is angular velocity in radian/second.

The maximal water power can be calculated using formula

$$P_{max} = \rho g Q H_v \quad (2)$$

where P_{max} is the maximum water power in Watt, ρ is water density in kg/m^3, g is acceleration due to gravity in m/second^2, Q is water flowrate in m^3/second, and H_v is vortex head in meter.

Then, the efficiency of the vortex turbine becomes

$$\eta = \frac{P_{shaft}}{P_{max}} \quad (3)$$

where η is efficiency in percent.

2.2. Vortex Turbine Discharge

The vortex turbine is a fixed propeller type water turbine, this type of water turbine has a blade where the water passes through the runner in an axial direction to the shaft. The fixed propeller type water turbine has an efficiency curve that is different from other types of water turbines as shown in Figure 1. The figure shows a graph of the efficiency comparison with the ideal discharge being met.

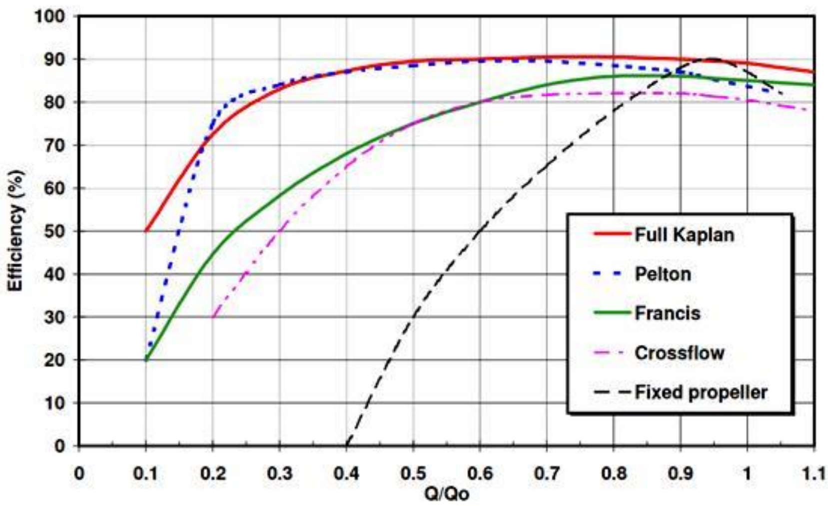


Fig. 1. Efficiency of different types of turbines [25]

The water turbine is designed to operate near its best operating point which is usually at a water flow rate of 80% of the maximum water flow. If the water turbine operates at a lower or higher flow rate than its best efficiency points then its efficiency will decrease. In determining a maximum discharge value for a vortex turbine design, it can be determined using the simplified Bernoulli equation. The maximum water flow velocity [26] is

$$v_{max} = \sqrt{2gH_v} \quad (4)$$

Therefore,

$$Q = v_{max} A_o \qquad (5)$$

where v_{max} is the maximum water flow velocity in m/s, and A_o is outlet area in m^2.

2.3 Vortex Flow

Vortex flow is a flow that can be visualized as a flow that can rotate about a vertical axis, this is due to the difference in pressure between the axis and its surroundings [27]. Vortex flow has a flow pattern that can be illustrated as in Figure 2. Where is gravitational potential energy per unit mass if gravity is constant and is fluid enthalpy per unit mass.

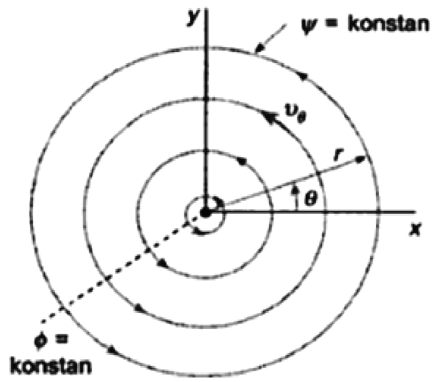


Fig. 2. Vortex flow line pattern

Based on the classification of rotating flow that occurs in a vortex turbine, it is a free vortex flow type. Free vortex flow is a vortex flow that occurs, even though there is no force on the fluid. The characteristic of free vortex flow in a vortex turbine is the tangential velocity of the rotating fluid particles at a certain distance from the centre of the vortex flow. The relationship between the velocity of the fluid *v* and its distance from the centre of the circle *r* is

$$v_T = \frac{2\pi r}{T} \qquad (6)$$

where v_T is tangential velocity in m/s, *r* is radius of rotation of fluid particles from center in meter, and *T* is period in second.

2.4 Research Procedure

This study simulates the performance of a vortex turbine against the resulting moment using a CFD (Computational Fluid Dynamics) simulation, namely Fluent. The runner condition in the simulation is made as if it rotates according to the angular velocity of the water flow (rotating frame method).

At the pre-processing stage, a three-dimensional basin model was created using Solidworks software with a runner depth of 4.5 cm and a semi-twisted curve blade of 30°, then proceeded to Spaceclaim software for turbine and volume distribution. The schematic and dimensions of the vortex turbine model are as shown in Figure 3 and 4.

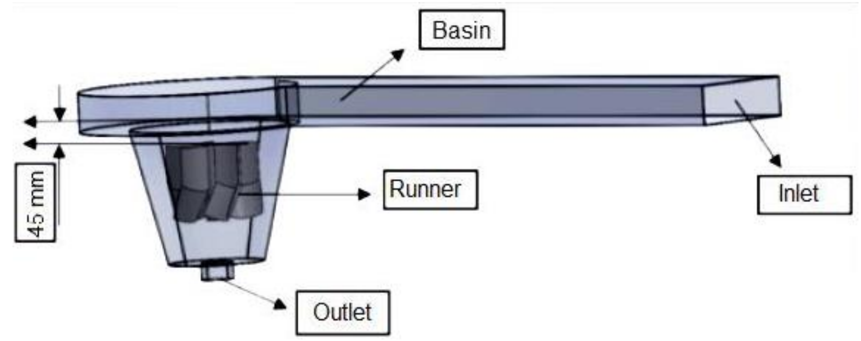


Fig. 3. Schematic of vortex turbine

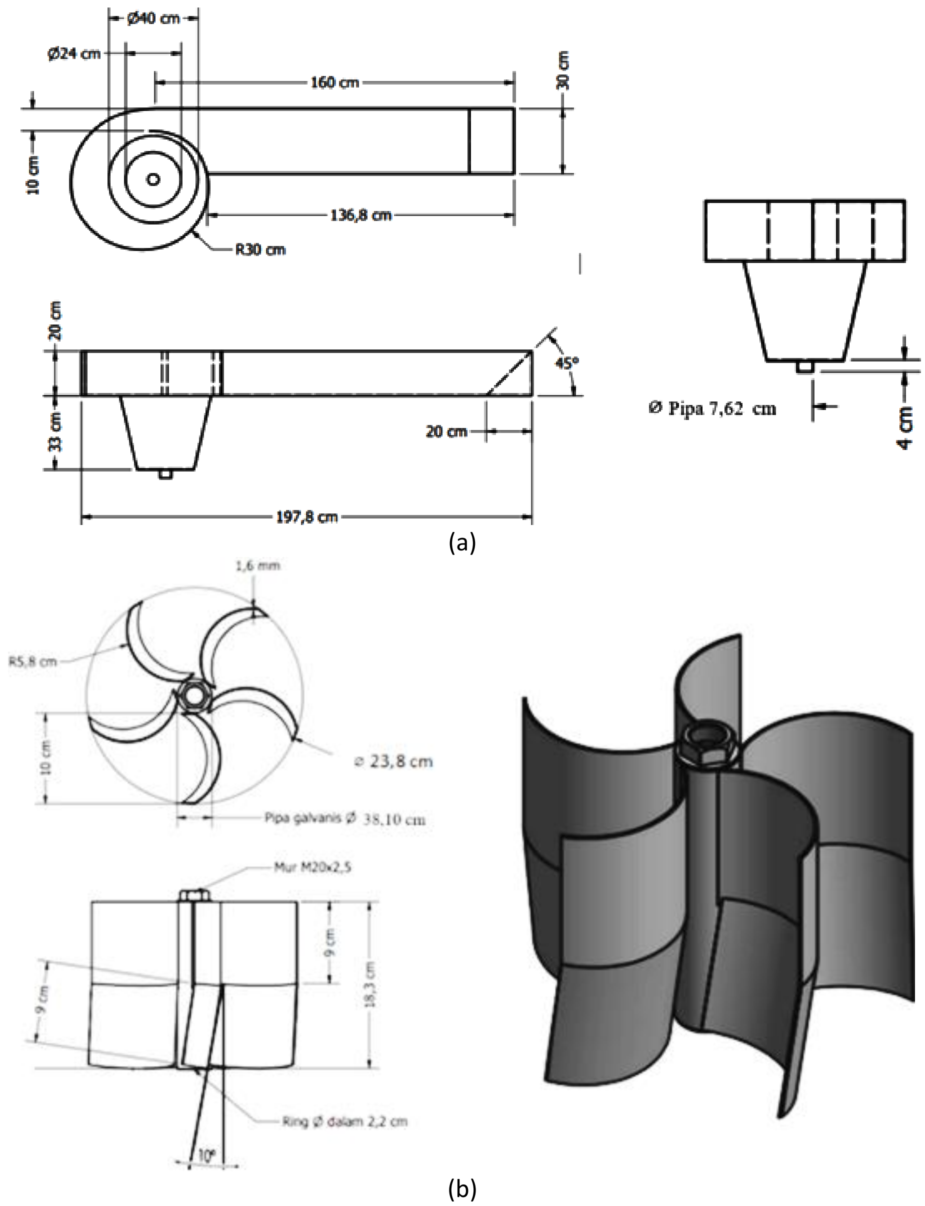


Fig. 4. (a) Design of basin model (b) Design of runner model

The solving steps are carried out in steady conditions with the gravity acceleration of 9.81 m/s^2, then, choosing the viscous equation of the SST k-ω model, defining the water-liquid material, determining the boundary conditions in the simulation system, choosing a simple solution method for completing the simulation. , made several report definitions to observe the torque and flow rate on the turbine runner, determined the initial guess using the hybrid initialize method, and ran the simulation until convergence on the momentum equation $<10^{-5}$.

Then, in post processing, data processing is carried out from the simulation results and observations of the velocity, pressure and streamline fields of the vortex turbine flow. The velocity and pressure fields are divided into 5, and the distance between the fields is 4.5 cm. The visual field of observation is as in Figure 5.

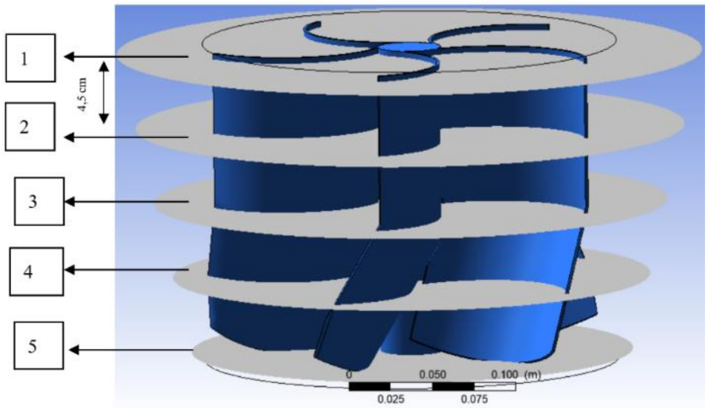


Fig. 5. Simulation observation field on vortex turbine runner

3. Results

3.1 Calculation Results

The maximum velocity of water flow in the vortex turbine is calculated based on the Bernoulli equation. Furthermore, the maximum discharge of water flow in the vortex turbine is calculated based on the continuity equation, so that the maximum discharge in this study is 0.01384 m^3/s. However, the water flowrate used in this vortex turbine simulation is 45% of the maximum discharge, which is 6.228 l/s or 0.006228 m^3/s. The results of the vortex turbine simulation in the form of torque for rpm variation are as shown in Table 1 and Figure 6.

Table 1
Torque of vortex turbine

Revolution (rpm)	Torque (N.m)
80	0.465
90	0.427
100	0.376
110	0.330
120	0.270

Figure 6 shows that the greater the rotation of the turbine runner, the smaller the torque generated. This is in accordance with the equation for the power of fluid engines which is the product of torque and power, so that for the same turbine power, the torque is inversely proportional to the rotation of the turbine. The greater the torque load, the smaller the turbine rotation.

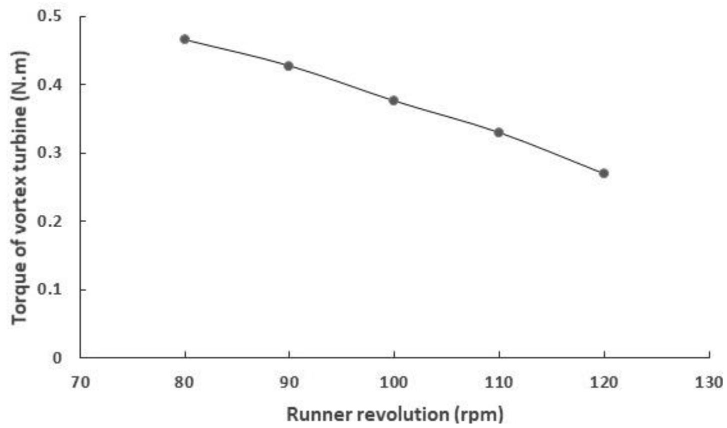


Fig. 6. Torque of vortex turbine

After getting the torque generated from the simulation, then calculations are carried out to get the value of the output power and efficiency of the vortex turbine from each variation of the vortex turbine rpm. Based on the Eq. (2) the input water power supply was calculated, it is 28.663 Watt at ratio of water flowrate about 45%. The turbine power calculation is based on Eq. (1) is used to get the value of the water power, and equation (3) to get the efficiency value of the vortex turbine. The results are shown in Table 2 and Figure 7.

Table 2
Power and efficiency of the vortex turbine

Revolution (rpm)	Power (Watt)	Efficiency (%)
80	3.910	13.64
90	4.044	14.11
100	3.951	13.78
110	3.808	13.28
120	3.471	12.11

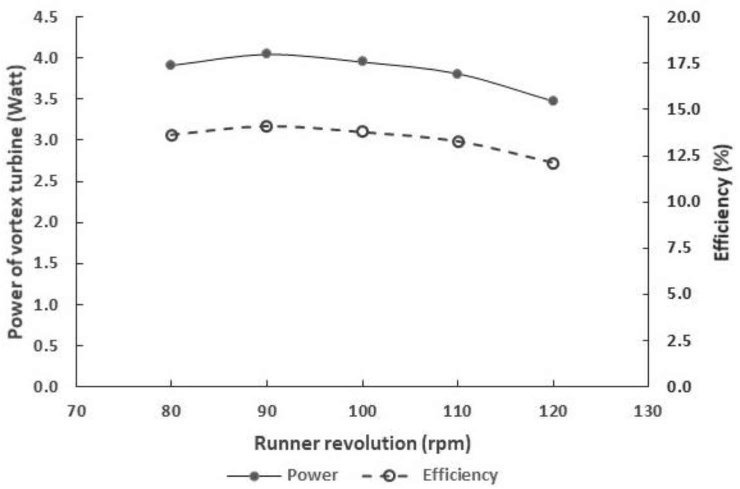


Fig. 7. Power and efficiency of the vortex turbine

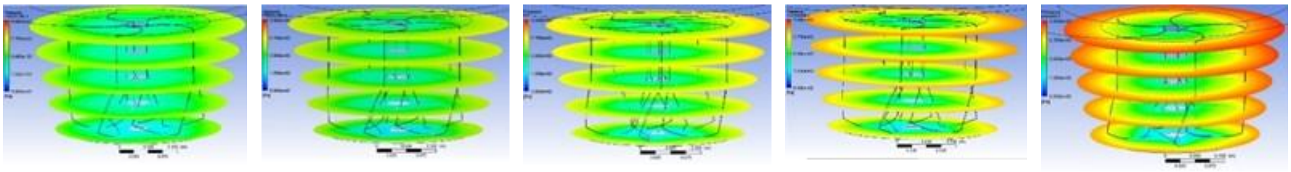
Table 2 and Figure 6 show that the larger the vortex turbine rotation setting, the power and efficiency tend to decrease. The graph shows that the best performance of the vortex turbine is at low speed, which is around 90 rpm at a flowrate ratio of 45% of the turbine propulsion water supply. Likewise, the efficiency is low, which is less than 20%.

This is in accordance with characteristics of the fixed propeller in Figure 1, where the turbine propulsion water supply flowrate ratio is 45%, the efficiency is less than 20%. The turbine rotation generated by the vortex turbine is relatively low because the head of the driving water source is low. For this reason, the implementation of a vortex turbine requires a v-belt or gear with a certain ratio in the transmission system to drive an electric generator that has a moderate rotation of 1500 rpm.

3.2 Simulation Results

In the simulation of fluid flow in the vortex turbine, pressure, velocity and flow patterns are observed in the field of observation, as shown in Figure 8 to 10. Simulations are carried out on variations in the rotation of the vortex turbine according to the calculation results, namely 80 rpm to 120 rpm.

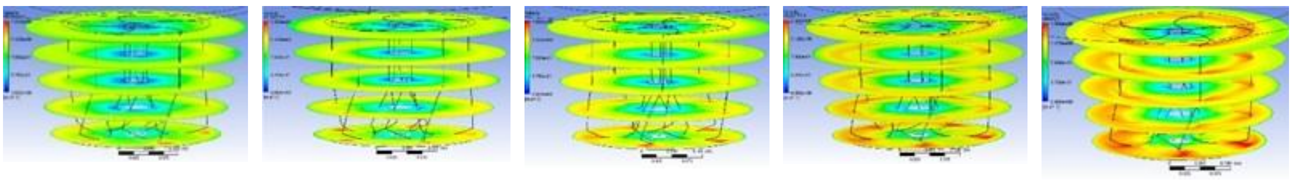
Figure 8 shows that as the rotation of the vortex turbine increases, there is an increase in fluid pressure in the basin area or the side of the basin wall, this can be seen in the colour of the pressure field which is getting redder with increasing rotation of the vortex turbine. However, on the other hand, the fluid pressure decreases from the inlet to the outlet basin. This happens because there is a conical reduction in the flow field.



(80 rpm) (90 rpm) (100 rpm) (110 rpm) (120 rpm)

Fig. 8. Pressure field of the vortex turbine

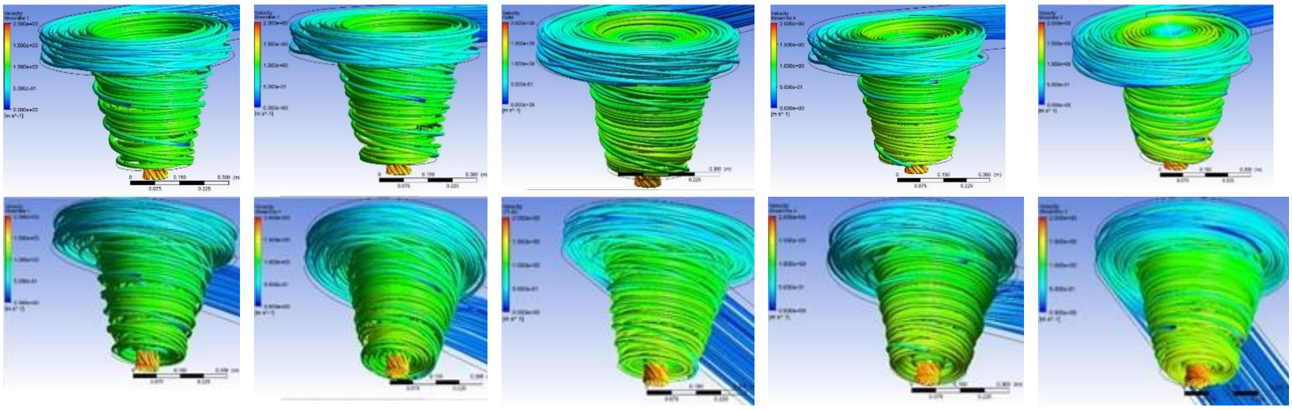
Similar to the pressure field, the fluid flow velocity in the vortex turbine basin also increases with the increasing rotation of the runner, as shown in Figure 9. However, in contrast to the pressure field, the fluid flow velocity from the inlet basin to the outlet is increasing, this is in accordance with the continuity equation. where the smaller the cross-sectional area of the flow the greater the flow velocity.



(80 rpm) (90 rpm) (100 rpm) (110 rpm) (120 rpm)

Fig. 9. Velocity field of the vortex turbine

Figure 10 shows that the streamline that occurs at 120 rpm has a dense flow pattern or there is a build-up of flow on the walls of the basin because the speed increases sharply. When the rotational speed of the turbine is higher, the water level at the top of the basin will increase because of the higher centrifugal force so that the turbine runner blade has not performed optimally to capture the flow. This is different from what happened at 80, 90 and 100 rpm the streamlined flow pattern did not accumulate on the runner wall and the pressure that occurred in the turbine runner area was also low. So that the vortex turbine with low rotation produces higher efficiency, especially at around 90 rpm.



(80 rpm) (90 rpm) (100 rpm) (110 rpm) (120 rpm)

Fig. 10. Streamline of the vortex turbine

The results of this study confirm with the results of research conducted by Pamuji in year of 2021. In this study, the performance of the vortex turbine was tested at variations of rotation of 80, 120, 160 and 200 rpm. The best power and efficiency are also achieved at a low speed of 120 rpm [23]. Accordingly, the trend of the vortex turbine performance graph in this study is corresponding to this study.

4. Conclusions

In accordance with the basic characteristics of a fixed propeller turbine, the best performance of a vortex turbine is produced at a low turbine runner rotation. The higher the rotation of the vortex turbine runner, the higher the pressure and velocity of the fluid and the water level at the top of the basin tends to rise due to centrifugal force and inhibits the flow rate of water flowing to the basin outlet. The results of this study are also in accordance with the results of previous similar studies so that the turbine power generated decreases. Therefore, vortex turbines are suitable for use in low head water flows such as agricultural irrigation canals.

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