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SINGLE-FACTOR ANALYSIS OF VARIANCE ON THE EFFECT OF BLADE'S NUMBER ON ROTOR DRAG-TYPE PERFORMANCE

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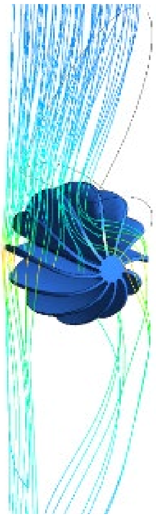
Graphical abstract



Abstract

The State Electricity Company supports 59% of the national electricity supply in Indonesia. The electricity supply from hydro energy is only 8.17%, so this value must be increased to reduce the supply of power plants sourced from fossil fuels. A water turbine is one of the main components in converting hydropower to electrical energy. A cross-flow type water turbine is one of the popular rotors in research in recent years. Several methods are used in turbine development research, including computational fluid dynamics and experimental methods. This research has been done using two methods: the experimental and CFD methods. The study was conducted on variations in the number of blades on the rotor, with variations in blades 3, 4, 6, 8, 10, and 12. This study aims to determine the effect of the number of blades on turbine performance. This study was carried out for five repetitions for each rotor. CFD analysis was performed using the Ansys Student version with the CFX solver. The meshing method is tetrahedral, with a speed limit of 4.91 m/s and outlet pressure according to room pressure. This study uses CFD to know the pressure contours and velocity streamlines. The results of this study were analyzed using a single-factor DOE. The most optimal number of blades is 3-blades producing 9.38 Watt of power, and the Coefficient of power is 0.0748. Analysis of Variance for the Single-Factor shows that the number of blades significantly affects the energy produced. Cross-flow rotor design with 3-blades is a good design alternative for hydro turbines.

Keywords: Coefficient of Power, Design of Experiment, Hydro-turbine, CFD, Number of the blade.

1.0 INTRODUCTION

At the beginning of 2021, the installation capacity of the power plant increased by 3,017.87 MW from the last year. This capacity increase aims to meet the national electrical energy needs that continue to increase yearly, as shown in Figure 1. The State Electricity Company supports 59% of the national electricity supply in Indonesia. The composition of the type of Power Plant used is shown in Figure 2, the power plant comes from 8.17% new hydro energy, so this value must be increased to reduce the supply of power plants sourced from fossil fuels [1]. One way to increase the supply of hydro energy plants is to develop tools used in the hydro energy conversion process.

A water turbine is one of the main components in converting hydropower to electrical energy. There are many types of water turbines, including the cross-flow type. Cross-flow type is one of the popular rotors in hydro-turbine and wind turbine research.

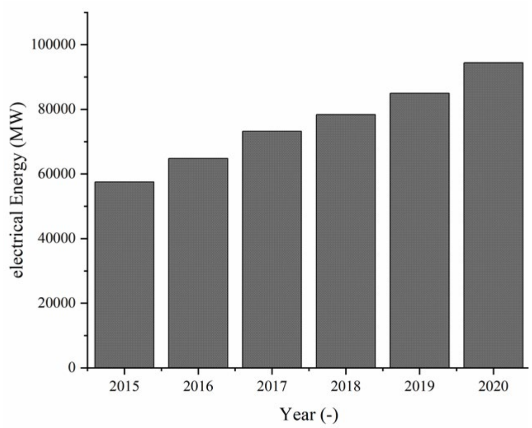


Figure 1 Electricity consumption in Indonesia [1].

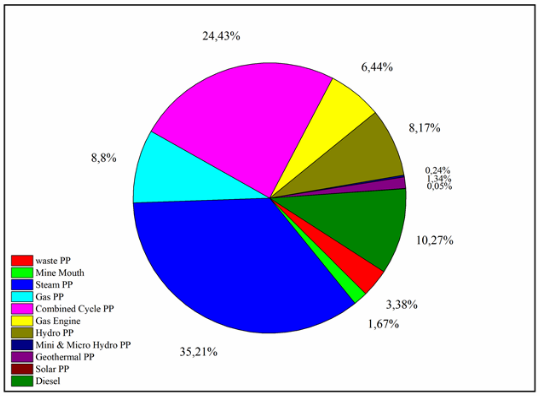


Figure 2 Sources of electricity supply in Indonesia by type of energy source [1].

Biswas et al. have researched a conventional 3-blade savonius design to compare wind and hydro turbines' efficiency [2]. Research conducted on the modification of the overlap ratio on savonius shows that the ratio 0.3 has the best performance compared to overlaps of 0, 0.1, 0.2, and 0.4 [3]. Modifying the blade shape by changing the arch-angle on the blade has been carried out on the Savonius water turbine. The arch angle used shows the best performance at a variation of 135 degrees [4]. Continuous research on savonius in water turbines has also been carried out. The first generation compares the drag-type and lift-type turbine with variations in the number of blades 3, 5, 6, and 10 applied to a VAWT, showing the best results produced by blades 5. The second generation is a renewal of the drag-type turbine. From the previous generation and prioritizes a directing system or blocking system so that water does not flow directly into the reverse rotation blade. The experimental results show that the steering system with optimal results is a slanted block with eye-shaped openings and 6-blades. The third generation develops an alternative combination between the previous generation, namely the drag-type hollow turbine with variations in blades 8, 10, 12, 15, 18, and 24 with a steering system. This combination produces greater electrical power and meets the needs required of the two previous generations [5]. Research on savonius generally deals with geometric modifications such as a number of stages [6], phase shift angle [7], the number of blades [8-10], material [11-13], overlap ratio [3], and summaries of other aspects [14].

There are several methods used in research to solve technical phenomena, including using FEM [15], CFD [6,16-18], and experimental [3, 4, 5, 8]. The experimental method is carried out by modeling using experimental apparatus. The FEM and CFD methods are carried out with the help of supporting software. Then, in processing research results, analysis using DOE is carried out further to refine the results [19, 20]. The research was done using experimental and CFD methods. This study aimed to determine the design with the best performance and obtain the pressure contour on the rotor as a design consideration. Then perform an analysis using a factorial design to assess the magnitude of the significant value of the influence of the number of blades factor.

2.0 PREPARATION DESIGN AND ANALYSIS

Figure 3 shows the rotor used in this study, where the rotor was fabricated using a 3D printer machine. The main design of the rotor is shown in Figure 4. The angle of curvature of the blades on the rotor is 70°. The number of blades is obtained by dividing the whole arc by the notation. The overall rotor diameter is 80 mm, the thickness of the rotor blades for the number three-blades, four-blades, and six-blades by 3 mm, and for the number of blades eigh-blades, ten-blades, and twelve-blades by 2 mm. The difference in the thickness of the turbine rotor is because the results from 3D Printing are not strong enough for experiments on the number of blades 3, 4, and 6. The number blades 8, 10, and 12 have a blade thickness of 2 mm because a thickness of 3 mm interferes with the ability of the blades to receive flow. Water. The variation on the rotor drag-type turbine is used to see the effect on the power generated by the generator.

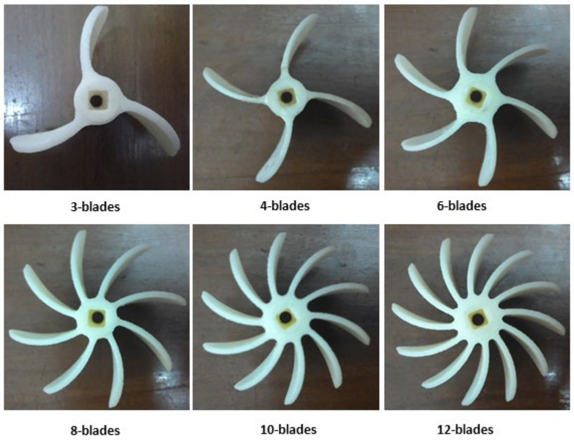


Figure 3 Variations of the drag-type rotor.

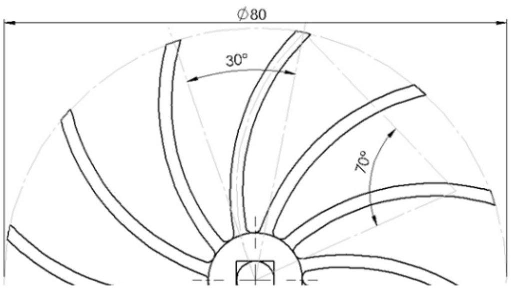


Figure 4 Drag-type rotor dimension.

Several parameters are used in the analysis of this research that has been done. These parameters include input power, output power, tip speed ratio, and power coefficient. The input power is the maximum power generated by the potential water falling from the reservoir, the inlet flow. In contrast, the output power is the electrical power produced by the generator. The second power is expressed in equations 1 and 2 [21]. Tip Speed Ratio is the ratio of the tangent speed or tangent speed at the tip of the blade or blade tip with the actual fluid velocity, shown in equation 3 [22]. The power coefficient is defined as the ratio between the actual power generated by the rotor blades and the power acting on the fluid, as shown in equation 4 [23].

$$P_i = \rho \cdot g \cdot Q \cdot H \tag{1}$$

$$P_{out} = v \cdot i \tag{2}$$

$$\lambda = \frac{0{,}5\ \omega D}{U} \tag{3}$$

$$C_p = \frac{P_{out}}{P_{in}} \tag{4}$$

Where P_i (Watt) is the input power, ρ (kg/m3) is the density of the water fluid, g (m/s2) is the acceleration due to gravity, Q (m3/s) is the fluid flow rate of water, and H (m) is the height specified head. Then P_{out} (Watt) is the output power, *v* (Volt) is the voltage, and *I* (Amperes), Where C_p is the power coefficient.

The research data were analyzed using one of the DOE methods, namely the variance analysis method. This statistical analysis method calculates the sum of squares aimed at equations 5-7. Then after performing calculations using these equations, the data are presented in Table 1 [24].

$$SS_T = \sum_{i=1}^{A} \sum_{j=1}^{n} y_{ij}^2 - \frac{y_{..}^2}{N} \tag{5}$$

$$SS_{Treatments} = \frac{1}{n} \sum_{i=1}^{a} y_{i.}^2 - \frac{y_{..}^2}{N} \tag{6}$$

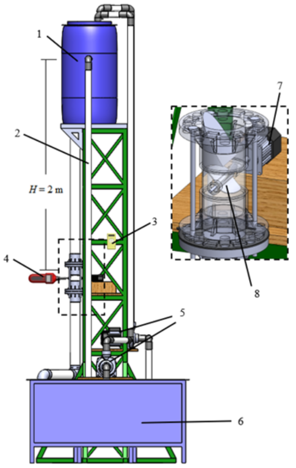
$$SS_E = SS_T - SS_{Treatments} \tag{7}$$

Table 1. The Analysis of Variance Table for the Single-Factor, Fixed Effect Model [24].

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F₀
Treatment	$SS_{Treatments}$	a-1	$MS_{Treatments}$	$\frac{MS_{Treatments}}{MS_E}$
Error	SS_E	N-a	MS_E	
Total	SS_T	N-1		

3.0 METHODOLOGY

The experimental data collection procedure was carried out in several stages. The first step in this research is to set the test apparatus, as shown in Figure 5. The turbine and alternator circuit is installed in the turbine housing. Turbine variations are tested alternately in the turbine housing. The alternator output is connected to a rectifier to convert the AC output of the alternator into DC. A multimeter determines the amount of voltage (V) and current (I) on the alternator. Water is flowed from the lower tank to the upper tank using a pump. Faucet openings are set to get different discharge variations. Then record the value of turbine rotation (rpm), voltage (V), and an electric current (I) generated in each turbine configuration. The research data observed in this study included discharge, rpm, voltage, and current. The voltage and current were observed using a multimeter. The rotation of turbine rotation was observed using a tachometer.



1. **Reservoir**
2. **Over Flow Pipe**
3. **Multitester**
4. **Tachometer**
5. **Water Pump**
6. **Water Tank**
7. **Alternator**
8. **Turbine**

Figure 5 Water turbine test apparatus.

The test is carried out on the turbine housing, installed with a locking system, and connected to the pipe. The head surface height is 2 m, maintained by a bypass pipe installed in the reservoir blocking system apparatus used at an angle of 300 and constant discharge. The data obtained in this test are rotations per minute, voltage, and electric current using a YASKAWA ELECTRIC AC servo motor alternator with a maximum power of 100 Watt and a maximum rotational speed of 3000 rpm. Incoming fluid flow discharge has a significant effect on the performance of the water turbine. A pump filled a water reservoir with a capacity of 600 lpm. The reservoir eliminates the pump power generated not to affect the turbine data collection results. The pump capacity can calculate the inlet fluid flow minus the overflow channel's discharge.

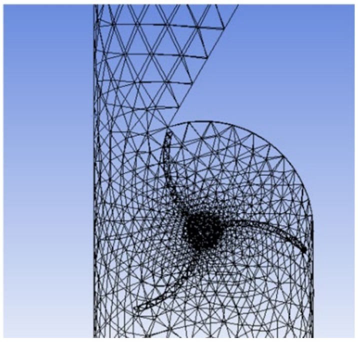


Figure 6 The result of the meshing process using Ansys.

This study also uses the CFD method to determine the pressure distribution on the rotor and the shape of the fluid flow. We are modeling using Ansys software with a CFX solver. The first step in this research is to make a three-dimensional design for each rotor. The schematic consists of the rotating and stationary zones [22-23, 25]. All zones were meshed using the tetrahedral [16] method. Figure 6 shows the results of the meshing process carried out. The grid that has been done produces several nodes and elements; the results of the grid meshing process are shown in Table 2. The total number of elements obtained from meshing is 119,743. The schematic of the simulation is shown in Figure 7. The boundary conditions used in this study are water velocity of 4.91 m/s and turbulence type K-Epsilon [6]. The outlet boundary conditions use the simulated walls' room temperature and no-slip conditions.

Table 2 The number of nodes, elements, and tetrahedra from variations in the number of blades.

Number of Blades	Number of Nodes	Number of Elements	Tetrahedra
3	25757	119743	119743
4	27286	125582	125582
6	30293	136567	136567
8	32346	143592	143592
10	34353	148745	148745
12	36642	155516	155516

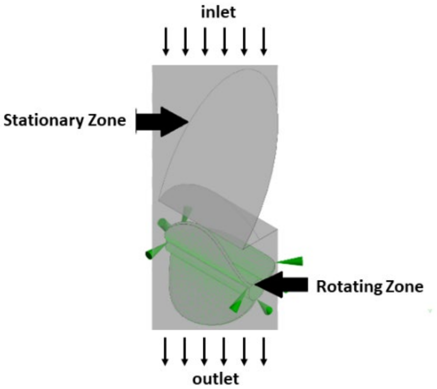


Figure 7 Simulation modeling schematic of water turbine using Ansys.

4.0 RESULTS AND DISCUSSION

Table 3 shows the research results on all variations in the number of blades. Variations in blades used were 3, 4, 6, 8, 10, and 12. This study was conducted for five repetitions. In general, rotors with 3-blades and 4-blades show better performance than variations in the number of other rotors. Figure 8 shows the distribution of research data presented in a scatter diagram, and Figure 9 in the form of comparative box plots. This research on Horizontal Axis Water Turbine results in a decreasing performance with an increasing number of blades. Table 3 shows that the rotor performance is described by the voltage, electric power/output value, and the power coefficient produced by each blade variation. The minimum value of *Cp* generated by the rotor with the number of blades 12 is 0.012. Then the maximum value created by the rotor with the number of 3 blades produces a *Cp* of 0.074. When viewed from the simulation results, the most significant torque value is also found in blade 3. Similar to the experimental results, the most effective electric power is in blade 3. Conformity is shown by the value of the difference (error) of 7%.

Table 3. Power Production of All Variation.

Number of Blades	Observed Etch Power (watt)				
	1	2	3	4	5
3	9.57	9.16	9.54	9.15	9.46
4	7.64	7.44	7.14	7.14	7.65
6	2.98	2.58	2.79	2.55	3.01
8	1.22	1.52	1.33	1.47	1.64
10	0.99	0.93	0.83	1.14	0.96
12	0.97	0.76	0.64	0.74	0.87

This Drag-type Turbine simulation was carried out to see the effect of the number of blades on the pressure contour on the rotor and the shape of the fluid flow. In this simulation, the various blades of the Drag-type Turbine were investigated, starting from the number of blades 3 to 12, shown in Figure 10 for pressure distribution and Figure 11 for the shape of fluid flow. In the streamline velocity Figure 11, the highest fluid velocity value is found in the gap between blade A and the pipe wall surface for each variation in the number of blades. The highest speed value is shown in red. In the pressure contour of Figure 10, the highest pressure value is on the blade's surface because the blade gets in contact with the fluid flow. Blade surface A of the pressure value in red is also found in the area around the shaft. In the number of 3 blades, the maximum pressure is 0.681 MPa. The maximum speed is 36.4 m/s. The average pressure of the rotor as a whole is 0.241 MPa. The average pressure on the blade surface A is 0.694 MPa.

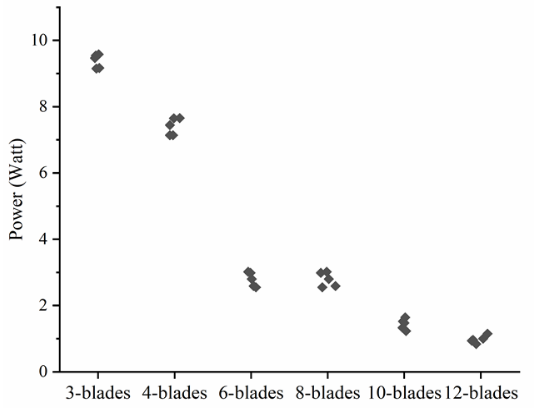


Figure 8 The distribution of research data is presented

The study results, shown in Table 3, were then analyzed using DOE. The single-factor analysis method is used by using equations 5-7. The analysis results are shown in Table 4, the Analysis of Variance Table for the Single-Factor, Fixed Effect Model. F_0 from Table 4 is then compared with the empirical F_0 value to show the significance of these factors. The F_0 generated from the analysis is 2,008, with a value greater than the empirical F_0 of 2.53 [21]. In a scatter diagram, the number of blades factor has a large significance value on the power generated by the rotor.

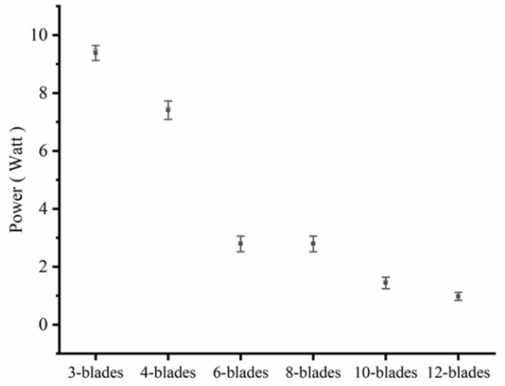


Figure 9 The distribution of research data is presented in Comparative box plots.

Table 4 The Analysis of Variance Table for the Geometry-Factor

Source of Variation	Sum of squares	Degrees of Freedom	Mean Square	F_0
Number of Blades	338.49	5	67.69	2008.89
Error	0.84	25	0.03	
Total	339.33	30		

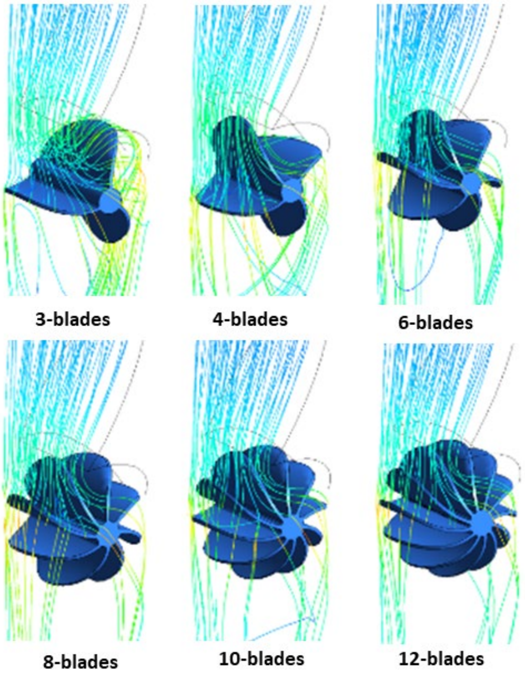
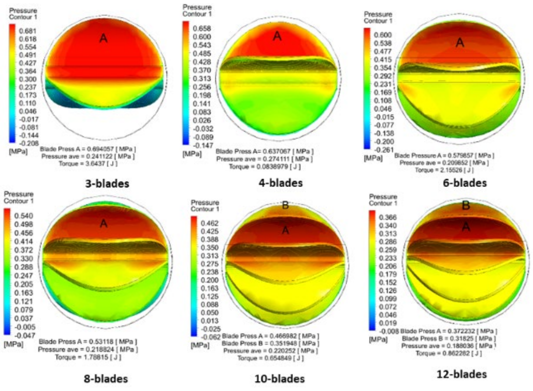

3-blades 4-blades 6-blades
8-blades 10-blades 12-blades

Figure 10 Rotor's streamline.



3-blades 4-blades 6-blades
8-blades 10-blades 12-blades

Figure 11 Contour pressure in Drag-type Rotor

5.0 CONCLUSION

Observations on the Horizontal Axis Water Turbine (HAWT) test equipment have been conducted to see the effect of variations in the number of blades on the electrical power generated. Variations in the blades used are 3, 4, 6, 8, 10, and 12. The results of these tests show the conclusion:

- 3-blades produce power and power coefficient respectively 9.38 Watt and 0.0748, and an average pressure of 0.694 MPa
- Analysis of Variance for Single Factor shows that the number of blades significantly affects the power produced, as indicated by the F0 value for the number of blades greater than the empirical F0 value.
- The 3-blades design on the turbine is a good design alternative for further development.

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