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Experimental Study on the Effect of Single Flow Disturber on the Performance of the Straight-Bladed Hydrokinetic Turbine at Low Current Speed

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ABSTRACT

Indonesian Marine Energy Association 2014 provided the results of ratifying the potential of ocean current energy in Indonesia of 17,989 MW. The amount is quite large for the results of several potential points in the territory of Indonesia. However, the potential of ocean currents in Indonesia has not been utilized optimally, even though the current turbine technology is developing rapidly in the world. The existing turbine technology that is already available worldwide cannot be applied directly in Indonesia. This is because the water condition in Indonesia is classified as low-speed current, unlike some countries in the world which are classified as high-speed current. Therefore, a turbine that can work in the condition of the territorial waters in Indonesia, in general, with a low current speed is needed. The turbine technology used in this study consists of turbine A (without a flow disturber) and turbine B (with a single flow disturber). The purpose of this study was to determine the increase in turbine performance at low current speeds. The method used in this study was an in-situ experiment because it was closer to the actual conditions. The results obtained from this study indicated that the addition of a single flow disturber could increase turbine performance at all variations of current speed, namely 0.4, 0.88, and 1 m/s. The most exciting result was that under the low current speed of 0.4 m/s, adding a single flow disturber could increase the ability to self-start from 0 rpm to 7.180 rpm and efficiency from 0 to 4%. In addition, at a current speed of 0.88 m/s with the addition of a single flow disturber, it could increase efficiency from 10.8% to 11.1%. At a current speed of 1 m/s with the addition of a single flow disturber, it could increase efficiency from 16.6% to 18%. That is, turbine B (with a single flow disturber) is very suitable to be applied in the territorial waters of Indonesia, which tend to have low current velocity.

1 Introduction

The turbine is one of the main technologies used to generate electricity other than a generator. The turbine is one of the most important technologies used to generate electricity alongside the generator [1]. The main component in the turbine is the blade, which is the most critical part because it converts kinetic energy into mechanical energy [2,3]. In general, turbines used by researchers in the world are operated at low current speeds such as, in Australia 1.5-2 m/s [4], China 3-4 m/s [5], Korea 3 m/s [6], Italy 2 m/s [7], and Columbia 1.5-2.5 m/s [8]. Meanwhile, the current velocity in several regions in Indonesia is classified as low, such as in the Strait at 0.7 m/s, Toyakapeh Strait at 0.57 m/s, and offshore Bengkulu at 0.22 m/s [9]. Low current speeds are in the range of 1 m/s [10]. Thus, turbines that have been available in several countries in the world cannot be applied in Indonesia [11].

Indonesian Marine Energy Association 2014 provided the results of ratifying the potential of ocean current energy in Indonesia of 17,989 Megawatts [9]. The potential is quite large, considering Indonesia is classified as having a low current speed. However, such a large potential is still not optimally utilized. So, it is necessary to study turbine technology that can operate in the condition of territorial waters in Indonesia, which tends to have low current velocity.

Based on the axis of rotation, turbines are divided into two types, namely, Vertical Axis Current Turbine (VACT) and Horizontal Axis Current Turbine (HACT) [12,13,14]. One of the advantages of VACT is that it can accept current flow from various directions so that the turbine can spin with unstable efficiency. In comparison, HACT can only receive from one direction of the incoming current, so the turbine rotation produces an inconsistent efficiency [15-18]. Thus, VACT will extract more current energy and obtain a more stable efficiency than HACT. Therefore, this study focuses on the design of VACT.

Vertical Turbine Design generally consists of two types: Darrieus and Savonius Turbines [12]. The Darrieus Turbine has a higher efficiency than the Savonius Turbine [19]. It is because the Savonius Turbine uses a dominant drag force rather than the lift force [20]. The development of the Darrieus Turbine made a helical design, then referred to as the Gorlov Turbine, which resulted in higher efficiency performance than the Darrieus Turbine, up to 35% [21]. However, some research developments, such as those [22], show that Darrieus and Gorlov Turbines produce the same efficiency, amounting to 29%. Besides, research was also conducted by [23], with the same design and parameters that the Darrieus Turbines produced an efficiency of 27%, while the Gorlov Turbine was under 25%. Experimental studies have also been carried out and show that the Darrieus Turbine produces an efficiency of 42%, while the Gorlov Turbine produces an efficiency of 20% [14]. However, Darrieus-type Vertical Turbines have lower efficiency than Horizontal Turbines, and the ability to start spinning or self-starting is very low [24,25]. Thus, the problem is a challenge for this study to improve the performance of Darrieus Vertical turbines on the self-starting and efficiency parameters.

Designing a Darrieus Vertical Turbine will not be separated from the choice of foil type because it will affect the lift force performance and efficiency. Symmetrical NACA is the best-performing type of foil for designing Darrieus Turbines [26]. Mohamed [26] has also reported his research on various kinds of foil, showing that symmetrical NACA 0018 produces the highest efficiency of 29%. The research results by [8] and [27] show that symmetrical NACA 634021 delivers 30% efficiency. Besides, NACA 634021 has good manoeuvrability, inspired by humpback whale flippers' fast movement compared to other species [28,29]. Therefore, in this study choosing NACA 634021 hydrofoil.

The number of foils influences hydrodynamic performance at a low tip speed ratio (TSR), representing a low current speed. Increasing the number of blades will result in better turbine performance under low TSR conditions [5]. The number of blades is a parameter to determine the turbine density (solidity) value. The turbine solidity value shows how much the turbine sweeps the area [5]. Bernoulli's law states that the lift force produced will be greater if the value of the sweep is enlarged. Research on the amount of foil has also been carried out by the 2D CFD simulation method, the results, which show that the performance of turbines with four foils at low flow velocities is higher than that of turbine with three and five foils [1]. So, this study chose the number of foils four.

In the case of feared low current speed, the turbine does not show the ability to turn or self-start, and the resulting efficiency will also be small. Thus, this study adds another component without changing the basic shape of the turbine, which is a flow disturber. Adding a flow disturbance in front of the turbine is inspired in previous research that can improve the performance [31]. This vertical foil is mounted parallel to the current direction before it hits the turbine. The addition of a flow disturber is to focus the direction of the flow towards the turbine so that the speed of the current around the turbine will be higher and able to increase the self-starting and efficiency of the turbine. The principle of action is inspired by a multiple hydrofoil diffuser [12], with a simplified and adapted form at the test site.

Based on those explanations, it is important to investigate the straight-bladed hydrokinetic turbine at low current speeds. This study analyses the performance of the straight-bladed hydrokinetic turbines with and without a single flow disturber at low current speed. The study is conducted with the in-situ experimental method in the open channel.

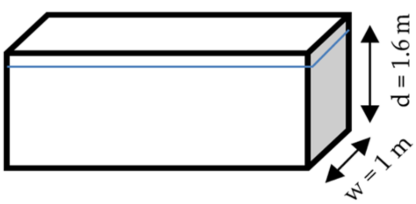
2 Design and Fabrication

2.1 Design of Turbine Model

The open channel structure will determine the design of the turbine model. The width of the open channel was used to determine the diameter of the turbine model, and the depth of the open channel was used to determine the span of the blade turbine model. The width (w) of the open channel was 1 m, height (h) was 1.7 m, and depth (d) was 1.6 m, as shown in Fig. 1.

The variation of the number of blades 3, 4, and 5 were simulated with Computational Fluid Dynamics (CFD) software using the current speed of 1.5 m/s. The result of the CFD analysis showed that the number of blades 4 had a higher performance at low *TSR* [2]. So, this study used blade number 4 for the design of the turbine model. Table 1 shows the design parameter and dimension used in this study.

(a)



(b)

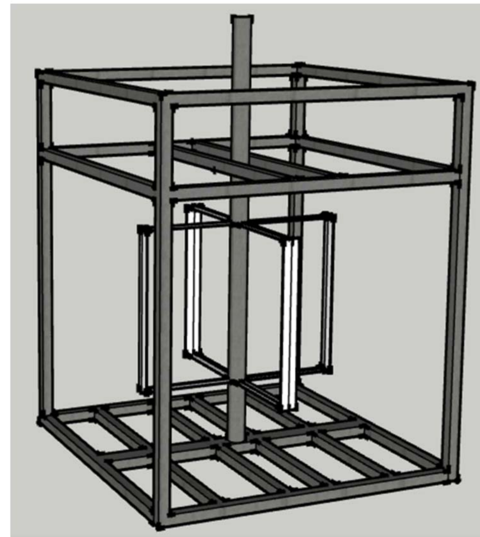
Figure 1 (a) The open channel, (b) Dimension of the open channel.

Table 1 Design of the turbine model.

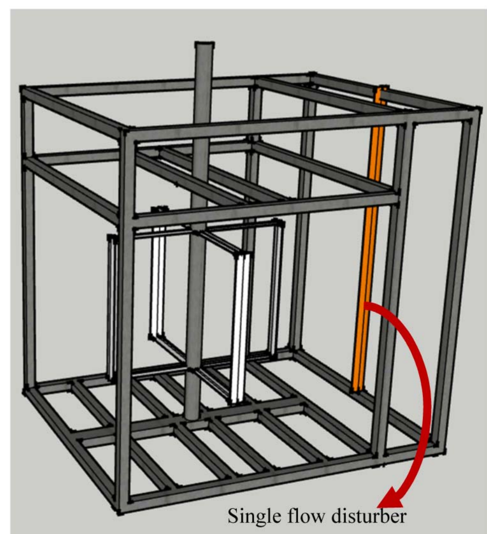
Design Parameter	Dimension
Number of blades	4
Number of struts	2 per blade
Blade sections	NACA 634021
Strut sections	NACA 0012
Blade chord	0.0571 m
Strut chord	0.0571 m
Turbine height	0.571 m
Turbine diameter	0.76 m
Shaft diameter	0.03 m

This study evaluated the performance characteristic of the straight-bladed hydrokinetic turbine A and B, as shown in Fig. 2. Turbine A is a variation model without a single flow disturber with the design parameter and dimension in Table 1.

Without changing the turbine dimensions, turbine B is a variation model with a single flow disturber. The dimension of the flow disturber chord is twice the blade chord, and the height is the same as the frame. Frame dimensions of the turbine A and B model are 0.9 m x 0.9 m x 1 m.



(a)



(b)

Figure 2 Design of turbine, (a) turbine A – original without flow disturber, (b) turbine B – modified with flow disturber.

2.2 Fabrication of turbine model

Fiber glass-resin composite material was used for straight-bladed hydrokinetic turbines for the blade, arm, and flow disturber. The shape of straight blades with foil NACA 634021 was fabricated in Fig. 3. Steel material was used for the shaft and frame of the turbine model.

The arm would connect blades to the shaft with two struts per blade with the help of two bearings for the upper and lower bases. After that, the bearing was welded to the struts. The frame model had been separately fabricated using steel material. The last step was to unite the turbine and frame, as shown in Fig. 4, and then painted it to avoid corrosion.

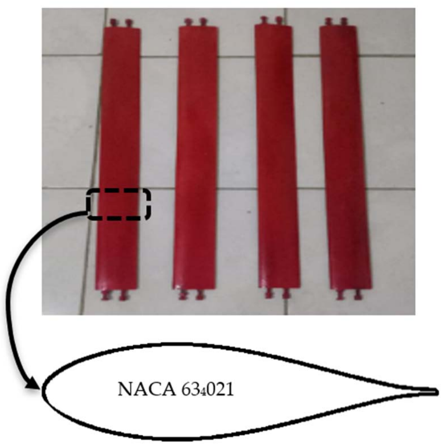


Figure 3 Fabricated straight-bladed turbines.

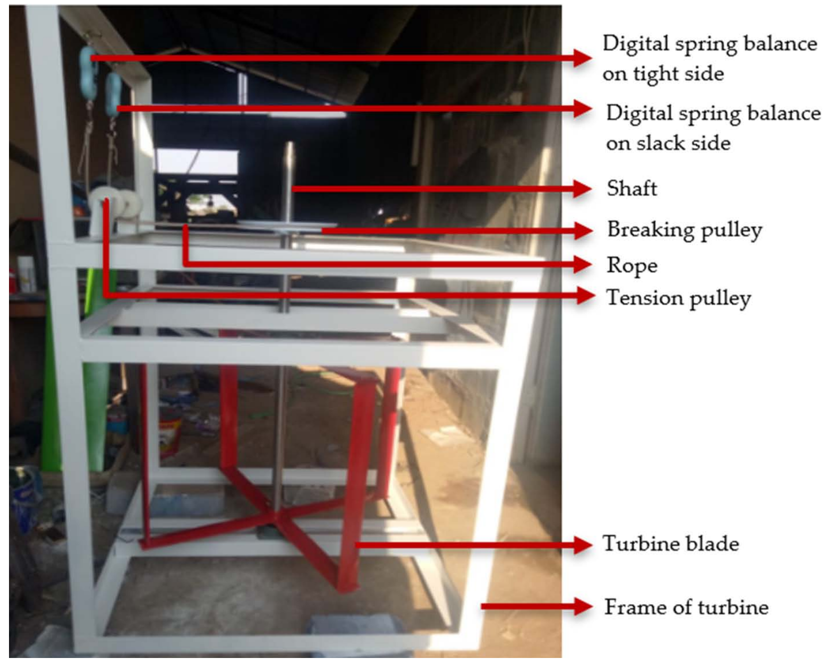


Figure 4 Straight-bladed turbine model.

3 Experimental Methods

The in-situ experiment of the model straight-bladed hydrokinetic turbine was conducted in an open water channel at the spring source channel Umbulan, Pasuruan, Indonesia. The turbine model was mounted in the 3 locations of the open channel, as shown in Fig. 5. The turbine was tested and immersed in water from the depth of 0 m to 0.8 m at the bottom of the mean water level, and at the above mean water level, mounted to smooth rotation of the turbine model. The flow disturber was mounted parallel to the direction of current flow before blowing the turbine model, as shown in Fig. 6.

The current speed measurement procedure used a propeller-type current speed meter of Dentan CM-1BX series with a measurement range of 0.1 – 6 m/s. The current speed was measured at 3 locations of the open channel, and then at each location, the current speed was measured at 3 different depths from the bottom mean water levels, such as 0 m, 0.8 m, and 1.2 m. Each depth recorded as much as 10 data, and the total current speed obtained 30 data. After that, overall, the average current speed data was calculated and then the current speed was obtained as shown in Table 2.

Table 2 Design parameter of the turbine model.

Locations	V (m/s)
A	1
B	0.88
C	0.4

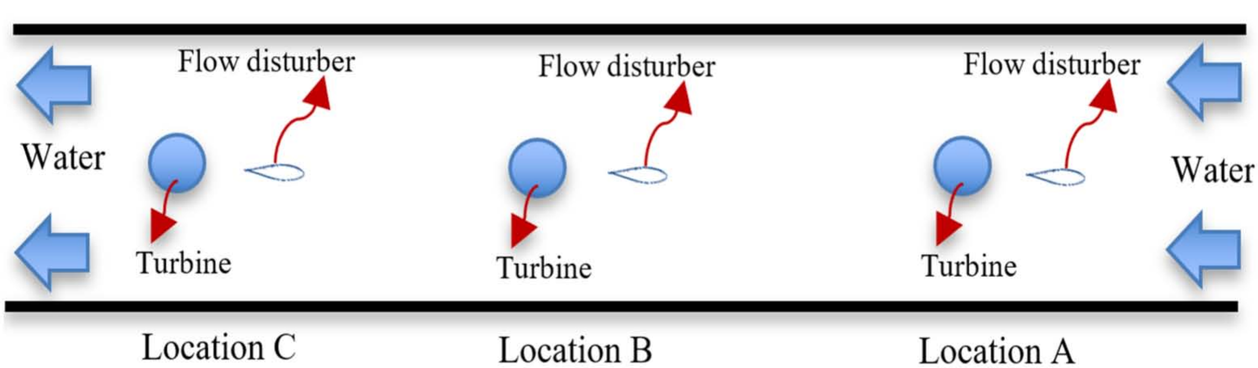
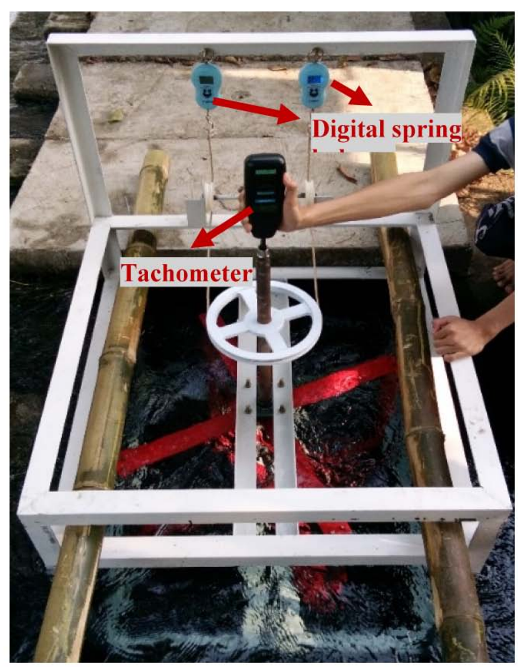


Figure 5 Schematic diagram of the open channel.

(a)

(b)

(c)



(d)

Figure 6 Mounted turbine set-up, (a) front view, (b) side view, (c) top view, and (d) measurement

The torque measurement procedure used the methodology [24] and [30]. This mechanical power measurement refers to the previous turbine experiment conducted in Towing Tank [25]. The components of the torque measurement instrument was composed of a breaking pulley, rope, two tension pulleys, and two digital spring balances with a measurement range of 0 – 5 kg (accuracy of 0.2%) as shown in Fig. 5. The torque was measured at turbines A and B at 3 different locations. Each turbine model recorded 20 manual data readings of the digital spring balances. After that, at each one, data had calculated as the difference between the tension in the tight side (*W*) and the tension in the slack side (*S*), then calculated average of (*W-S*). The torque (*T*) was calculated with equation 1 using ref [24].

$$T = 9.81 \cdot (W - S) \cdot r_p \quad (1)$$

where r_p is the radius of the breaking pulley.

The rotational speed measurement procedure used a contact-type tachometer with a measurement range of 0.5 – 1999 RPM (accuracy of 0.05%). The rotational speed was measured at turbines A and B at 3 different locations. Each turbine model recorded 20 data of manual readings of the digital tachometer and then calculated the average rotational speed. The turbine's rotational speed (ω) is represented by the *TSR*, as shown in equation 2.

$$TSR = \omega R/V \quad (2)$$

where R is the radius of the turbine and V is the inlet current speed. It is shown that *TSR* is the ratio of speed at the tip of the blade to the current speed.

The turbine power was obtained from the multiplication of the torque and the rotational speed, as shown in equation 3. The kinetic power obtained was available in water, as shown in equation 4.

$$P_{turbine} = T \text{ x } \omega \quad (3)$$

where ω in rad/s ($\frac{2\pi}{60}\,rpm$) and T in Nm.

$$P_{kinetic} = ½\, \rho\, A\, V^3 \quad (4)$$

where ρ is the density of water (1000 kg/m^3), and A is the turbine swept area which is obtained from the multiplication of the turbine height (H) and the turbine diameter (D).

The turbine power output is represented by the power coefficient (Cp), which is the product of turbine power ($P_{turbine}$) and kinetic power ($P_{kinetic}$), as shown in equation 5.

$$C_p = \frac{P_{turbine}}{P_{kinetic}} \quad (5)$$

4 Results and Discussion

4.1 Effect of single flow disturber on self-starting

The self-starting parameter is one of the turbine performances that can be seen from the relationship between the current speed and turbine rotational speed. In this case, self-starting was measured at the minimum current speed conditions needed to turn the turbine. In this discussion, the performance of turbine A (without flow disturber) was compared with the performance of turbine B (with flow disturber) through self-starting parameters (Fig. 7).

Fig. 7 shows that at the condition of the minimum current speed (0.4 m/s), turbine A did not show the ability to spin or self-starting with a value of 0 rpm. However, after getting the addition of a flow disturber (turbine B), it had shown self-starting ability with a value of 7.180 rpm. In this case, the flow disturber could improve the turbine's performance with self-starting parameters at low current speeds. In addition, all current speed ranges showed that turbine B (straight line in yellow) was above the curve of turbine A (straight line in red). That is, turbine B could improve the ability to spin the turbine for the better.

After adding a flow disturber, improved self-starting capability occurred because there was a deflection of the flow direction toward the turbine rotor (marked with a red sign in Fig. 8b). This means that the flow velocity was around the turbine rotor was higher than before the flow disturber was added. Thus, the kinetic power of the flow around the turbine rotor became even greater because it was a cube function of flow velocity. This can increase the ability to spin the turbine. The forms of turbine flow A and B are visually shown in Fig. 8.

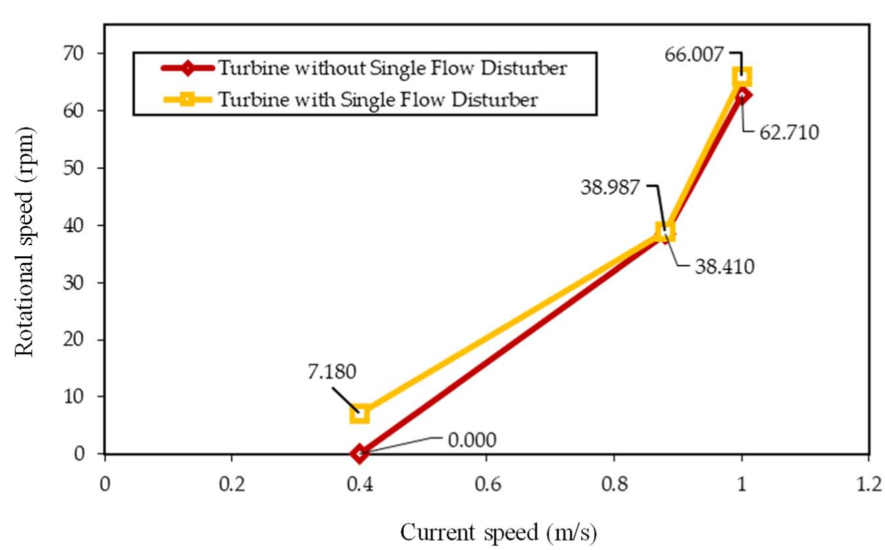
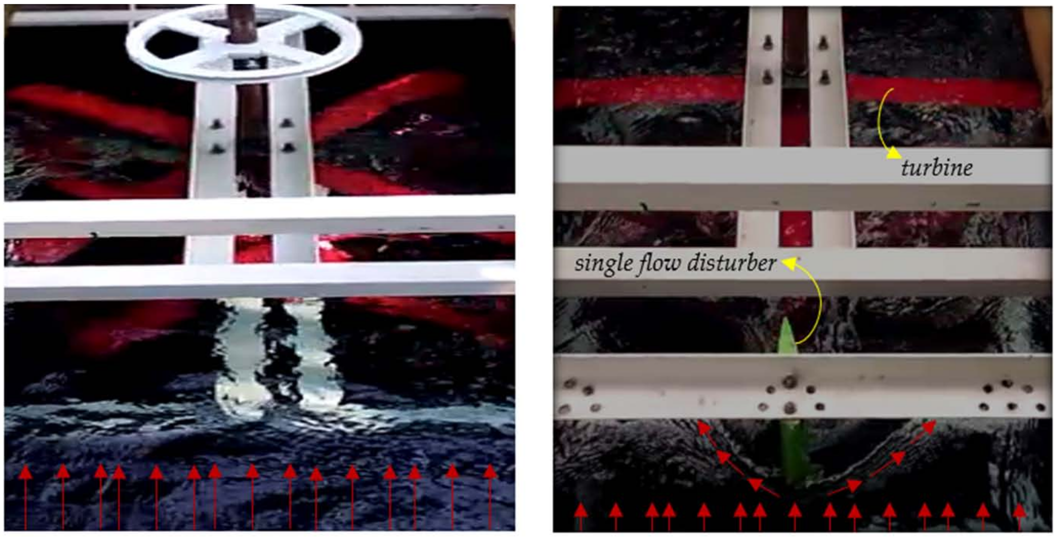


Figure 7 Comparison of turbine A and B on self-starting.



(a) (b)

Figure 8 Form of flow direction (a) turbine A (b) turbine B.

Fig. 8a shows that before being given an additional flow disturber, it was seen that the flow direction did not occur and tended to be parallel. However, after an additional flow disturber was given in Fig. 8b (shown by the blue arrow), the flow direction was deflected (indicated by the red arrow) near the turbine rotor. That caused an increase in the ability to spin the turbine.

Thus, in the discussion, it can be concluded that adding a flow disturber can increase the ability to self-starting at low current speeds. Therefore, the results of this study are very suitable to be applied to conditions in Indonesian waters that are classified as low current speed.

4.2 Effect of single flow disturber on efficiency

The efficiency parameter is one of the turbine performances that can be calculated from equation 5, which is the ratio between the mechanical power of the turbine and the kinetic power of water. In this discussion, the results of the performance of turbine A (without flow disturber) were compared with the performance of turbine B (with flow disturber) through the efficiency parameters. Fig. 9 is an efficiency curve that is a function of the current speed according to the test location i.e., location A (1 m/s), location B (0.88 m/s), and location C (0.4 m/s). The current speeds in this location are below 1 m/s therefore can be classified as low current speed [25, 31].

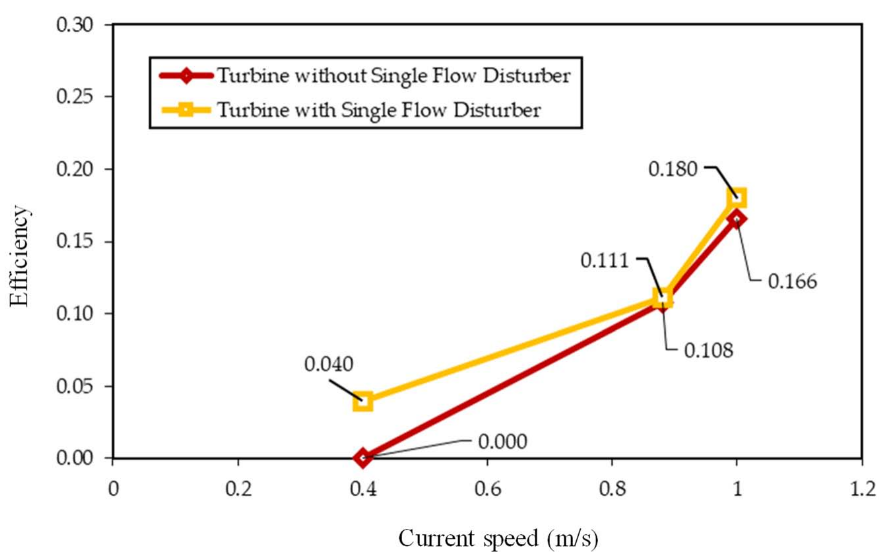


Figure 9 Efficiency of turbines A and B on current speed.

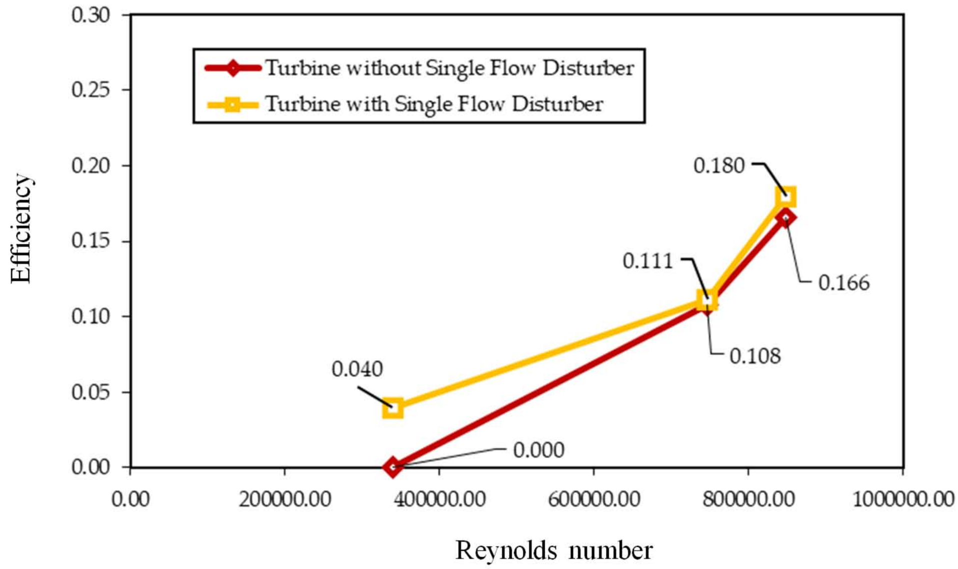


Figure 10 Efficiency of turbines A and B on Reynolds number.

Fig. 9 shows that turbine B (straight line in yellow) was above turbine curve A (straight line in red) in all current speed ranges. That is, turbine B had shown the results of improved turbine performance through the parameter efficiency of current speed. The peak efficiency in the results of this study occurred at 1 m/s current speed conditions, where the maximum efficiency of turbine A was 0.166, and turbine B was 0.180. Adding flow disturber could increase peak efficiency by up to 8.4%. Likewise, when the current speed condition was 0.88 m/s, adding a flow disturber could increase efficiency up to 2.77%. Other research supports the result that the flow disturbance can increase efficiency; the maximum coefficient of power value reported at 0.52 with a current velocity of 0.54 m/s [31]. In the condition of a minimum current speed of 0.4 m/s, turbine A did not show efficiency results. That is, the kinetic power available in water was very small to drive a turbine, so the turbine could not extract the kinetic power from the water, which caused zero efficiencies. However, after being given an additional flow disturber that directed the flow to the turbine rotor to be able to extract the kinetic power from the water to produce efficiency.

Fig. 10 shows a turbine efficiency A and B graph for the Reynolds number. Reynolds number value is obtained from equation 8, which is a function of current speed. The efficiency of turbine A is indicated by the red dot and line, while the yellow dot and line show turbine B. The efficiency curve for the Reynolds number shows the same pattern in turbines A and B. In addition, it can be clearly seen that the curve with the yellow dot and line is above the curve with the red dot and line. The addition of a flow disturber can improve the turbine's performance through the efficiency parameter to the Reynolds number.

The peak efficiency in the results of this study occurred in the Reynolds number 848,214, where the maximum efficiency of turbine A was 0.166, and turbine B was 0.180. That is, the addition of a flow disturber could increase peak efficiency by up to 8.4%. Likewise, when the condition Reynolds number 763,393, the addition of flow disturber could increase efficiency up to 2.77%. Whereas in Reynolds number 339.286, turbine A did not show efficiency results. That is, the kinetic power of water was very small to drive a turbine, so the turbine could not extract the kinetic power from the water, which caused zero efficiencies. However, after being given an additional flow disturber that directs the flow to the turbine rotor to be able to extract the kinetic power from the water to produce efficiency.

In general, turbine researchers always connect the efficiency curve with Tip Speed Ratio (*TSR*). The *TSR* value is obtained from equation 2, a function of turbine rotational speed. Table 3 shows the value of *TSR* in turbines A and B, with clearly visible differences in the value of *TSR*

Table 3 TSR at turbine A and B

Locations	Current speed (m/s)	Turbine A		Turbine B	
		Rotational speed (rad/s)	*TSR*	Rotational speed (rad/s)	*TSR*
A	1	6.564	2.494	6.909	2.625
B	0.88	4.020	1.736	4.081	1.760
C	0.4	0.000	0.000	0.752	0.712

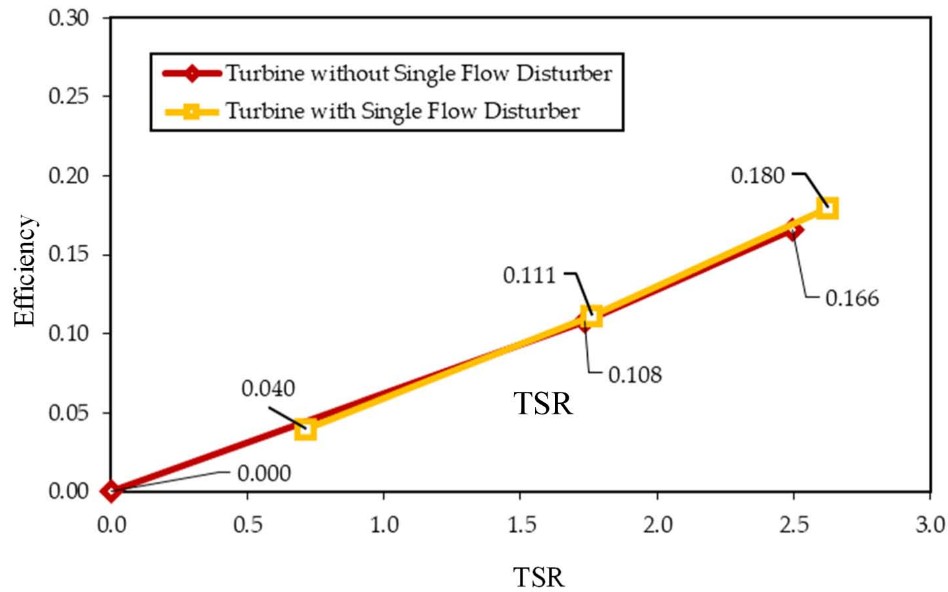


Figure 11 Efficiency of turbines A and B on *TSR*.

in the two turbines under the same current speed conditions. In all current speed conditions, turbine B had a higher *TSR* than turbine A. This means that turbine B produced a higher rotational speed due to the addition of a flow disturber.

Fig. 11 is a graph of the efficiency of turbines A and B against *TSR*. The efficiency of turbine A is indicated by the red dot and line, while the yellow dot and line show turbine B. On the efficiency curve against *TSR*, it can be seen that the curve with the yellow dot and line is above the curve with the red dot and line. That is, the addition of a flow disturber can improve turbine performance through the efficiency parameters of the *TSR*.

The peak efficiency of turbine A occurred at *TSR* 2.494, and under the same current speed conditions, the peak efficiency of turbine B occurred at *TSR* 2.625. The peak efficiency values in turbines A and B were 0.166 and 0.180, respectively. That is, the addition of a flow disturber could increase peak efficiency by up to 8.4%. Whereas in the condition of minimum current speed, turbine A did not produce *TSR* and efficiency because it did not show the ability to rotate during testing. However, after the addition of the flow disturber, the turbine showed a *TSR* value of 0.712 and an efficiency of 0.04 because the turbine had shown the ability to rotate during the test. That is, the addition of a flow disturber can increase peak efficiency at low current speeds.

Thus, in the discussion, it can be concluded that adding a flow disturber can increase efficiency at low current speeds. The peak efficiency improved by 8.4% after the turbine was given an additional flow disturber component. This result is confirmed with previous research that adding a flow disturbance in front of the turbine can improve the coefficient of power from 0.35 to 0.46 at current speed of 0.6 m/s [31]. Thus, the results of this study are very suitable to be applied to conditions in Indonesian waters that are classified as low current speed.

4.3 Effect of single flow disturber on power

The power parameter is one of the turbine performances obtained theoretically using equation 3, which is the product of turbine torque and turbine rotational speed. The torque value and turbine rotational speed obtained directly from the test results can be shown in Table 4.

Table 4 Torque and rotational speed

Turbine A			Turbine B		
T (N.m)	ω (rad/s)	$P_{turbine}$ (Watt)	T (N.m)	ω (rad/s)	$P_{turbine}$ (Watt)
5.475	6.564	35.936	5.640	6.909	38.965
4.230	4.020	17.006	4.305	4.081	17.567
0.000	0.000	0.000	0.735	0.752	0.5520

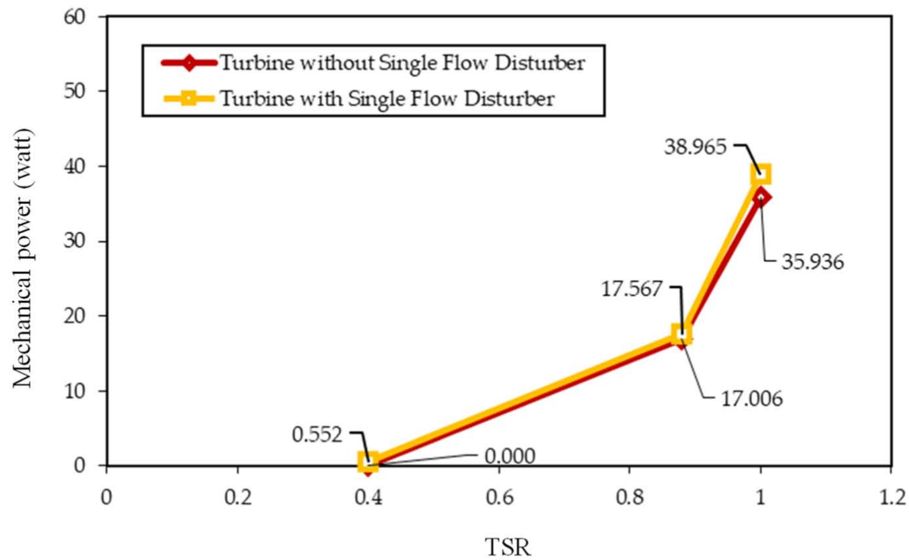


Figure 12 Power of turbines A and B on *TSR.*

In this discussion, the performance results of turbine A (without flow disturber) were compared with the performance of turbine B (with flow disturber) through the turbine mechanical power parameters. Fig. 12 is a mechanical power curve that is a function of the current velocity according to the test location, i.e., location A (1 m/s), location B (0.88 m/s), and location C (0.4 m/s). The mechanical power curve against the current speed in turbine A is shown in the red dot and line, while turbine B is shown in the yellow dot and line. These curves clearly show that turbine curve A is above turbine curve B. Adding a flow disturber can improve turbine performance through mechanical power parameters to the current speed.

The peak mechanical power of the turbine in the results of this study occurred at a current speed of 1 m/s, where the maximum mechanical power of turbine A was 35.936 watts, and turbine B was 38.965 watts. Adding a flow disturber could increase the turbine's mechanical power peak by up to 8.4%. Likewise, when the current speed condition was 0.88 m/s, adding a flow disturber could increase efficiency up to 2.77%. Whereas at the current velocity condition of 0.4 m/s, turbine A did not show the results of mechanical power. That is, the kinetic power of water was very small to drive a turbine, so the turbine could not extract the kinetic power from the water, which caused zero mechanical power. However, after being given an additional flow disturber that directs the flow to the turbine rotor to be able to extract the kinetic power from the water to produce turbine power.

Fig. 12 also shows clearly that curves A and B have the same pattern. Besides, the two curves show that the relationship between current speed and mechanical power was proportional. The results of this study had shown that the higher the current speed value, the higher the mechanical power generated by the turbine. This follows the theory discussed in equation 1, namely, that the mechanical power of the turbine is strongly influenced by the function of the current cube speed. Thus, if the value of the current speed is increased, the turbine's mechanical power will be large.

Thus, in the discussion, it can be concluded that adding a flow disturber can increase the mechanical power of the turbine at a low current speed. The peak mechanical power of the turbine increased 8.4% after the turbine was given an additional flow disturber component. As a result, the findings of this study are well suited for use in low current speed situations in Indonesian waters.

5 Conclusion

The in-situ experiment of straight-bladed hydrokinetic turbines for power generation at low current speed in Indonesia is successfully done. The results of this study case showed that adding the single flow disturber increased the ability to self-start in all low current speed ranges. The rotational speed peak of turbine B was 66.007 rpm, an increase of 5.25% from turbine A. The effect of flow disturber from the results of this study, with experimental methods, had shown an increase in turbine efficiency in all low current speed ranges. The peak efficiency of turbine B was 0.180, an increase of 8.4% from turbine A. The effect of flow disturber from the results of this study, with experimental methods, had shown an increase in turbine mechanical power in all low current speed ranges. The peak mechanical power of turbine B was 38.965 watts, an increase of 8.4% from turbine A.

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