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Experimental Study on a Horizontal Axis Tidal Turbine with Diffuser and Brim

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Abstract. Ocean current energy is a potential renewable energy source that can be developed in Indonesia using tidal turbines. The advantages of ocean current energy as an energy source are that its electricity generation can be predicted, more efficient than wind turbines, and suitable for use in archipelagic countries having many straits with high current speeds such as Indonesia. Research to optimize the performance of tidal turbines has been carried out and shows that the installation of diffusers with brims can increase the performance of tidal turbines. This study's objective is to analyze the effect of brim height variation on the power coefficient on horizontal axis tidal turbines was carried out and validated the results of numerical studies that had been previously done. To achieve the objective of this study, this experiment was conducted using the 244 cm x 140 cm x 120 cm flowing tank with artificial current propelled by two 15 mm-diameter propellers driven by an electrical motor. Flow straighteners and guide vanes were mounted in the flowing tank to maintain the flow uniform in the test section. In this study, the tip speed ratio value was varied from 1 - 5 and used a brim height of 0.1D and 0.2D at diffuser angles of 10.43° and 15.34°. The results of the study showed that the highest power coefficient value was 45.9% at TSR 2 obtained at a diffuser angle of 10.43° and a brim height of 0.3D.

INTRODUCTION

Since fossil energy has a high death rate per Terra Watt-hour of electricity generated, with coal at 32 and oil at 18 deaths, we need to shift towards renewable energy as a safer way to generate electricity [1]. One potential alternative energy source is tidal energy, which is predictable and provides a continuous supply of energy, making it a reliable source of electricity all day [2]. Based on a study of the Electricity Supply Business Plan (RUPTL) 2021-2030, Indonesia has many potential points for the development of ocean current power plants, including Alas Strait, Bali Strait, Lombok Strait, Sape Strait, and Larantuka Strait, each of which has the potential to generate as much as 10 MW of electricity [3]. Tidal energy is created by harnessing the kinetic energy from tidal current waves that pass-through turbines [4]. This makes it an ideal source of energy for archipelago countries with high-speed current straits, such as Indonesia. Indonesia has several straits that have the potential for generating energy from tidal currents due to their high current speeds, such as Riau Strait with an estimated current velocity of 1.39 m/s, Alas Strait with a current speed of 2.4 m/s, and Larantuka Strait with current speeds of 3.0 m/s [5]. Additionally, the electrification ratio of its surrounding areas has not yet reached 100% [6], with the current electrification ratio in NTT of 92.8%. As a result, the development of renewable energy generation from ocean currents is highly potential in these locations. Some previous studies suggested investigating ways to improve the performance of wind turbines, such as utilizing a wind lens device, a device that is installed around a turbine system made up of a diffuser shroud that has a wide-ring brim at its exit [7]. The wind lens can increase the speed of the wind passing through the turbine rotor by creating a vortex in the low-pressure area behind the brim-equipped diffuser [8]. This leads to a significant increase in power coefficient, by a factor of 2 to 5 compared to a regular wind turbine, for the same turbine diameter and wind speed which can

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make wind energy more efficient and feasible [8], [9]. A few experimental and numerical studies regarding tidal turbines were also carried out to improve the performance of tidal turbines. Numerical work has been conducted by Ambarita et al. to investigate the optimum diffuser angle for maximizing power coefficient while minimizing the cavitation effect of horizontal axis tidal turbine with NACA-4616 airfoil using multi-objective Genetic Algorithm (GA)-ANN method, resulting in the optimum angle of diffuser at 20.04°[10]. The effect of diffuser equipment on the power coefficient of horizontal axis tidal turbines (HATT) with NACA-4616 airfoil was then validated in numerical and experimental studies [11]. The experimental study was conducted using a circulating water channel using two diffusers, one with the optimum angle at 20.04° and another diffuser angle at 10.43°, resulting in the maximum power coefficient at 43.6% at 133 rpm using a 20.04-degree diffuser, and 30.3% using a 10.43° diffuser at 85 rpm [12]. Further research to improve the performance of tidal turbines was conducted by Kamil et al. [13], who carried out a numerical study to investigate the effect of adding a brim to the outlet diffuser of a horizontal axis tidal turbine that already used a diffuser. The results showed that varying the height of the brim on a tidal turbine with a diffuser had a significant effect on the power coefficient produced. The higher the brim height, the higher the power coefficient that could be achieved, due to the vortex formed in the low-pressure region that arose after the turbine was installed on the diffuser [7], [12].

In this current study, experimental work is done to analyze the effect of brim height variation on the power coefficient on horizontal axis tidal turbines. It is also to validate the results of numerical studies that had been previously done.

EXPERIMENTAL METHODS

Test Facilities

This experimental study was conducted at the fluid mechanic laboratory at Universitas Indonesia, Depok, Indonesia using the 244 cm x 140 cm x 120 cm circulating water channel as seen in Fig.1 with a water level of 80 cm. The turbine, together with the brim-equipped diffuser was mounted inside the channel, resulting in a maximum channel blockage of 0.252 for the 10.43° diffuser with a brim height of 0.3D, which must be considered in tidal turbine experimental studies [14].

The direction of water flow in the circulating water channel was visualized in Fig.1. The water flow was propelled by two 15 mm-diameter propellers driven by an electrical motor as seen in Fig.1 with legends 1, 3, and 4. Before reaching the turbine, the water passes through a honeycomb-type-flow straightener as seen in legend 2 to ensure a uniform flow upon reaching the turbine that is already equipped with a diffuser and brim. A guide vane, as seen with legend 10 in Fig.1 is implemented behind the turbine system to prevent backflow that may disrupt the experimental test section. The flow then proceeds to the channel and circulates back.

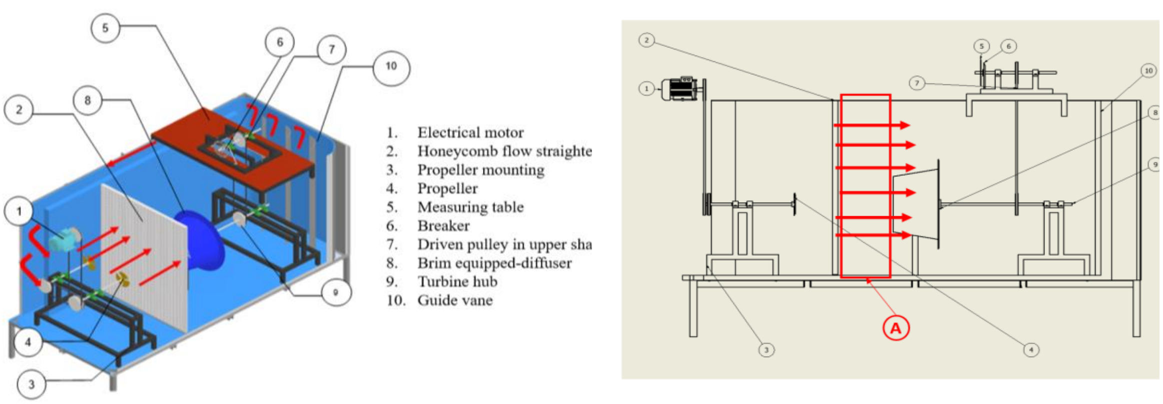
Rotor Geometry and Brim-Equipped Diffuser

The rotor geometry was designed to be identical to previous studies [10]-[8] that used the NACA 4616 air foil with 3-blades and 0.3 m-diameter. The blade geometry details for this experiment can be seen in previous research [11]. The 3 turbine blades were manufactured using 3D printing with PLA plastic filament with 0.2 mm layer thickness. The 3D-printed blades are coated with a thin layer of resin and then mounted on an aluminium hub connected to a shaft with SS-304 material. The assembly of the rotor geometry and diffuser is represented in Fig.3. The brim-equipped diffuser was fabricated using a 4-mm plywood-based material resin-infused with fiberglass. To fulfil the material requirements for withstanding high fatigue loads in the underwater environment, this material was chosen due to its resistance to corrosion, high strength-to-weight ratio, and design flexibility for use in complex shapes [14]. After the diffuser geometry has been established, the surface of the diffuser is polished to achieve a completely smooth and uniform finish. Following this, the brim-equipped diffuser is then painted with oil-based paint. Lastly, the fabrication of the brim extension is carried out using a 1.2 mm thick zinc plate, which is cut to match the outlet diameter of the 10.43° and 15.34° diffusers. The brim is then coated with oil-based paint and installed to the outlet of the diffuser using bolted connections. The brim for the 10.43° diffuser is manufactured with two different heights, 0.1D (3 cm) and 0.3D (9 cm). On the other hand, for the 15.34° diffuser, the brim is made with heights of 0.1D (3 cm) and 0.2D (6 cm).

Experimental Setup

To achieve the objective of this experimental study, which is to determine the power coefficient of a tidal turbine through torque measurement at various rpm variations, the experimental setup was designed as can be seen in Fig.1(a). A measuring table is fabricated as a platform for placing measuring instruments and their supporting devices to avoid underwater measurements, as can be seen in Legend 5. It consists of a braking system and a torque measuring device called a breaker that is mounted on a aluminum shaft above the water as can be seen in Fig.1(a) with legend 6 and connected to the tidal turbine shaft underwater via a V-belt and pulley system transmission as can be seen in legend 9. The V-belt and pulley system transmission has an estimated efficiency of 75% due to losses resulting from usage, amounting to 5% losses [15], and losses due to slip factor in the v-belt operation of up to 18% [16] that already considered during measuring the turbine torque in this experimental study.

The braking system is a vital component that enables the variation of rpm from high to low. It is linked to a breaker that applies force to the load cell through a steel needle which then gives load on the load cell surface. The load cell sensor is then connected to the laptop using a data acquisition device called NI-USB 6211.



(a) (b)

FIGURE 1. Isometric Section (a) and Cross Section (b) of Experimental Setup with "A" Represent the Test Section

Data Collection Phase

The data collection phase was conducted using three measurement tools: a tachometer to measure rpm, a current meter to measure flow velocity, and a load cell setup to measure tidal turbine torque. The tachometer used in this experiment is a digital tachometer that operates by shooting a laser onto a marked moving object, then the rotational speed of the moving object will be read by the tachometer. This model, HT-522, has an accuracy of 0.033%.

The torque measurements are conducted by using a load cell setup as can be seen in Fig.2. A 12V power supply is utilized to provide power to the load cell. Due to the small voltage generated by the 500g load cell, an amplifier is required to increase the voltage that will be read by the NI USB-6211. The voltage produced from the load cell then can be seen on the laptop using LabVIEW 2019 software. The load cell needs to be calibrated first to establish the voltage-to-mass gradient equation, enabling torque calculations to be performed. The voltage-to-mass gradient equation can be seen in equation 1 below:

$$y = 0.2488x - 0.0227 \tag{1}$$

where y represents the mass (kg), and x represents the average voltage produced from the load cell device. The torque calculation is then performed using this equation 2 below.

$$\tau = Fr = mgr \tag{2}$$

where τ represents the torque (Nm), m represents the mass (kg), g represents the gravitational acceleration (m/s2), and r represents the radius (m).

The data collection phase is conducted by performing an inspection to ensure the experimental setup is following the designed specifications. This includes verifying the pulley alignment, and v-belt tension, and ensuring that all joints in the experimental setup have been properly installed. After the inspection is completed, the electric motor switch is turned on to drive the electric motor at a maximum rotation speed of 1400 rpm, which drives two propellers connected with a v-belt system to create an artificial flow. A current meter is then used to measure the flow velocity at 9 points in the test section, which are considered to represent a uniform flow as it approaches the diffuser as can be seen in Fig.3. The propellers on the tip of the current meter must be positioned at a 90° angle to the direction of water flow in the test section. Once the water flow reaches the desired velocity, data collection begins by applying brakes to the breaker until the target rpm is reached, as measured by a tachometer. At the same time, the needle on the breaker will press and exert load on the load cell, while LabVIEW software on a laptop is executed to record voltage data from the load cell that experienced the force from the breaker needle. This voltage data is then converted into mass using a voltage-to-mass gradient equation as can be seen in Equation i.

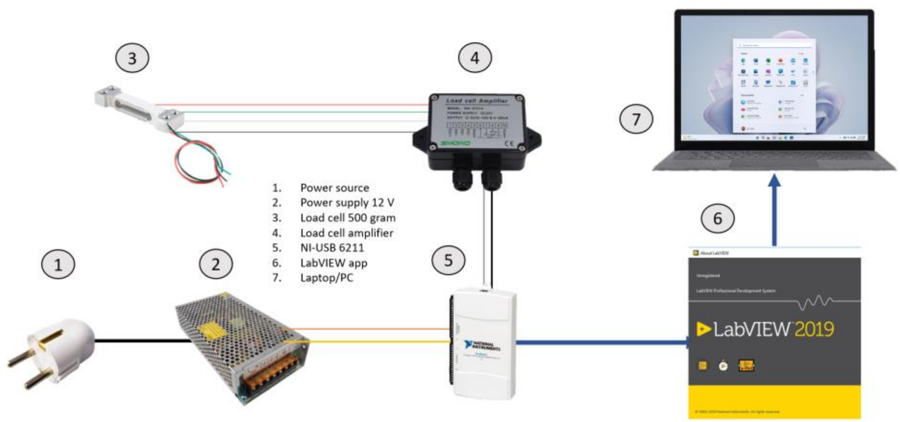


FIGURE 2. Load Cell Setup

The turbine's torque at the target rpm can then be calculated using Equation 2, and the C_p value can be determined using an equation that can be seen in Equation 3.

$$C_P = (\tau\omega)/(0.5\rho A V^3) \tag{3}$$

where C_p represents the power coefficient, *A* represents the cross-sectional area of the turbine (πR2), and *V* represents the inlet velocity (m/s).

Finally, the Tip Speed Ratio (TSR) is varied from 1 to 4 by adjusting the rpm through the braking system. The same method is applied to measure the C_p value on various diffuser angles with different brim height variations. Uncertainty analysis is also included in this experimental study. Uncertainty for each measuring tool, namely the tachometer, current meter, and load cell, are 1.14%, 2.5%, and 2.12% respectively. First, this experimental study was conducted using a diffuser angle of 15.34° with a brim height of 0.1D. The same method was then repeated using a brim height of 0.2D. Subsequently, the next experimental study was then conducted using a different diffuser angle, namely 10.43° with brim heights of 0.1D and 0.3D.

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(a) (b)

FIGURE 3. The Designed Geometry (a), and Manufactured Geometry (b) Brim-Equipped Diffuser with an Angle of 10.43°

RESULTS AND DISCUSSION

Before analyzing the power coefficient of the tidal turbine with a brim-equipped diffuser, it is necessary to analyze the flow characteristics both before and after passing the diffuser inlet. A current meter is then used to measure the flow velocity at 9 points as can be seen in Fig.4, which are considered to represent a uniform flow between the flow straightener and the diffuser inlet. Flow velocity values at 9 points can be seen in Fig.4 with an average velocity of 0.711 m/s. Meanwhile, the velocity inside the diffuser varies from 0.9 m/s to more than 1 m/s. This proves that the water flow on the inside of the diffuser inlet experiences an increase in velocity.

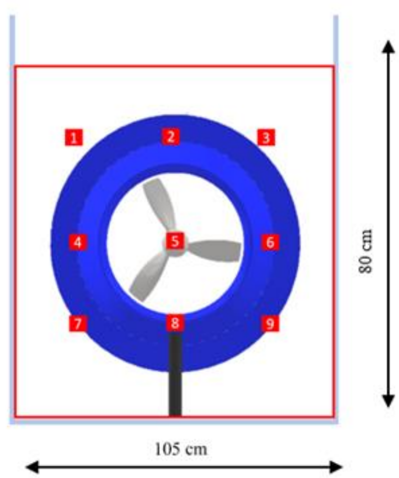


FIGURE 4. Flow Velocity Test Point in Front of Diffuser Inlet

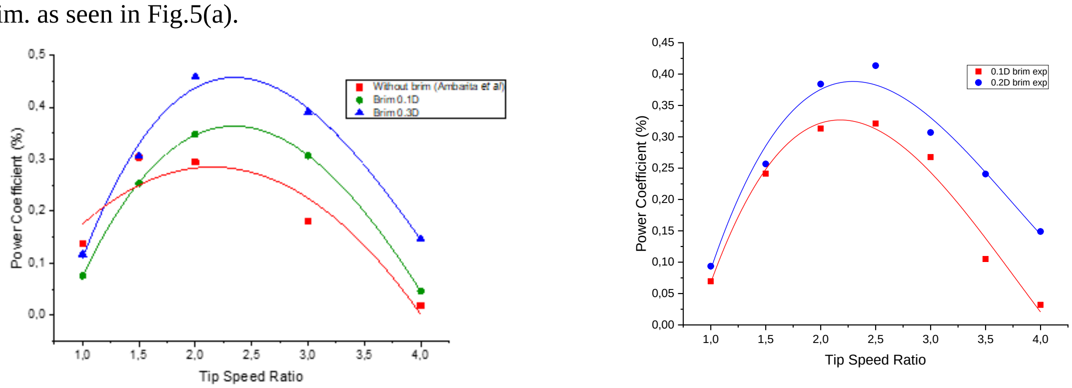
TABLE 1. Flow Velocity Value in Test Point in Front of Diffuser Inlet

Position	*v* (m/s)
1	0.5
2	0.7
3	0.8
4	0.6
5	0.8
6	0.7
7	0.7
8	0.8
9	0.8
average	0.711

Power Coefficient

The C_p result of this experimental study by varying TSR from 1 to 4 using a tidal turbine with a 10.43° diffuser equipped with 0.1D and 0.3D brim was shown in Fig.5(a). The C_p obtained was then compared with the previous experimental study which examined the C_p value of a tidal turbine at the same diffuser angle without using brim[11]. A previous study by Ambarita et al was able to produce a maximum C_p value of 30.3% achieved at 85 rpm or around TSR 2 using a 10.43 diffuser without a brim. The comparison of C_p results obtained by this experiment was then compared to the previous study. The comparison of results can be seen in Fig.5(a).

The data collection phase was performed 5 times for each variation of TSR, within each different diffuser angle and brim height. This means a total of 20 data collections are conducted, considering 5 variations of TSR with 2 variations of diffuser angles and 2 variations of brim heights. In this experiment, the maximum C_p value increased to 36.3% at TSR 2.5 using a 0.1D brim and experienced a significant increase in C_p value to 41.3% at TSR 2 using a 0.3D brim. as seen in Fig.5(a).



(a)

(b)

FIGURE 5. Comparison in Power Coefficient Result Using 10.43° without Brim and With Brim Height of 0.1D and 0.3D (a) and Comparison in Power Coefficient Result Using 15.34° without Brim (b)

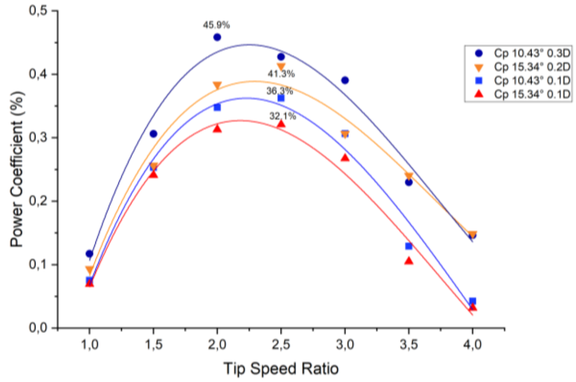


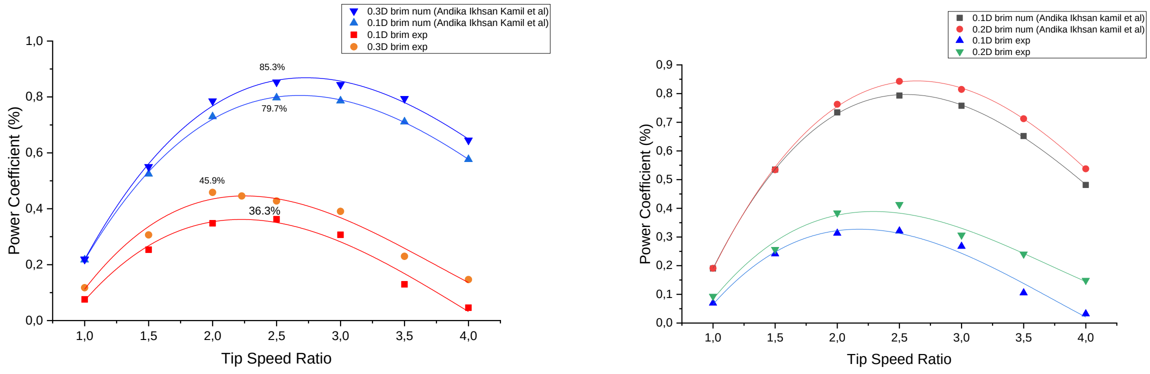
FIGURE 6. Comparison of C_p Results in Different Diffuser Angle and Brim Height Variations

Meanwhile, to reinforce the previous results on the 10.43° diffuser, another diffuser with a different angle namely 15.34° was tested. The C_p results from the experimental study using a tidal turbine with a diffuser angle of 15.34° equipped with 0.1D and 0.2D brim was shown in Fig.5(b). It is found that the maximum C_p results significantly increase from 32.1% at TSR 2.5 with a brim height of 0.1D to 41.3% at TSR 2 when using a higher brim height of 0.2D. The C_p results for each variation of diffuser angle and brim height were then compared in Fig.6. Based on the comparison in Fig.6, It is found that the highest C_p value is obtained using a diffuser angle of 10.43° with a brim of 0.3D, reaching 45.9%. The second-highest C_p value, namely 41.3% is achieved using the diffuser angle of 15.34° with a brim of 0.2D. The third-highest C_p value is obtained for the 10.43° diffuser angle with a brim of 0.1D, measuring 36.3%. The lowest C_p maximum value is recorded for the 15.34° diffuser angle with a brim of 0.1D. Therefore, it is found that a brim-equipped diffuser can produce more C_p with the same TSR compared to a diffuser that is not equipped with the brim.

Comparison Between Experimental and Numerical Studies

One of the main objectives of this experiment is also to validate the numerical studies that have been done using a computational fluid-dynamic method to find out the effect of brim height at different diffuser angles on increasing the power coefficient produced by the horizontal axis tidal turbine. The limitations of the experimental setup have been solved in various approaches. The honeycomb-type flow straightener is used to ensure uniform flow when passing through the turbine. To overcome the tank length of 2.44 m which is too short, the guide vane was installed behind the turbine in the circulating current to prevent backflow that may disrupt the experimental test section as can be seen in Fig.1.

Fig.7 visualizes the comparison between C_p values obtained in this experimental and previous numerical study. It was found that the maximum power coefficient value obtained from the experiment using a diffuser with an angle of 10.43° was 45.9% using a 0.3D brim, while the power coefficient obtained from numerical studies using the same diffuser angle and brim height was 85.3%, resulting in 38.4% difference between experimental and numerical method. In the diffuser with an angle of 15.34°, maximum C_p was obtained at 41.3% at 0.2D brim, while numerical studies obtained the maximum C_p at 84.3%, resulting in a 43% difference. The difference in power coefficient values between numerical studies and experimental study occurs because of several losses factors, such as mechanical losses caused by friction between the bearing and shaft, friction in diffuser, turbine, and propeller foundation in the experimental setup, uncertainty in measurement instruments, and limitation of the channel test area as presented in blockage ratio of the experiment [11]. Environmental factors caused by rust and electric motor vibration can also influence the difference between experimental and numerical studies.



(a) (b)

FIGURE 7. Comparison of C_p Results Between the Experimental and Numerical Study on 15.34° Diffuser Angle (a) and Comparison of C_p Results Between the Experimental and Numerical Study on 10.43° Diffuser Angle (b)

CONCLUSION

This study's objective is to analyze the effect of brim height variation on the power coefficient on horizontal axis tidal turbines was carried out and validated the results of numerical studies that had been done before. The two diffusers with different angles, namely 10.43° and 15,34°, and brims with different heights, namely 0.1D and 0.2D for the 15.34° diffuser and 0.1D and 0.3D for the 10.43° diffuser were fabricated and tested using circulating water channel with 2.44 m length, 1.40 m width, and 1.2 height with water level of 0.8 m at Universitas Indonesia, Depok, Indonesia. This study found that this experimental study obtained the maximum C_p value of 45.9% at TSR 2 using a diffuser angle of 10.43° and brim height of 0.3D, whereas the numerical study obtained the maximum C_p value of 85.3% at TSR 2 with a flow velocity of 0.7 m/s. Moreover, an experimental study using a 15.34° diffuser obtained a maximum C_p value of 41.3% with a brim height of 0.2D, with a maximum C_p value of 84.3 obtained from numerical studies with a flow velocity of 0.7 m/s. In conclusion, It is observed that in horizontal axis tidal turbines with a brim-equipped diffuser, using smaller diffuser angles and higher brim heights will result in higher power coefficient values. Differences in maximum C_p results between the experimental study and numerical study occurred due to loss factors from bearing friction, friction in the foundation of turbine, diffuser, and propeller in the experimental setup, uncertainty in measurement instrument, limited channel area, and environmental factors caused by rust and vibration.

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