

## Effect of the Number of Blades and Variations in Position of Straight Blades on Vortex Turbine Efficiency

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### Abstract

The need for electrical energy continues to increase every year so that alternative renewable energy sources are needed. One potential renewable energy is water energy by utilizing flat river flow or very low head. Vortex turbines can be applied at very low head. This research was conducted to identify the features of the most efficient vortex turbine. From the literature review, it is known that there has been no research on the effect of the number of straight vortex turbine blades in relation to their placement in the basin hole. The research methodology was laboratory testing using five different straight blades. The runner is made of PVC material with the number of blades 3, 4, 5, 6, and 8. Tests were carried out with three variations in the position of the blades, namely the blades above the outlet hole, half submerged, and completely submerged. The water discharge used is 0.003 m<sup>3</sup>/s. Based on the test, it is known that the maximum efficiency is 33.93%, which is when the blade with a total of three blades is positioned half submerged in the outlet hole. Validation was conducted using CFD ANSYS CFX simulation where the results were relatively similar to the test. The case was simulated with a multiphase free surface model of water and air with a stationary domain on the basin and a rotating domain on the runner. The potential implication of this study is that by using a simple blade model, namely a straight model, satisfactory results can be obtained when the blade is placed correctly on the vortex turbine basin.

## 1. Introduction

Although Indonesia has considerable renewable energy reserves, its growth has not been optimized due to the long distance between energy supply areas and customers. In addition, the investment to apply renewable energy technology is quite high. One way to utilize renewable energy sources is by using vortex turbines. This type of

turbine utilizes the flat river flow (very low head) which is usually located not far from residential areas. The advantages of very low head turbines are inexpensive system installation costs, low civil work costs due to little civil construction, high reliability, simple shape, easy operation, and no adverse effects on fish populations [1].

The vortex turbine utilizes the water vortex as an energy medium. River water is channeled through an inlet to a carrier channel on the side of the river, where it reaches a whirlpool tank or basin. The energy from the whirlpool formed in the basin will rotate the vertical shaft turbine blades. The turbine shaft then rotates the generator to produce electrical energy. After rotating the turbine blades, the water will exit the hole under the whirlpool tank and flow back to the river through the outlet [2],[3]. The results of the study show that the average efficiency of vortex turbines is still lower than that of conventional propeller turbines. The efficiency of vortex turbines ranges from approximately 14% to 40% [4]-[6]. Kaplan turbines have an efficiency of approximately 76% to 90% [7]-[9], Archimedes screw turbines have an efficiency of approximately 72% [10], and an ultra Z-Blade designed water reaction turbine has an efficiency of approximately 66% [11]. Vortex turbines offer higher efficiency than traditional undershot or overshot water wheels, with efficiency in the range of 35% [12]-[14]. The efficiency of vortex turbines is also higher than that of vertical axis water turbines, which have an efficiency of 5.93% [14]. Several researchers have tried to conduct research to improve the efficiency of vortex turbines such as by the use of baffle plates on the blades [15],[16], the use of multilevel blades [17]-[19] and the use of conical basins [20],[21].

One of the problems with vortex turbines is selecting a turbine with the right number of blades [22]. Power et al. [2] have varied the cross-sectional area and number of blades. From the research results, the highest efficiency value was obtained at 15.1% using a turbine with a blade area of 500 x 150 x 2 mm, 4 blades, an inlet height of 25 cm, and a flow rate of 0.65 l/s. Other research on vortex turbines was carried out by Hakim & Wibowo [23]. From his research, it was found that increasing the height of the blades on straight-blade turbines greatly affects the power and efficiency produced. This is because by increasing the height of the blades on the turbine, the area of the blades exposed to fluid impact becomes greater, even though the turbine is not completely submerged when loaded. Compared to a turbine that is resistant to loading even when fully submerged, the influence on power and efficiency increases with the area of the blades that were submerged by fluid.

In terms of blade shape, several researchers have also compared them. Nauman [24], Dhakal et al. [25], and Kueh et al. [26] suggested that curved blade profiles outperform flat ones in terms of efficiency. In addition to the turbine blades, the basin design also influences the efficiency of the vortex turbine. The initial design of the basin was carried out using general laws of fluid mechanics such as the continuity equation and the Bernoulli equation [27]. Dhakal et al. [25] investigated the influence of basin shape on the performance of vortex turbines. This research analyzes different basin structures to maximize output power. Vortex turbines with conical basins produce more power than cylindrical basins. From his research, it is known that the efficiency of a turbine with a conical basin is 36.84%, while the efficiency of a cylindrical basin is only around 27.75%. This can be explained by the fact that at the same water discharge, as the flow area in the basin cone decreases, the velocity will increase. Thus, a vortex turbine with a conical basin produces greater power than a cylindrical basin [25]. The research conducted by Dhakal et al. [25] combines prototype testing with computational fluid dynamics (CFD) simulation.

The use of CFD in research has several advantages, such as cost savings, good accuracy, and the ability to comprehensively visualize fluid flow phenomena in a system. By creating virtual models, CFD can save on the costs of physical manufacturing and testing. Through CFD simulations, several researchers have conducted studies to develop geometric parameter models to find the most efficient design for renewable energy power plants [28]-[30]. CFD is also used to analyze the aerodynamic performance of a design [31] and to validate test results [32]. This study was conducted using straight vortex turbine blades and a cylindrical basin. The reasons for using straight blades and a cylindrical basin are that these models are easy to make, inexpensive, lightweight, and easy to apply in remote areas. From the literature review that has been conducted, there has been no research on the effect of the number of straight vortex turbine blades in relation to their placement in the basin hole. Based on the background described above, this study tested vortex turbines using straight blades with variations in the number of blades and their positions on a cylindrical basin. The potential implication of this study is that satisfactory vortex turbine performance can be achieved even with a simple blade model if the blades are positioned correctly.

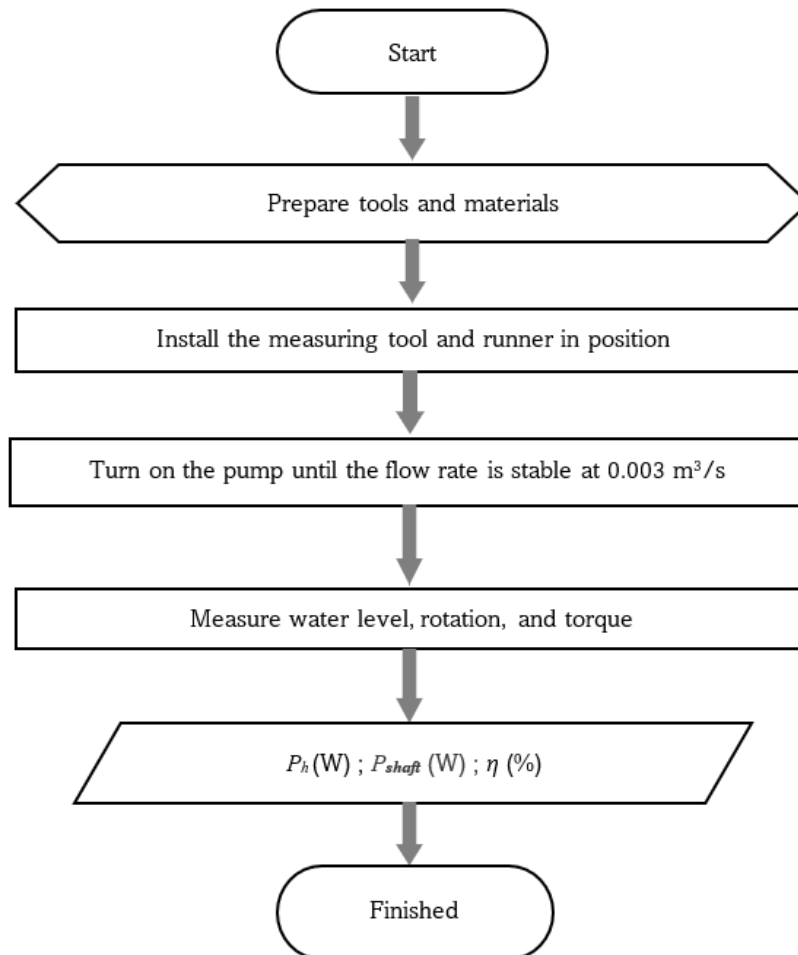
## 2. Methodology

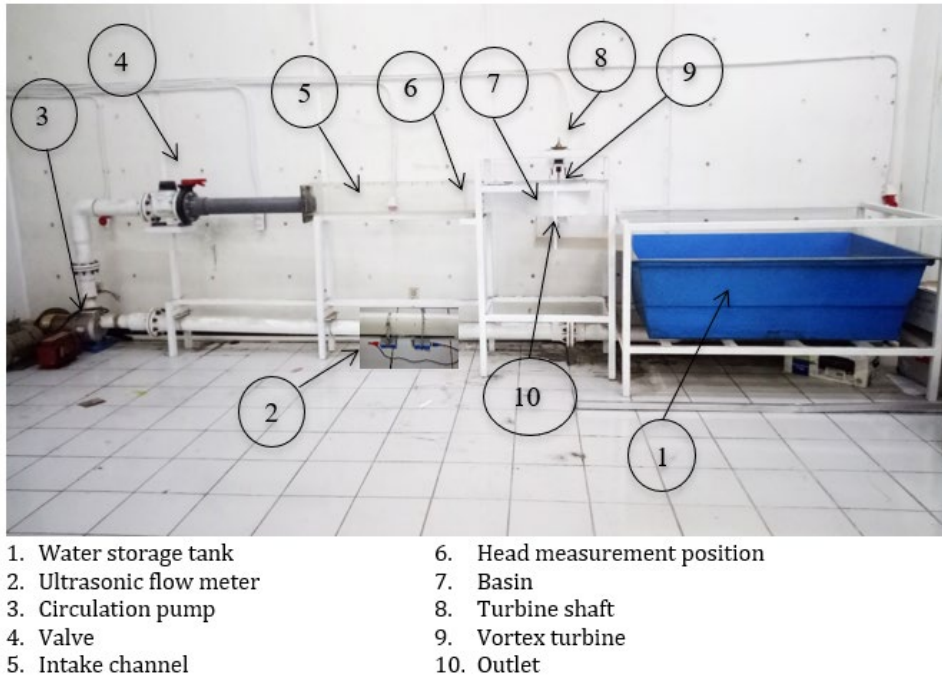
### 2.1 Turbine Performance Testing in the Laboratory

The characteristics of vortex turbines differ from those of other turbines, so laboratory testing is required to determine the rotation produced by vortex turbines. The tools and materials used are listed in Table 1. The tools used include a tachometer to measure turbine shaft rotation, a torquemeter to measure turbine shaft torque, and an ultrasonic flowmeter to measure water discharge. The testing flow can be briefly described as shown in Fig. 1, while the gravitational vortex water turbine experimental setup is shown in Fig. 2.

**Table 1** Tools and materials

No.	Tools and materials	Specification
1	Tachometer	<ul style="list-style-type: none"> <li>Digital Tachometer Hioki FT3405</li> <li>Rotation range 0.5-9999 r/min</li> </ul>
2	Torquemeter	<ul style="list-style-type: none"> <li>LUTRON model TQ-8800 FITUR:</li> <li>Torque probe 15 Kg-cm,</li> <li>Accuracy +/- 1.5%</li> </ul>
3	Ultrasonic Flowmeter	<ul style="list-style-type: none"> <li>Linearity: 0.5 %</li> <li>Accuracy: 1%</li> <li>Measuring Pipe Size: DN50-700mm</li> </ul>
4	Runner	<ul style="list-style-type: none"> <li>Material: PVC</li> <li>Number of blades: 3, 4, 5, 6, and 8</li> <li>Width 30 mm</li> <li>Height 65 mm</li> <li>Internal diameter 40 mm</li> <li>Outer diameter 100 mm</li> </ul>

**Fig. 1** Test scheme flowchart



**Fig. 2** The gravitational vortex water turbine experimental setup

The initial stage of testing is to prepare the testing tools and equipment. Water is stored in a reservoir. Next, the control valve on the water line is fully opened. The ultrasonic flowmeter is placed in the water inlet. The position of the two sensors must be parallel so that the discharge can be read accurately. Install the blade on the turbine shaft in the specified position. Then, turn on the power source via the panel box. Adjust the pump discharge by adjusting the frequency on the inverter until it is stable at  $0.03 \text{ m}^3/\text{s}$ . Water discharge can be seen from ultrasonic flowmeter monitor. After constant discharge, the height of the incoming water is measured using a ruler. The turbine rotation speed per minute will be measured using a tachometer directed at the turbine shaft. To obtain the torque value, a load is placed at the upper end of the turbine shaft. By pressing the button slowly, we will get more data variations. The data obtained was taken from the turbine position without load (maximum rotation) up to maximum load (rotation 0). Hydrolysis power is the potential power of water at a certain height generated by a turbine. The hydrolysis power in the vortex turbine is calculated by:

$$P_h = \rho \cdot g \cdot H \cdot Q \quad (1)$$

where  $P_h$  is the hydraulic power of water (W),  $\rho$  is density ( $\text{kg}/\text{m}^3$ ),  $g$  is the acceleration due to gravity ( $\text{m}/\text{s}^2$ ),  $Q$  is water discharge ( $\text{m}^3/\text{s}$ ), and  $h$  is head (m). The output power produced by the turbine as a result of converting water potential energy into mechanical energy is:

$$P_{shaft} = T \cdot \omega \quad (2)$$

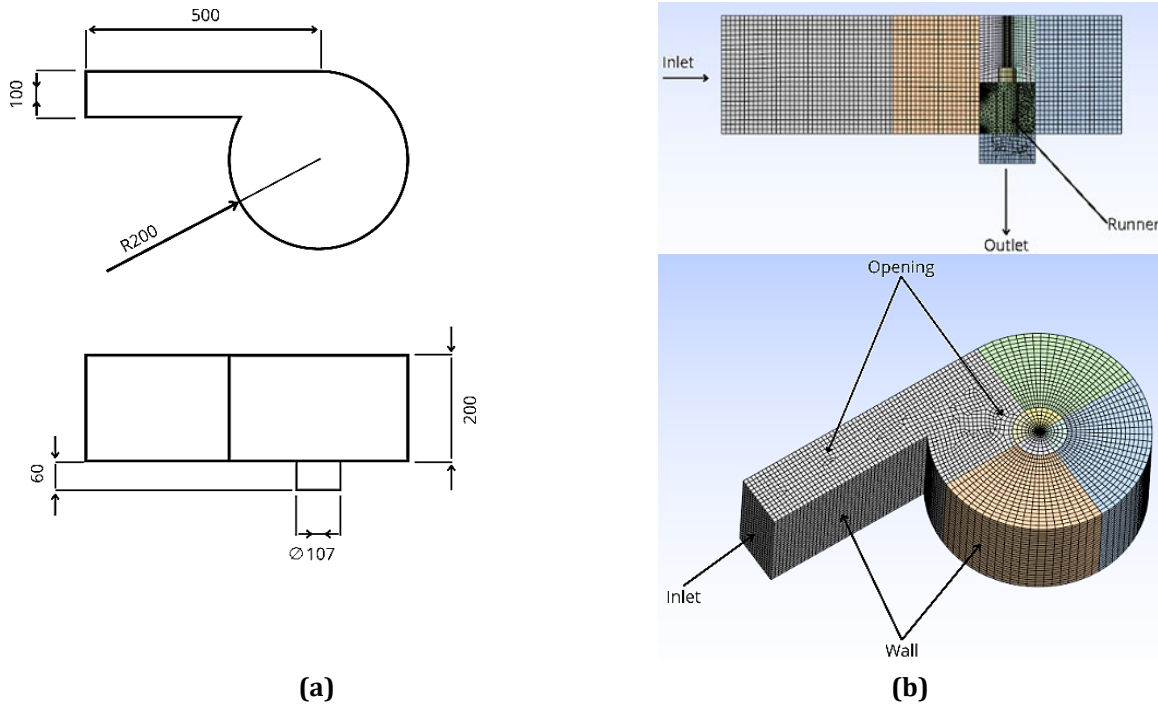
where  $P_{shaft}$  is mechanical power (W),  $T$  is torque (Nm), and  $\omega$  is angular speed (rad/s). In measurements, it is often found that the rotating speed measuring instrument does not measure angular speed, so the conversion for rpm to angular speed is, where  $n$  is the rotational speed in units of revolutions per second (rps). The efficiency (%) of the turbine is calculated using the equation:

$$\eta = \frac{P_{shaft}}{P_h} \cdot 100\% \quad (3)$$

## 2.2 CFD Simulation

In this study, CFD simulation was performed using ANSYS CFX software for validation. The flow model used was a free surface model of water and air. The vortex turbine design and computational domain are shown in Fig. 3. In the basin geometry, there is a cavity as a space to be filled by the runner domain. The vortex turbine geometry is divided into several sections (multi-blocks) to create a structured mesh with a basic hexahedral (six-sided cube) shape. The mesh results have an average skewness value of 0.15951 with an orthogonal quality of approximately

0.8. With these values, the mesh results can be considered very good. Meshing around the runner is made tighter so that CFD produces more accurate data, especially around the rotating domain (runner). At the intersection of the rotating and stationary domain meshes, there is an interface to connect the two.



**Fig. 3** Vortex turbine model description (a) Basin geometry; (b) Meshing

In CFD simulation, the flow equations used in the solver stage based on the law of continuity and Navier Stokes equations in cylindrical coordinates are as follows.

$$\frac{\partial v_r}{\partial r} + \frac{\partial v_z}{\partial z} + \frac{v_r}{r} = 0 \quad (4)$$

$$v_r \frac{\partial v_\theta}{\partial r} + v_z \frac{\partial v_\theta}{\partial z} - \frac{v_r v_\theta}{r} = \nu \left( \frac{\partial^2 v_\theta}{\partial r^2} + \frac{1}{r} \frac{\partial v_\theta}{\partial r} - \frac{v_\theta}{r^2} + \frac{\partial^2 v_\theta}{\partial z^2} \right) \quad (5)$$

$$v_r \frac{\partial v_r}{\partial r} + v_z \frac{\partial v_r}{\partial z} - \frac{v_\theta^2}{r} + \frac{\partial \rho}{\rho \partial r} = \nu \left( \frac{\partial^2 v_r}{\partial r^2} + \frac{1}{r} \frac{\partial v_r}{\partial r} - \frac{v_r}{r^2} + \frac{\partial^2 v_r}{\partial z^2} \right) \quad (6)$$

$$v_r \frac{\partial v_z}{\partial r} + v_z \frac{\partial v_z}{\partial z} + \frac{\partial \rho}{\rho \partial z} = g + \nu \left( \frac{\partial^2 v_z}{\partial r^2} + \frac{1}{r} \frac{\partial v_z}{\partial r} + \frac{\partial^2 v_z}{\partial z^2} \right) \quad (7)$$

where  $v_\theta$ ,  $v_r$  and  $v_z$  are the tangential, radial, and axial velocity components,  $\rho$  is the density of water,  $g$  is gravity, and  $\nu$  is kinematic viscosity. The turbulent model used in this vortex turbine simulation is the  $k$ -Epsilon ( $k$ - $\epsilon$ ) model. The  $k$ - $\epsilon$  model is a fairly comprehensive turbulence model with two equations that allow turbulent velocity and length scale to be determined independently. The transport equations for the standard  $k$ - $\epsilon$  model are as follows. Besides, the setup used in the vortex turbine simulation is shown in Table 2.

$$\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \epsilon - Y_M + S_k \quad (8)$$

$$\frac{\partial}{\partial t} (\rho \epsilon) + \frac{\partial}{\partial x_i} (\rho \epsilon u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + G_{1\epsilon} \frac{\epsilon}{k} + (G_k + G_{3\epsilon} G_b) - G_{2\epsilon} \rho k \epsilon^2 S_\epsilon \quad (9)$$

**Table 2** CFD simulation setup

Fitur	Setup	Annotation
Analysis type	Steady state	
Flow model	Multi phase	Water and air
Domain type	Multi domain	Domain 1: stationary, Domain 2: rotating
Turbulence model	k-Epsilon	None head transfer
Bouyant flow	On	Gravity: $y = -9,8 \text{ m/s}^2$ Bouyant reference density $1,22 \text{ kg/m}^3$
Multi phase	Homogenous model	Free surface model
	Fluid spesific model	Density difference
	Fluid pair model	Surface tension coefficient $0,072 \text{ N/m}$ , Surface tention model: continuum surface force Interphase transfer: free surface
Boundary conditions	Inlet	Mass flow rate Fluid value: air = 0, water = 1
	Outlet	Static pressure. Relative pressure 0 Pa
	Opening	Opening pres. And dirn. Relative pressure 0 Pa Fluid value: air = 1, water = 0
	Wall	No slip wall, smooth wall
	Blade	No slip wall, smooth wall
Interface domain	Frozen rotor	Specified pitch angles

### 3. Results and Discussion

#### 3.1 Laboratory Testing

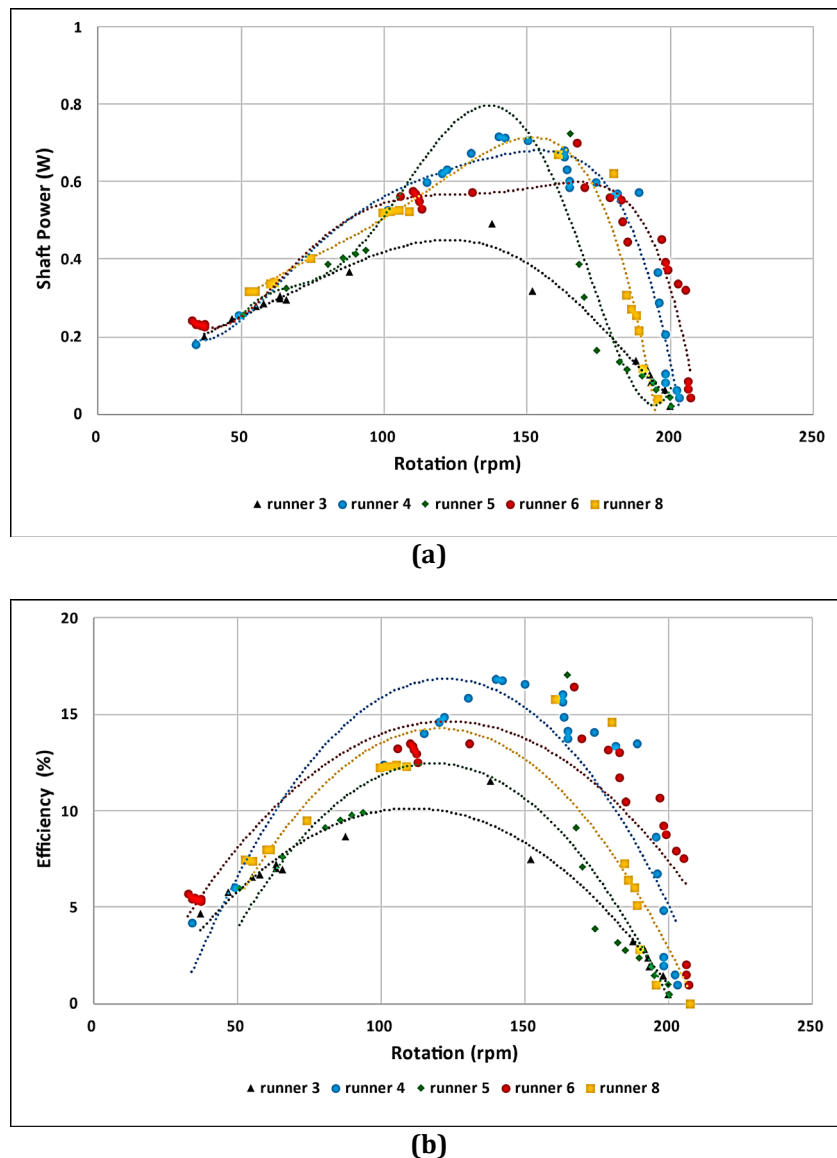
In vortex turbines, there are several main factors that affect turbine efficiency, including water height (head), flow speed, turbine rotation, and shaft torque.

##### 3.1.1 Turbine Performance with Blades Above the Outlet

In the first test, the bottom of the runner was set to be level with the basin floor. The head was calculated from the basin floor to the water surface height. With a water flow rate of  $3 \text{ l/s}$ , the water level at the inlet was measured at  $14.5 \text{ cm}$ , which is the turbine head. From the flow rate and head, the potential electrical power can be calculated, amounting to  $4.3 \text{ W}$ . The performance test results of the vortex turbine are presented in graphical form as shown in Fig. 4. The maximum torque occurs when the turbine rotation is equal to zero, but the maximum turbine rotation occurs when there is no load. From this test, the maximum rotation of the five types of vortex turbine runners is almost the same, which is around  $201\text{-}207 \text{ rpm}$ . The maximum torque of this test increases as the number of blades increases where in the runner with the number of blades 3, 4, and 5, the maximum torque is relatively the same, which is about  $5.2 \text{ Ncm}$  to and  $5.4 \text{ Ncm}$ . While the runner with the number of blades 6 and 8, the maximum torque is greater at  $7.2 \text{ Ncm}$  and  $6.1 \text{ Ncm}$ . From Fig. 4(a), it can be seen that the variation in the number of blades greatly affects the mechanical power produced where with the increase in the number of blades, the mechanical power tends to increase. The maximum turbine mechanical power with the number of blades 3 is  $0.491 \text{ W}$ . While at the number of blades 4 and 5, the maximum mechanical power is higher at  $0.718 \text{ W}$  and  $0.725 \text{ W}$ .

Furthermore, with the increase in the number of blades, the maximum mechanical power produced tends to decrease. Runner with the number of blades 6 and 8, respectively, has a maximum mechanical power of  $0.7 \text{ W}$ , and  $0.672 \text{ W}$ . The maximum mechanical power generated by the vortex turbine for variations in the number of blades at the position of the blade above the outlet hole is  $0.725 \text{ W}$  by using 5 blades. This is in line with the research results of previous researchers where vortex turbines with 5 blades have the greatest torque [15]. Fig. 4(b) shows the graph of rotation vs efficiency of the vortex turbine. From the Fig. 4(b) it can be seen that there is an increase in efficiency in the 3 to 5 blades test where when using 3 blades, the vortex turbine efficiency is  $11.53\%$ , increasing to  $16.87\%$  and  $17.05\%$  when using 4 and 5 blades. The efficiency of the vortex turbine with

runner type using 6 and 8 blades is 16.45% and 15.79%. So, the maximum efficiency produced by the vortex turbine for variations in the number of blades at the position of the blade above the outlet hole is 17.05% using a runner with 5 blades. The amount of turbine rotation and load torque when producing maximum efficiency is 165 rpm and 4.2 Ncm.



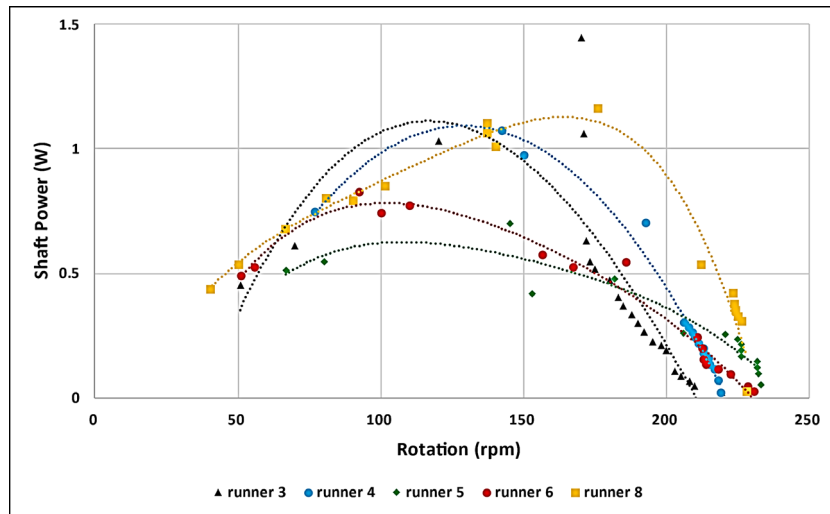
**Fig. 4** Vortex turbine performance graph at the blade position above the outlet hole (a) Power; (b) Efficiency

Based on the results obtained, there are differences from previous research, namely Sritram and Ratchaphon [22], who tested the effect of variations in the number of blades with 3 blades, 5 blades, and 9 blades on the efficiency of the prototype. From these tests, it was found that the more the number of blades, the greater the efficiency and mechanical power of the turbine. Meanwhile, in this test, the efficiency and mechanical power of the turbine increase as the number of blades increases to a certain extent, and will decrease again if the number of blades continues to be increased. In general, the shape of the inverted parabola-shaped curve of shaft power and efficiency of the vortex turbine is in accordance with the simulation and experimental results conducted by Guzmán et al. [33] and Nishi et al. [34].

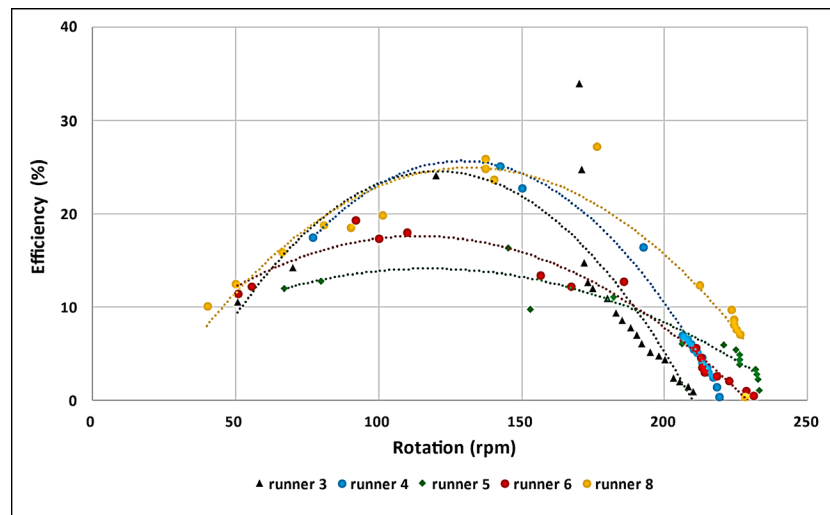
### 3.1.2 Turbine Performance with Half-Submerged Blades in the Outlet Hole

The second test involved placing half of the turbine runner submerged in the outlet hole. With a water discharge of 3 l/s, the water level at the inlet was measured at 14.5 cm. The results of the second test are shown in Fig. 5. From this second test, the maximum rotation of the five types of vortex turbine runners is slightly greater than the previous test, which is around 219-233 rpm. The maximum torque of this test is obtained when the vortex turbine uses 4 blades which is 10.8 Ncm. This is greater when compared to using 3 blades with a torque of 8.6

Ncm, 5 blades with a torque of 7.5 Ncm, 6 blades with a torque of 9.6 Ncm, and 8 blades with a torque of 10.6 Ncm. As shown in Fig. 5(a), the maximum mechanical power generated by the vortex turbine when using blades 3, 4, and 5 tends to decrease. The maximum mechanical power will rise again when using 6 and 8 blades. This phenomenon is different from the previous test. There is a decrease in mechanical power from 1.444 W when using 3 blades to 1.071 W using 4 blades. In addition, a decrease in turbine mechanical power also occurs when using 5 blades, which is 0.700 W. The amount of mechanical power increases when using 6 blades and 8 blades, which is 0.828 W and 1.16 W.



(a)



(b)

**Fig. 5** Vortex turbine performance graph when the blade is half submerged in the outlet hole (a) Power; (b) Efficiency

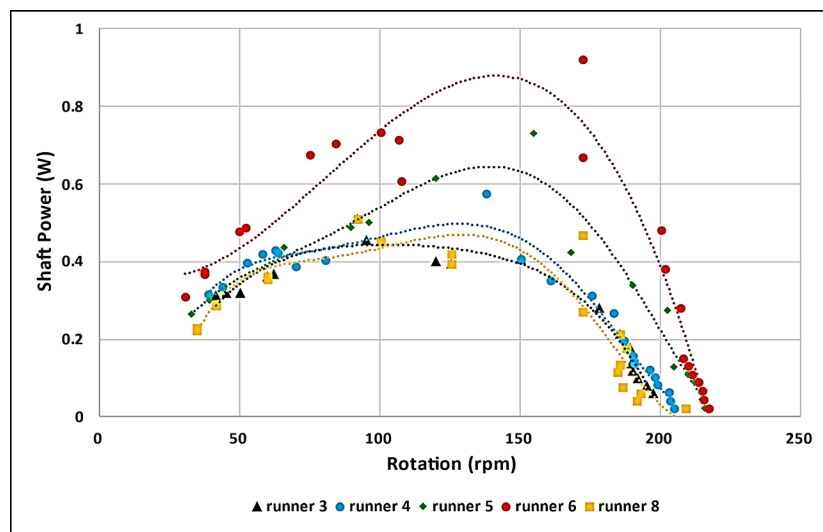
Subsequently, the mechanical power generated by the turbine when using 8 blades is almost the same as the mechanical power generated when using 3 blades. The maximum power generated by the vortex turbine for variations in the number of blades with half-dipped blades position at the outlet hole is 1.444 W using 3 blades. From Fig. 5(b), it can be seen that there is a decrease in efficiency in the 4 blades test which is 25.17% of the previous test using 3 blades. In addition, a decrease in efficiency also occurred in the test using 5 blades, the efficiency decreased quite drastically to 16.45%. This is the lowest efficiency produced by the turbine. While the increase in efficiency occurred when using 6 and 8 blades, which amounted to 19.46% and 27.26%. The maximum efficiency produced by the vortex turbine for variations in the number of blades with half-dipped blades position at the outlet hole is 33.93% by using 3 blades, with the resulting torque of 8.1 Ncm at 170.31 rpm.

Based on the results obtained from this second test, the mechanical power and efficiency were higher than in the first test. As is known that the vortex turbine will move in two directions, namely the tangential direction due to the push of incoming water hitting the turbine blade and the axial direction according to the direction of the exit of water from the outlet hole [35]. The vortex turbine blade with the runner position submerged halfway in

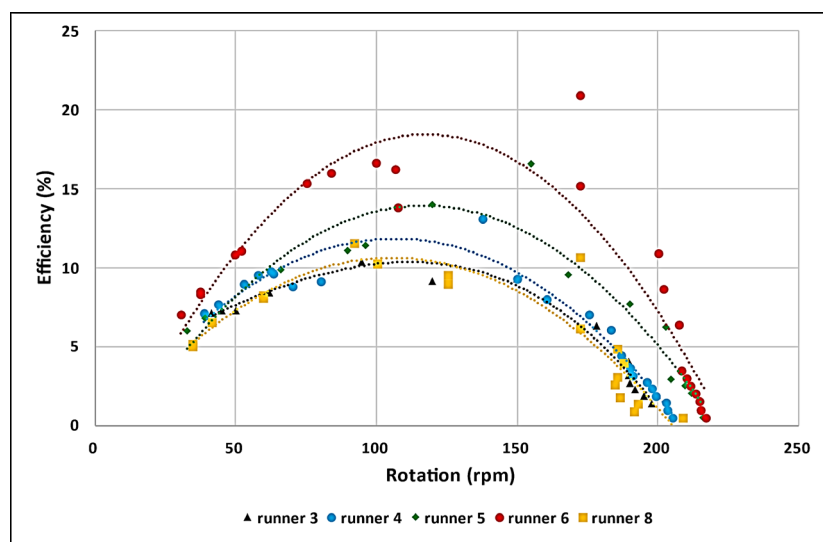
the outlet hole will maximize both directions of water flow. So that with this position in addition to utilizing the tangential force of water, the axial force of water occurring at the outlet hole of the basin is also utilized so that the power and efficiency of the vortex turbine becomes higher. The technique of placing half-submerged vortex turbine blades in the outlet hole is almost the same as using blades installed by forming an angle (oblique) where the water coming out axially through the outlet hole will also hit the blade and thus the axial velocity component will also play its role in rotating the blade. The shaft torque will increase when the blade is mounted at an angle [35].

### 3.1.3 Turbine Performance with Submerged Blades in the Outlet Hole

The third test was conducted with the top of the runner parallel to the basin floor. With a water discharge of 3 l/s, the water level was measured at 15 cm, which was higher than the two previous tests. Thus, the potential electrical power in this test was also slightly higher, at around 4.4 W. The test results are shown in Fig. 6. According to the results of this third test, the maximum rotation of the five different kinds of vortex turbine runners will rise to a certain point when the number of blades grows, and then fall when the number of blades is increased once again. In line with the turbine rotation, the maximum torque of the vortex turbine also increases as the number of blades increases to a certain point, and will decrease again when the number of blades is increased again. Runners with the number of blades 3, 4, 5, 6, and 8 have a rotation of about 202 rpm, 205 rpm, 216 rpm, 217 rpm, and 213 rpm, respectively. While the maximum torque produced by each type of runner is 7.4 Ncm, 8.4 Ncm, 9.2 Ncm, 9.9 Ncm, and 7.2 Ncm. From this it is known that the maximum rotation and torque are obtained on the runner with 6 blades.



(a)



(b)

**Fig. 6** Vortex turbine performance graph when the blade is submerged in the outlet hole (a) Power; (b) Efficiency

As seen in Fig. 6(a) where the number of blades affects the rotation and mechanical power of the vortex turbine. In the position of the runner submerged in the outlet hole, the more the number of blades used, the more the blade area will be in contact with water so that the turbine rotation speed will increase. Experimentally, the results of this third test are in line with the research of Del Rio et al. [29] where if the number of turbine blades increases to a certain point, the power that the turbine can extract will likewise increase; if the number of blades increases still more, the power will begin to decline. However, the more blades the heavier it will be, which also has a negative impact on the turbine's angular velocity ( $\omega$ ) which decreases [2]. At the maximum point of each vortex turbine blade number, turbine rotation and load torque are directly proportional to mechanical power. In this test, the maximum turbine mechanical power generated when using 3, 4, 5, and 6 blades is 0.511 W, 0.577 W, 0.729 W, and 0.920 W, respectively. The maximum power is obtained when each turbine rotation is 92.12 rpm, 137.8 rpm, 154.84 rpm, and 172.44 rpm. When the blade is added to 8 pieces, there is a significant decrease in the maximum power of the turbine which is 0.511 W at 92.12 rpm. The maximum power generated by the vortex turbine when the blade is immersed in the outlet hole is 0.920 W using 6 blades.

From Fig. 6(b) it can be seen that the maximum efficiency value of each number of blades of the vortex turbine tends to increase along with the increase in the number of blades and will fall back when the number of blades continues to be added. This is also in line with the research of Del Rio et al. [29]. The efficiency produced by turbines using 4, 5, 6, 7, and 8 blades is 11.61%, 13.11%, 16.57%, 20.91%, and 11.61%, respectively. The lowest efficiency produced by the vortex turbine is 11.61% with 3 and 8 blades, while the largest maximum efficiency produced by the vortex turbine for variations in the position of the blades immersed in the outlet hole is 20.91% by using 6 blades at a turbine rotation of 172.44 rpm and a torque of 5.1 Ncm. Based on the results obtained, there are similarities with previous research by Sritram & Suntivarakorn [15]. The research was conducted to determine the water flow pattern when hitting the vortex turbine blade. From the test results, it was found that the torque value increased when the number of blades increased from 2 to 5. The surface area of the blade in contact with water becomes larger, resulting in a higher torque. However, when the blades used increase to 6 or 7, the distance between the blades becomes smaller, and this reduces the impact of water flow on the blades so that the torque decreases [15].

### 3.1.4 Maximum Efficiency Produced by the Turbine

Furthermore, the highest efficiency obtained from the three runner positions of the vortex turbine is compared and made in one graph to facilitate the analysis as shown in Fig. 7. As shown in the Fig. 7, among the three installation positions of the turbine blades, the highest efficiency is achieved when the runner is installed half submerged in the outlet hole. The efficiency value of 33.93% was obtained using 3 blades with a mechanical power of 1,444 W. Furthermore, the second highest efficiency was obtained when the runner was positioned submerged in the outlet hole at 20.91% with a mechanical power of 0.920 W when using 6 blades. Meanwhile, the smallest maximum efficiency was obtained when the runner was installed above the outlet hole with an efficiency of 17.05%, power of 0.725 W, using 5 blades. In the three runner positions, the highest efficiency of each runner position is obtained when the turbine rotation is around 150-170 rpm and this is the optimal rotation point of the designed vortex turbine.

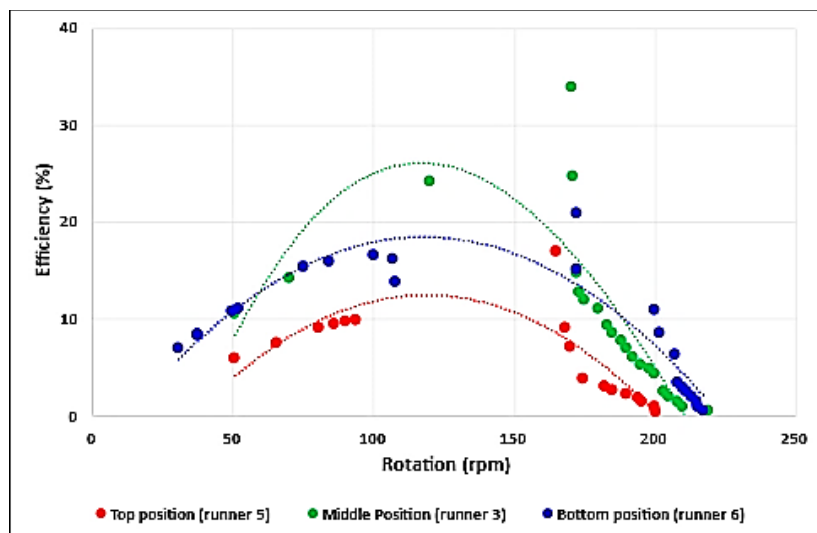


Fig. 7 Graph of maximum efficiency for turbine rotation in all positions

The highest turbine rotation is obtained when the blade is installed half submerged in the outlet hole. In this condition, the turbine with the blade surface experiences greater water momentum, resulting in greater mechanical power and efficiency. The mechanical power generated is directly proportional to the efficiency of the turbine, where with increasing power, the efficiency of the vortex turbine also increases. From the vortex turbine test, the largest efficiency value of 33.96% was obtained. This is greater than research conducted by several previous researchers who also used flat and curved type runners such as Power et al. [2], Saleem et al. [35], and Guzmán et al. [33]. However, some studies have also resulted in greater vortex turbine efficiency such as those conducted by Rahman et al. [4] and Shabara et al. [5] with a maximum efficiency of 42.1% and 42%.

### 3.2 CFD Validation

To validate the results obtained from the experiment, ANSYS CFX CFD simulation was conducted. Due to the different characteristics of vortex turbines compared to other types of turbines, laboratory testing was conducted first in this study to determine the actual rotation of the vortex turbine. Next, in this CFD simulation, the turbine rotation was adjusted to the rotation at the maximum efficiency point during the experimental testing, with the same discharge of 3 l/s. The CFD simulation results in the form of a graph of the number of blades vs. efficiency are shown in Fig. 8. The CFD results produce an efficiency trend that is almost the same as the test where the highest efficiency is obtained when the runner is installed half submerged in the outlet hole. The curve line when the runner is installed above the outlet hole is the same as the runner installed submerged in the outlet hole, which is in the form of an inverted parabola. While when the runner is installed in a half-submerged position in the outlet hole, the curve is parabolic. The average difference in efficiency from CFD and experimental results at the position of the runner installed above, half submerged, and submerged in the outlet hole is 4.20%, 9.89%, and 3.99%, respectively. In some tests, the efficiency of the CFD-generated vortex turbine is relatively similar where the difference is only less than 1%, so the difference between CFD and experimental results is still acceptable.

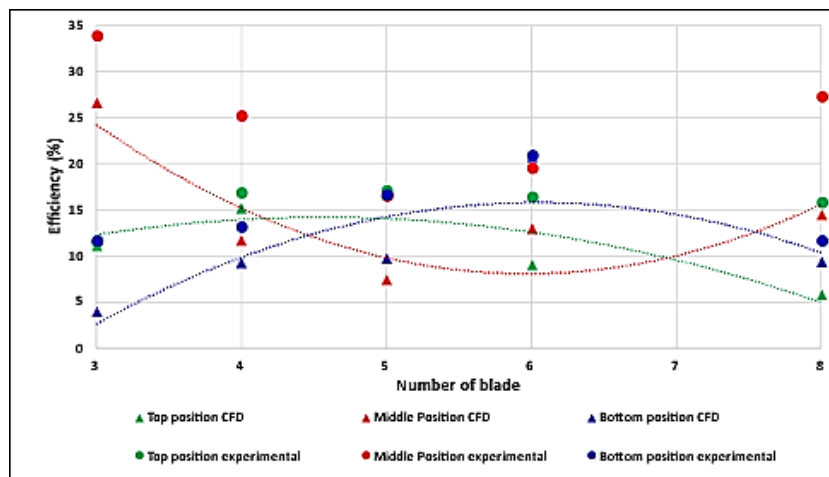


Fig. 8 Comparison of vortex turbine efficiency: Experimental and CFD

The comparison of water surface heights occurring in basins with various runner positions is shown in Fig. 9, while Fig. 10 shows the water volume fraction contours on the (y,z) plane at the centre of the basin circle. From Fig. 9, it can be seen that the water level that occurs in the basin when the turbine runner is installed at the top of the outlet hole is almost the same as the runner submerged in the outlet hole. This is in line with the experimental results where the maximum turbine rotation of the two positions is relatively almost the same, which is around 201-217 rpm. This condition is slightly different when the runner is installed half submerged in the outlet hole. In this position the water level that occurs is slightly higher and also the maximum turbine rotation is also higher, which is around 219-233 rpm. The height of the vortex formed in the basin chamber when the runner is installed half submerged in the outlet hole also increases.

As can be seen in Fig. 10, based on the CFD simulation results, the vortex formed is uneven but quite stable. The air core vortex clearly displays the boundary between the water and air regions. Around the runner near the inlet side, the water is more filled than the opposite side. Likewise, at the beginning of the outlet hole, the side near the inlet is more filled with water. This is because the shape of the basin used is cylindrical so that water fills more in the space near the inlet side. However, the water flow that occurs in the basin towards the outlet flows quite well / smoothly.

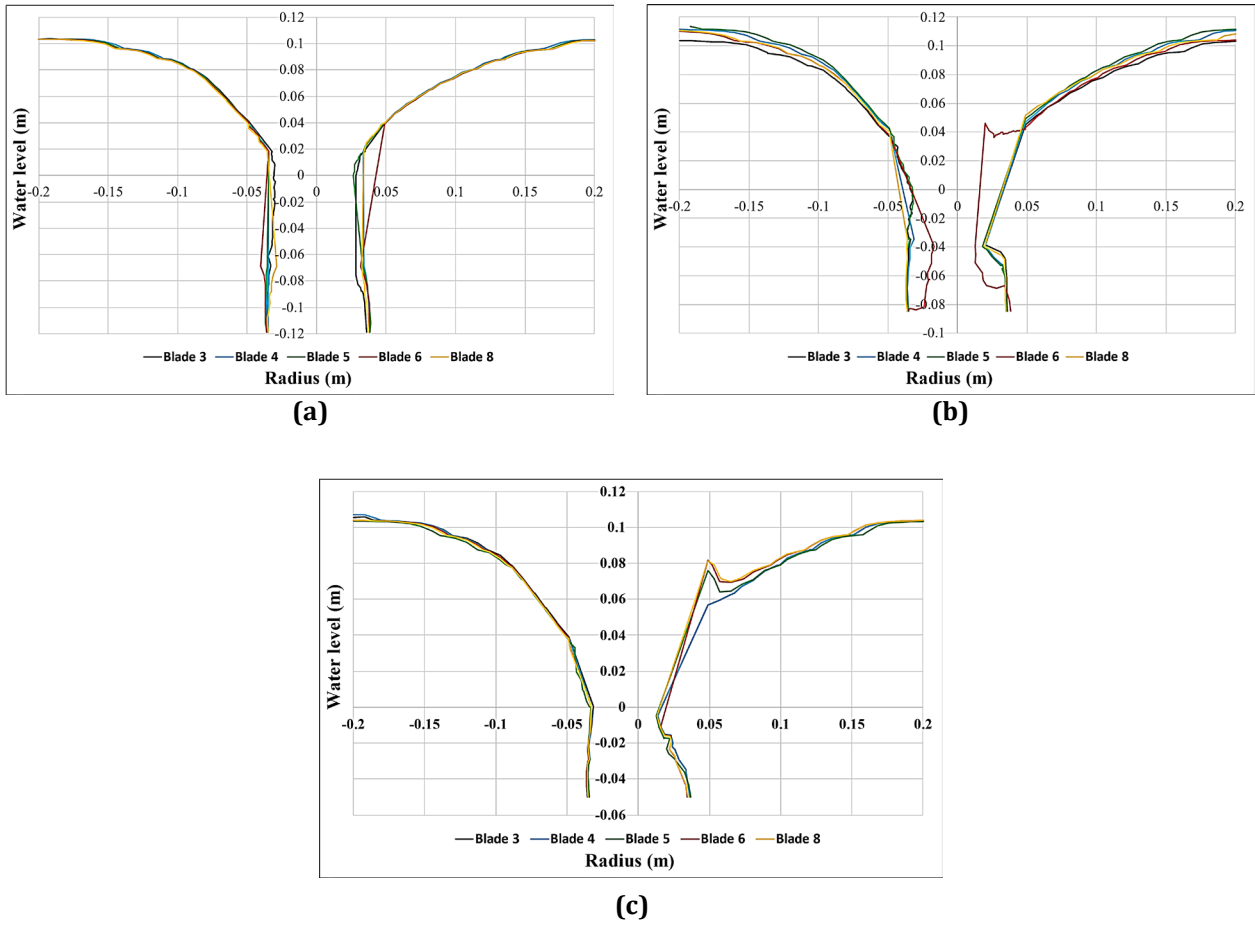


Fig. 9 Comparison of water surface height at various runner positions (a) Bottom; (b) Centre; (b) Top

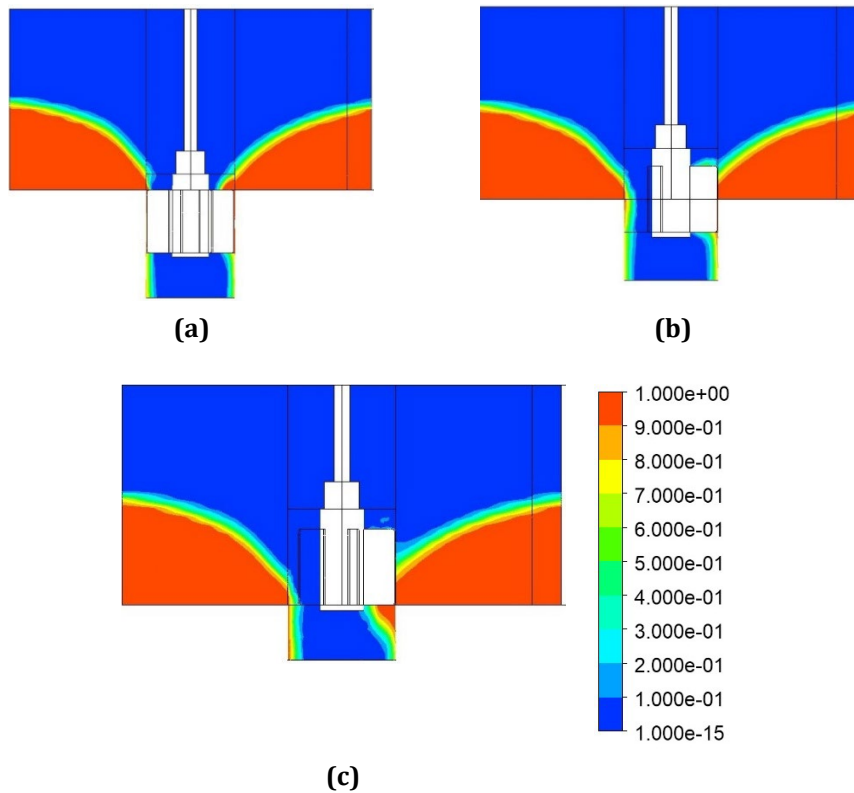


Fig. 10 Water volume fraction in the (y,z) plane (a) Bottom; (b) Centre; (b) Top

#### 4. Conclusions

In this study, vortex turbine testing has been carried out to determine the effect of the number of blades and variations in their placement position on the mechanical power and efficiency produced. The runner used is a flat type with a width of 30 mm, height of 65 mm, inner diameter of 40 mm, and outer diameter of 100 mm. This test is based on the experimental method. From the test results, it can be concluded that the maximum mechanical power and efficiency are produced by using three blades in the testing position half submerged in the outlet hole. The maximum mechanical power generated was 1.444 W, and the maximum efficiency was 33.93% at a turbine rotation of 170.31 rpm and a torque of 8.1 Ncm. For all types of blades 3, 4, 5, 6, and 8, the position of the runner half submerged in the outlet hole produces the greatest average value of efficiency which is around 24.5%. Meanwhile, the other two positions, where the runner is above the outlet hole and completely submerged in the outlet hole, have almost the same average efficiency of around 14.7%. These test results have been validated with CFD where the results are relatively similar to the test. With an average efficiency difference of about 6%, the CFD and experimental results are acceptable. From this test it can be concluded that to produce the highest power and efficiency of the vortex turbine with flat and basin type cylindrical blades, the runner must be installed in a position half in the outlet hole.

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#### Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

#### Author Contribution

*The authors confirm contribution to the paper as follows: **Effect of the Number of Blades and Variations in Position of Straight Blades on Vortex Turbine Efficiency**: Ridwan Arief Subekti: **Conceptualization, methodology, formal analysis, writing—original draft**; Fazila Mohd-Zawawi: **supervision, resources, validation**; Kamarulafizam Ismail: **supervision, resources, validation**; Setia Subekti: **formal analysis, writing—review and editing**; Mukhtar Effendi: **formal analysis, validation**; Anjar Susatyo: **methodology, formal analysis**; Ahmad Fudholi: **supervision, writing—review and editing**. All authors have read and agreed to the published version of the manuscript.*

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