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Optimal Design of Guide Vane for Improving Mini Hydro Power Plant Efficiency by using Twin Axis Vertical Turbine

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ABSTRACT

This research aimed to increase the efficiency of a pico-hydropower plant with Banki type turbines by installing a guide vane system as the inlet water control. It was observed that the inlet angle of attack and the number of turbine blades had affected the efficiency of the pico-hydropower plant. Moreover, a computational fluid dynamics (CFD) simulation was conducted for validation by creating a guide vane with inlet angles of 5 to 30 degrees and a turbine with 15–40 blades. The turbulent model in the SOLIDWORKS Simulation was selected as the fluid dynamic model. The simulation results statistically showed that the inlet angle of attack had a greater influence on the torque than the number of blades, with P-values of 1.1893x10-7 and 0.3915, respectively. The efficiency investigation using a 25-blade turbine with inlet angles of attack of 5, 10, 15, 20, 24, and 30 degrees, showed that the turbine with the 24-degree inlet angle of attack had exhibited the highest system efficiency at 45.83%. This research focused on vertical axis Banki turbine, which has been designed for electrical generation in irrigational canal only. In the practical demonstration, a 3-kW electrical generator system was installed across the canal, and the system efficiency was also investigated. The results showed that the maximum system efficiency was at 48% with a 0.7 m system head and a flow rate of 0.4 m3/s. This represents results which were higher than predicted from the simulation at 45.83% and a greater performance than that of the generating system without a guide vane at 34.96%.

1. INTRODUCTION

In countries where there are waterfalls and small rivers, micro hydropower plants can be used to harness hydro energy from these water systems. Micro hydropower (MHP) plants can be applied to small water resources to generate and deliver electricity to villages far from electrical transmission lines. MHP is an electrical generating system that is suitable for use in remote areas. The advantage is small and low-cost system while comparing to large electrical generating system. In addition, this system can be connected to a mini-grid system for on a grid system. MHP has been increasingly promoted for use in developing countries due to its low cost of production and environmental friendliness. MHP plants have power generation capacities that do not exceed 100 kW. Since it is a low-head electrical generating system, it has been designed to work in water head lower than 10 m. [1]. Therefore, selecting the appropriate turbines for the head level and water flow rate plays an important role in providing highly efficient power generation and can consequently lower production costs. Compared to other type of turbines, the Banki turbine, also called cross flows turbine, can be perfectly used with a low head system. Moreover, it is the turbine that can operate at lower head and flow rates [2]. Selecting a suitable type of turbine and properly installing it are essential factors that can yield a highly efficient power plant. It is also found that the cross-flow turbines are suitable for medium to low head water. The water head should be less than 15 m, for which the given average turbine efficiency would be 77% [1]. A pico-hydropower plant has a capacity of less than 5 kW [9]. Moreover, it was also found that Kaplan Propeller Francis and cross-flow are the turbine that appropriate for the resource with head less than 10 m. [1]. It is also found that cross-flow turbine is more simple design and construction than Kaplan Propeller and Francis [3]. Moreover, a cross flow turbine has low construction costs due to its simple production technology. However, various design factors, such as the inlet angle of attack and the number of blades, need to be considered when designing for use with a low water head. In a study examining a cross flow turbine with 15 to 40 blades set with an inlet angle of attack between 15 and 32 degrees and using a single turbine installed horizontally at a low water head of 5-10 m, the average turbine efficiency was observed to be 75.4% [4]-[9]. In addition, there are highest turbine efficiency of 88% was obtained when the inlet angle of attack was set to 24 degrees for a 25-blade

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turbine with a diameter ratio of 0.68 [10]. Moreover, attempts have been made to make it possible for the Banki turbine to function in water sources that have relatively low head levels, such as canals, irrigation ditches, and factory water pipe systems. In all of these systems, the low head level had been slightly less than 3 m. Although in such cases, the water head level is low, the flow rate of water through the system had remained high because of the high energy input. In addition, attempts to apply this method to water sources less than 3 m have been limited to a maximum turbine efficiency of 40-55% [11]-[14].

However, it has been found that a very low head power generation system is currently being developed with a head level of between 0.5-6 meters, with a turbine that has an efficiency of between 75-90%. However, it requires a high flow rate of water between 0.2 – 30 m^3/s. Some examples are an Archimedes screw, an overshot wheel, a breastshot wheel, an undershot wheel, a low head Kaplan, and a low head Francis. [15]. Moreover, for the cross-flow turbine with a 26-blade horizontal twin axis turbine, the results indicated that the turbine's coefficient of power (Cp) had been different because the horizontal installation had caused the retrieval of different kinetic energy levels on the upper and lower turbines. This was a result of the different revolution speeds of the twin turbines and different Cp values, which contributed to the drawbacks caused by the unequal speeds of the two turbines that were observed in the twin-horizontal cross-flow turbine system [16]. Moreover, the design of a 20-blade crossflow turbine, which had been installed in a factory pipe system in a factory with a vertical axis and an inlet angle of attack of 24 degrees, was similarly examined. The maximum turbine efficiency was rated at 42.4%, while the tip speed ratio (TSR) was 0.70 [17]. From the disadvantages, a comparative study was conducted to determine the capacity of vertical cross-flow turbines in which both single and dual turbines had been vertically installed. Both turbines had equal configurations with 25 blades, a 24-degree inlet angle of attack, and a diameter ratio of 0.68. The turbines were tested in an irrigation canal at low head levels of 0.8 m. The system efficiencies for the single vertical axis turbine and twin vertical axis turbines were rated at 21.13% and 32.36%, respectively [18]. Figure 1 shows the pico-hydropower plant with a vertical axis hydro turbine that is applicable for low headwater sources. The twin vertical axis turbines were found to be highly capable of activating the flow in the canal and have been widely deployed for commercial purposes. It was revealed that a 1.5 kW hydropower plant with 25 blades had provided an average turbine efficiency of 54.6%, while the system efficiency averaged at 34.96% [19]. However, this experiment was observed to have one weakness: the inlet nozzle of the turbine was not set at the proper angle. If this weakness were to be corrected, both the electricity production capacity and system efficiency could be increased. More recent studies and experiments have explored the operation of vertical twin axis turbines with a controlled inlet angle of attack and a set number of turbine blades. The results were discussed and were compared with the findings obtained from the horizontal single-axis experiment. The evidence indicates that the installation of vertical twin axis turbines in low headwater sources can be challenging due to differences in the volume flow rates, which directly affect the torque and capacity of electricity production.

To increase the efficiency of the vertical axis twin turbines, this article is focused on: 1) designing a guide vane and determining its effects on the proper control of the inlet angle of attack and 2) determining the number of turbine blades, which would be the most appropriate for the installation of a vertical twin axes turbine. Moreover, a computational fluid dynamics (CFD) model was also employed to determine the optimum angle of inlet attack and the proper number of blades to be used in the vertical twin axis turbine for a low water head.

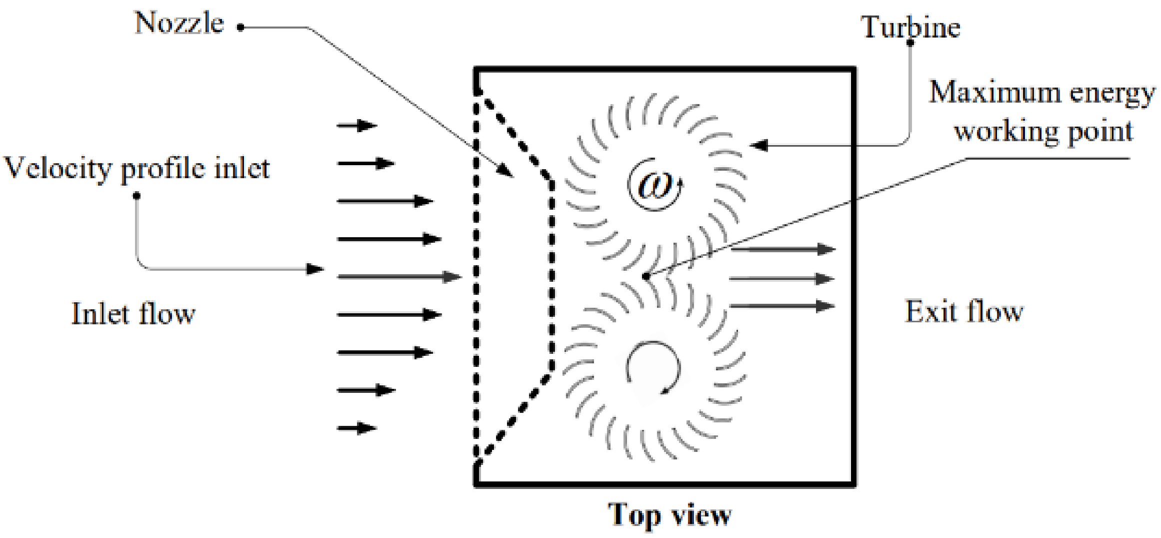


Fig. 1. The installation of the twin axes vertical turbine [21].

2. MATERIALS AND METHODS

To study and design cross-flow turbines for optimum usage in low head systems, the components and characteristics of the turbine that are needed to produce maximum performance must be carefully considered. The cross flow turbine's performance can be described as follows.

2.1 The Efficiency of the Cross-flow Turbine

The theoretical turbine power output is based on the correlation of the flow rate with the absolute velocity that flows into the turbine with the inlet angle of attack [3], as presented in Equation 1:

$$P_{output} = \rho Q u_1 \left(V_1 \cos\alpha_1 - u_1\right)\left(1+\psi\right) \tag{1}$$

in which Q is the water discharge, m^3/s; V_1 is the peripheral velocity of the turbine, m/s; u_1 is the inlet velocity of the fluid, m/s; α_1 is the inlet angle of attack with the unit of degrees; and ψ is the reduction parameter value of 0.98 [3].

The power input of the inlet can be obtained from Equation 2:

$$P_{input} = \frac{\rho Q V_1^2}{2C_d^2} \tag{2}$$

in which C_d is the reduction parameter value of 0.98 [3]. The torque $\left(T_{turbine}\right)$ can be calculated from Equation 3:

$$T_{turbine} = \frac{P_{output}}{\omega} \tag{3}$$

The ω is the angular velocity of the turbine, which can be obtained from Equation 4:

$$\omega = \frac{2\pi N}{60} \tag{4}$$

in which N is the speed of the turbine in rpm. The turbine efficiency is the ratio between the power output (Equation 1) and the power input (Equation 2). The turbine efficiency can be obtained from Equation 5:

$$\eta_{turbine} = \frac{V_1\left(u_1 \cos\alpha_1 - V_1\right)\left(1+\psi\right)}{\left(u_1^2 \big/ 2C_d^2\right)} \tag{5}$$

As previously described, the effects of this factor on the efficiency of the cross-flow turbine are composed of the inlet velocity and the inlet angle of attack, as shown in Equation 5. The effect also depends on the design characteristics of the turbine, which are described in the next subsection. The system efficiency of the experiment is the ratio between the power output and the power input, which can be obtained from Equation 6.

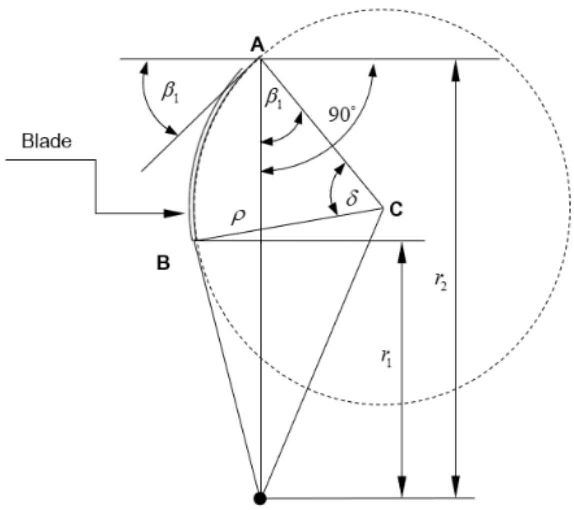


Fig. 2. The components of a cross flow turbine.

2.2 The Cross-flow Turbine Design

The characteristics of the blade are shown in Figure 2, which can be used in a cross-flow turbine and in which the inlet blade angle [6] can be calculated based on Equation 6.

$$\beta_1 = \tan^{-1}\left(2\tan\alpha_1\right) \tag{6}$$

The curvature of the blade was calculated from Equation 7:

$$\rho = \left(\left(r_1^2 - r_2^2\right) \big/ \left(2r_1 \cos\beta_1\right)\right) \tag{7}$$

The central angle was calculated from Equation 8:

$$\delta = 2\left(\tan^{-1}\left(\frac{\cos\beta_1}{\left(\sin\beta_1 + \left(r_2/r_1\right)\right)}\right)\right) \tag{8}$$

in which $r_{1,2}$ is the internal and external radius of the turbine, m. The diameter ratio is the ratio of the internal diameter and the external diameter of the turbine. Likewise, the inlet angle of the attack started from 22-32 degrees with steps of 2 degrees, and the proper diameter ratio with a value of 0.68 was proposed. It was found that maximum efficiency could be obtained with an inlet angle of attack equal to 24 degrees [10]. In addition, it was found that there was a design equation for a guide vane. These guide vanes were able to provide the optimum angle of attack for the turbine. In addition, it was found that there had been a design equation for the guide vanes and that these guide vanes had been able to provide the optimum angle of attack for the turbine [20].

2.3 Guide Vane Design

The purpose of the guide vane is to assist in providing greater optimal control of the inlet angle of attack which can be designed in the following manner [20].

It was discovered that the radius of the guide vanes would change in accordance with the angle of the nozzle (BOC), as shown in Figure 3 (a). Moreover, it was discovered that the radius could be calculated by using the following correlated Equations (9)-(12):

$$r(\theta) = K\theta + r_1 \tag{9}$$

in which $r(\theta)$ is the upper wall radius and K is a constant. The following was determined from Equation 10:

$$K = \frac{1}{\lambda - \gamma}\left(\frac{S_0 \cos\alpha_1 + r_1}{\cos\gamma} - r_1\right) \tag{10}$$

in which λ is the inlet discharge angle (degrees). When considering Figure 3 is (a) and (b), the rectangular AOD was referred to and was determined using the Equation 11:

$$\gamma = \tan^{-1}\frac{S_0 \sin\alpha_1}{S_0 \cos\alpha_1 + r_1} \tag{11}$$

The height of the nozzle (S_0) was derived from the Equation 12:

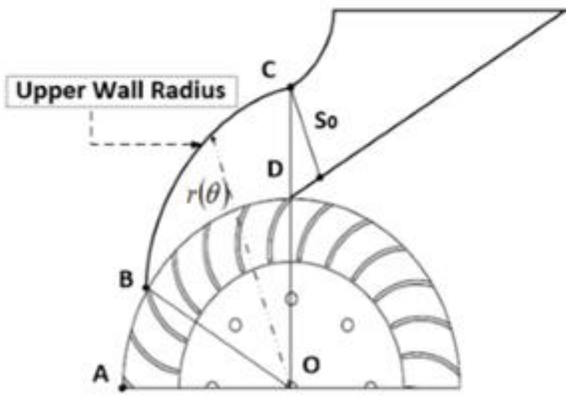
$$S_0 = \lambda(r_1 \sin\alpha_1) \tag{12}$$

2.4 The Vertical Axis Twin-Turbine Model and Numerical Method

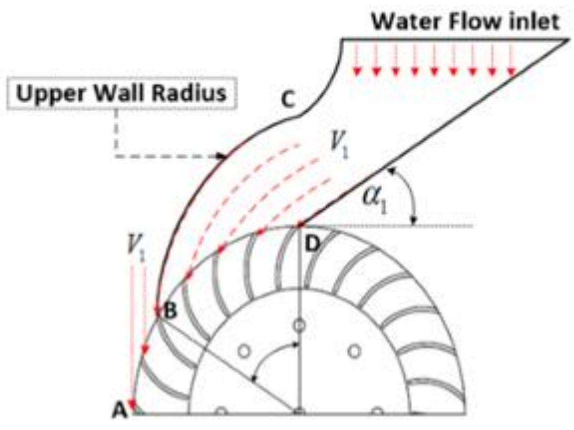
The mathematical model that corresponded to the experiment was very important for flow simulations in order to produce correct and confident outputs. The appropriate and correct design of the cross-flow turbine makes the flow simulation more dependable.

2.4.1 The model

This research aimed at creating a pico-hydropower plant that could be placed in a water distribution canal that measured 2.5 m wide and 1.8 m deep. This system produced a maximum electrical power of 3.0 kW. With the open flow of the water in the targeted canal, it was necessary to install flow barriers that would reduce the impact of the flow. These barriers were designed to have two inlet channels, nozzles, and venturi. A guide vane was attached to the edge of the barrier to control the inlet angle of attack at the desired degree, as illustrated in Figure 4.



(a)



(b)

Fig. 3. (a) The turbine's curvature to obtain hydropower; and (b) The inlet profile into the blades after the installation of the nozzle curvature.

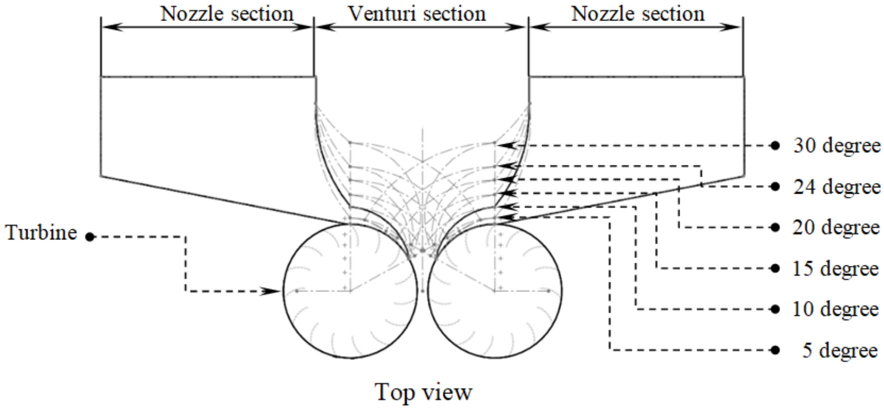


Fig. 4. The model of the vertical twin axis turbine.

The latter process involved the creation of a turbine model with a defined inlet angle of attack and a defined number of blades. Accordingly, this research created a total of 36 models to study the impact of the inlet angles of attack at 5, 10, 15, 20, 24, and 30 degrees and to test the impact of turbines with 10, 15, 20, 25, 30, 35, and 40 blades, as shown in Table 1. These conditions were employed to study the effects of torque by using a fluid simulations program.

The Computational Fluid Dynamics method (CFD) has been widely used to investigate the performance and behaviors of hydro turbines and other fluid mechanisms [21]-[26]. Moreover, the SOLIDWORKS Simulation is another reliable and conventional device that can be used to study fluid flow behaviors [24]. For incompressible isothermal flow investigations, the fluid flow behaviors can be explained by using the continuity equation and the momentum equation. Furthermore, it was found that the turbulence model had been a crucial factor when investigating flows that were highly turbulent. The turbulence model type was $k-\varepsilon$ and damping functions, which were proposed by Lam and Bremhorst [27] describe the laminar, turbulent, and transitional flows of homogeneous fluids involving turbulence conservation laws.

2.4.2 Grid independence

The proper number of elements can be obtained by comparing the torque deviations which were observed in the simulation results. Figure 5 shows the element independence test with four cases of investigations. The process began by creating a model and by allocating a greater number of elements to the model. The purpose was to test the levels of torque from the time when they differed greatly until the time when their values came closer to one another.

In this test, an increase of 200,000 elements at each time was investigated in order to analyze the changes in torque and the optimum numbers of elements. The range of tested elements was between 200,000 (dx=4.57 mm., dy=4.67 mm., and dz=3.07 mm.) and 2,000,000 elements (dx=3.97 mm., dy=3.82 mm., and dz=2.64 mm.). It was found that changes in the torque had been inconstant, and the highest differences had been at 200,000 – 1,400,000 elements. To further this element range, the changes in the torque had been constant and had decreased at an average of 0.0149% for 1,600,000 - 2,000,000 elements. Therefore, the optimal model should be at 1,600,000 elements because it represents the least change in the torque and in the initial constant torque as shown in Figure 5.

In an incompressible isothermal flow investigation, the fluid dynamics can be explained by using the continuity equation and the momentum equation. Furthermore, when investigating the highly turbulent fluid, it was found that the turbulence model had been a crucial factor. The correct selection of a turbulence model that is suitable for the boundary conditions and the flow characteristics should help to increase the reliability of the results.

Table 1. The investigation of the turbines based on the divisions of six characteristic groups.

Number of Blades	Inlet angle of attack (degrees)
15	5-10-15-20-24-30
20	5-10-15-20-24-30
25	5-10-15-20-24-30
30	5-10-15-20-24-30
35	5-10-15-20-24-30
40	5-10-15-20-24-30

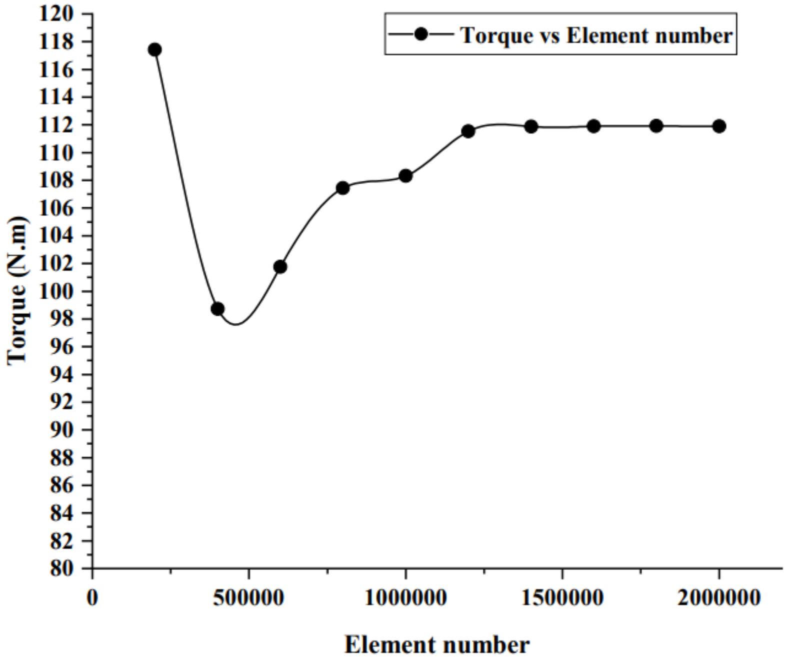


Fig. 5. The results of the grid independence test.

2.4.3 The boundary conditions

To investigate the torque that was being generated in the turbine during the processes of the fluid simulation, it was important to allocate the boundary conditions exhibited the factors of the experiment. In this research, the boundary conditions had the following features: 1) the volume flow rate was 0.4 m^3/s, 2) the turbine speed was 120 rpm (fixed rotor condition), 3) the pressure outlet was set equal to the atmospheric pressure, 4) the model wall was symmetrical, and 5) the water properties were fluid. It was hypothesized that the torque powers would be different. This hypothesis was based on the fact that the kinetic power of water differs based on the different numbers of blades and the different inlet angles. The water jet attacked the turbine with an inlet angle of attack, which caused the blades to spin at an angular velocity and then generate the turbine's torque output and power output as illustrated in Figure 6.

These factors were allocated in the SOLIDWORKS Flow Simulation program to obtain the torque generated from the different conditions. However, the confidence of the simulation had to be validated. The comparison between the simulated results and the experimental results is addressed in the next subsection, which focuses on validation.

2.4.4 Validation

To validate the result, the power output generated from the simulation program was compared with the power output obtained from the experiment [18]. As a trial, a pico-hydropower plant was installed across an irrigation canal with a low head of 0-0.80 m. The power output, which was recorded for the different system heads, is reported in Table 2. The boundary conditions were allocated during the validation, while the rotational velocity of the turbine (rpm) was changeable according to the head.

After the flow inlet was set, other factors influencing the power output were then adjusted. It was shown that during validation that the amounts of electricity, which had been produced in the experiment and the simulation, were more likely to increase when the low head level was higher. Therefore, the average prediction error was 3.28%. In this way, the fluid flow simulation was studied. The output results were taken as the designated conditions for constructing the turbine and for comparing the tests with the turbine without a guide vane.

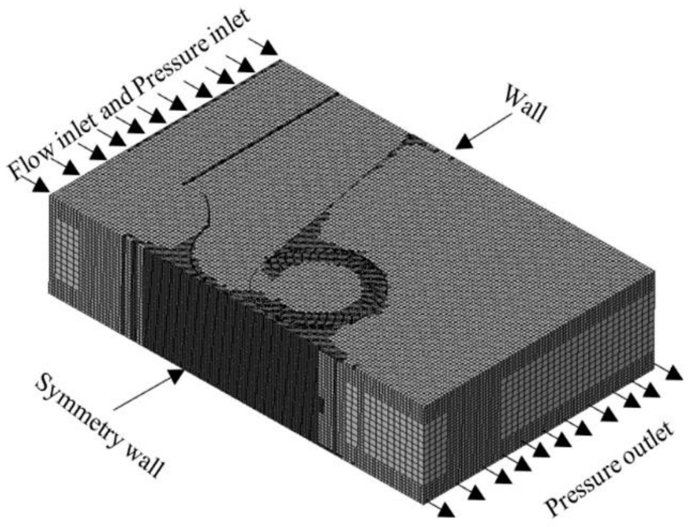


Fig. 6. The allocation of the boundary conditions in the vertical twin axis turbine model.

Table 2. A comparison of the torques obtained from the experiment and the flow simulation.

Head (m.)	Power output (W)		Error (%)
	(Experiment)	(Simulation)	
0.25	48.00	45.65	4.90
0.30	92.25	97.82	6.04
0.40	158.90	163.97	3.19
0.50	214.60	221.49	3.21
0.60	288.75	298.65	3.43
0.70	393.00	404.19	2.85
0.80	570.00	584.73	2.58

3. EXPERIMENTAL FACILITIES AND TEST DESCRIPTIONS

The results from the flow simulation indicated that the 25-blade turbine with an inlet angle of attack of 24 degrees had demonstrated the highest system efficiency. Other related factors from this experiment were used to assist in designing the turbine by observing the computations from Equations (6)-(8) with regard to the following: an inlet blade angle of 41.68 degrees, an inner diameter of 0.34 meters, blade curvatures of 0.088 meters, and a central angle of 58.08 degrees. Based on these specifications, the turbines together with their holding structures and an electricity generator system were generated. To test the system efficiency, data was collected on the following related factors: the input energy and the output energy. The factors, which were related to the input energy were the system head and volume flow rate inlet.

The measurement of the volume flow rate was performed using a probe meter (range 0.1-6.1 m/s, accuracy 0.1 m/s), as shown in Figure 7(a) which was employed to gauge the average velocity inlet at the point of entry. In order to specify the input energy and output energy of the system, data on the volume flow rate inlet and the system head was then collected. A screen was developed to provide a real-time display of the current and voltage produced by the mini-hydropower plant, as shown in Figure 7(b).

3.1 Installation and Experiment

The pico-hydropower plant was designed to be installed across an irrigation canal, which causes a rise in the head level and the accumulation of potential energy in the system. The system head was found by determining the differences in the water levels at the front and in the rear of the system, as shown in Figure 8.

The turbine was designed with three flow inlet chambers. The influx of the water was directed into the nozzle section and venturi section, as presented in Figure 4. As the water velocity was increased, higher levels of kinetic energy were generated when the fluid passed into the nozzle and the venturi. The kinetic energy was transferred to the turbine and was then transformed into mechanical energy, which was utilized in the generator to produce electricity. The electricity produced by the system was used with a lightning device, with a maximum load of 3 kW.

The output current and voltage were displayed on a digital screen. Data was collected on the system head, the flow rate, and the current and voltage produced by the system from a head level of 0-0.7 m. This collected data was analyzed so that the system efficiency could be determined.

(a)

(b)

Fig. 7. (a) the inlet velocity test tool; and (b) the current and voltage control and measurement panel.

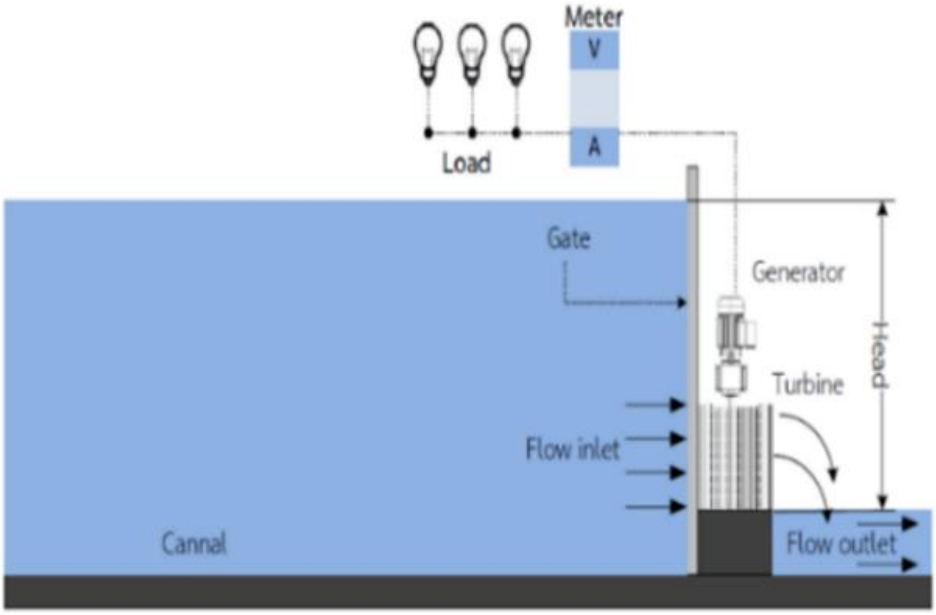


Fig. 8. The installation of a cross-flow hydropower plant with twin axes vertical turbine.

4. RESULTS

4.1 Statistical Analysis

The analysis of variance (ANOVA) was used to investigate the effects of the inlet angles of attack and the number of blades. It was found that the inlet angle of attack (P-value=1.1893x10-7) had a greater effect on the torque value than the number of blades (P-value=0.3915), as shown in Table 3. Since the blades used in this study were 2.5 mm thick, increasing the number of blades decreased the cross-section area of flow. As a result, the water flow was directly changed. However, in this study the number of blades may be too small (15-40 blades). Therefore, the effect on torque was found to be less than the influence of the inlet angle of attack. In the future, if the number of turbine blades is more than 40, it may have a greater effect on the torque than the inlet angle of attack. Next, the characteristic of torque was studied by using a computer simulation, with an inlet angle ranging between 5 and 30 degrees.

4.2 Simulation Results

Figure 9 shows a correlation between the torque and the inlet angle of attack of the turbines with 15- 40 blades. It was noted that the torque value had become relatively small as the inlet angle of attack increased. The lowest torque was observed at an inlet angle of 24 degrees.

The 25-blades turbine had shown the highest torque when the inlet angles were 5, 10, 15, 20, 24, and 30 degrees, and the output torque for each angle was as follows: 195.00, 153.72, 128.14, 114.72, 106.27, and 115.73 Nm., respectively. The simulation results found that after a guide vane had been installed to control the inlet angle of attack, the average inlet water velocity was affected. The changed of torque was curved with a minimum torque value at an angle of 24 degrees. The torque was increased when the angle was 30 degrees. The results indicated that the maximum torque had occurred with 25 blades and that velocity had been the parameter that had most strongly affected the torque.

Table 3. The analysis of effects of the number of blades and the inlet angles of attack using ANOVA.

	Coefficients	Standard errors	t-stat	P-values
Intercept	161.9770	14.8884	10.8794	$1.8820\text{x}10^{-12}$
Number of blades	0.3861	0.4418	0.8682	0.3915
Inlet angle of attack	-2.9677	0.4484	6.7167	$1.1893\text{x}10^{-7}$

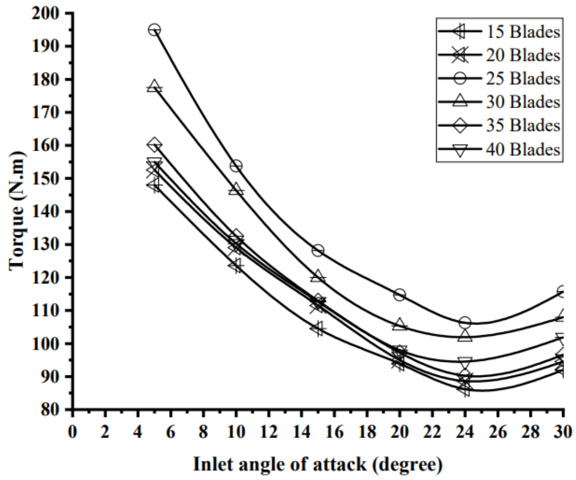
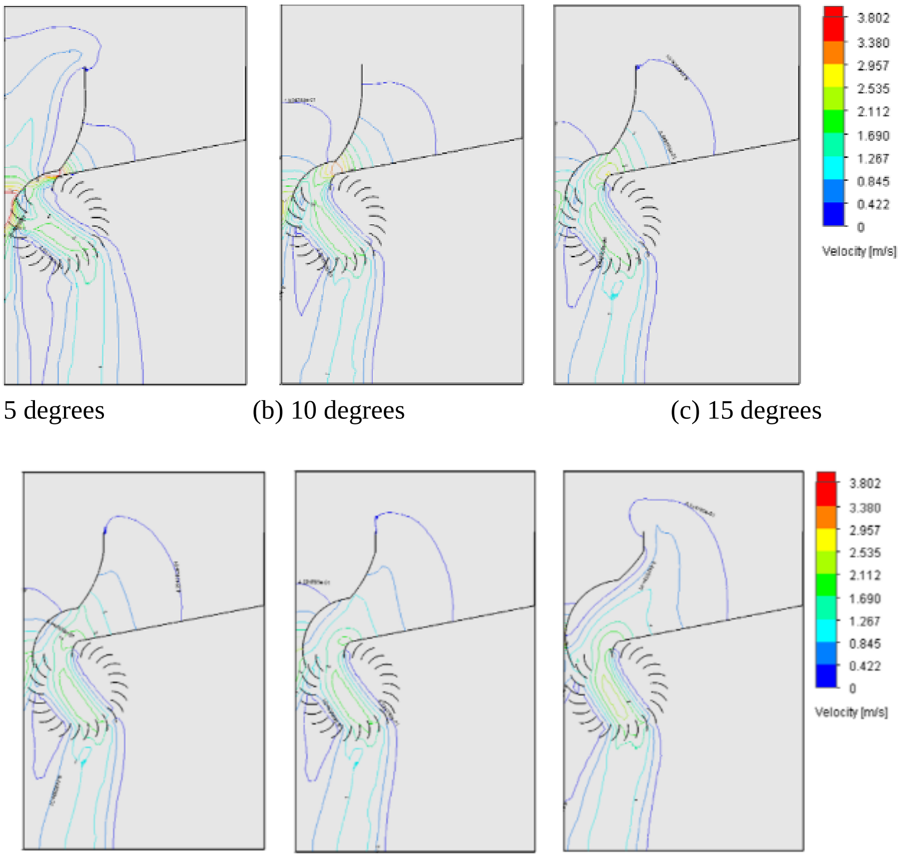


Fig. 9. The correlation between the torque and numbers of blades.

Figure 10(a)-(f) shows the results that were obtained from the flow simulation of blades with a guide vane and with inlet angles of attack of 5, 10, 15, 20, 24, and 30 degrees. It was observed in the flow simulation that the installed guide vane had affected the cross-sectional area of the venturi and nozzle section. If the degree of the inlet angle was small, then the cross-sectional area of the nozzle section was also reduced. This accelerated the water jet passage, which is explained in the mass balance equation. Considering the flow distribution shown in Figure 10(a-f), the water flow velocity decreased as the inlet angle increased by 2.88, 2.31, 2.02, 1.83, 1.69, and 1.86 m/s. Figure 10(f) shows that the average water inlet velocity increased with the influence of the guide vane which had been installed at a water attack angle of 30 degrees. Due to that angle, the upper wall radius of the guide vane increased and, as a result, the cross-section area of water flow through the venturi section decreased. As a result, the water was forced to flow more through the nozzle section. Therefore, the velocity and flow rate of water flowing through this part was increased. Changes in water velocity also affected the power input (Equation 2) and the system efficiency.

Figure 11 illustrates the tendency of changes in the power input and system efficiency due to variations in the inlet angle of attack. When the inlet angle of attack was increased, the power input of the turbine decreased. The highest power input was observed at an inlet angle of attack of 5 degrees, while the lowest was reported at 24 degrees. Moreover, it was also found that changing the power input had affected the turbine efficiency, as shown in Equation 5. More specifically, the system efficiency was increased when the angle was increased from 5 to 24 degrees, while the efficiency was decreased at an angle of 30. Accordingly, the highest system efficiency (45.83%) was observed at 24 degrees, whereas the system efficiency decreased to 41.23% at an inlet angle of attack of 30 degrees.

This behavior could be described by stating that the water, which flows through the cross-flow turbine can be divided into two stages. Each stage has a different transfer of water energy to the blade. It was found that the energy transfer at 1st and 2nd stage had been 68.5% and 31.5%, respectively, depending on the water jet inlet angle attack at the blade inlet [28]-[31]. When the inlet angle of attack is higher than 24 degrees, the water jet is deflected toward the runner center in the first stage, possibly leading to retardation effect in the second stage [10].



(a) 5 degrees (b) 10 degrees (c) 15 degrees

(d) 20 degrees (e) 24 degrees (f) 30 degrees

Fig. 10. The velocity distribution of the 25 blades and the inlet angles of attack ranging from 5 to 30 degrees.

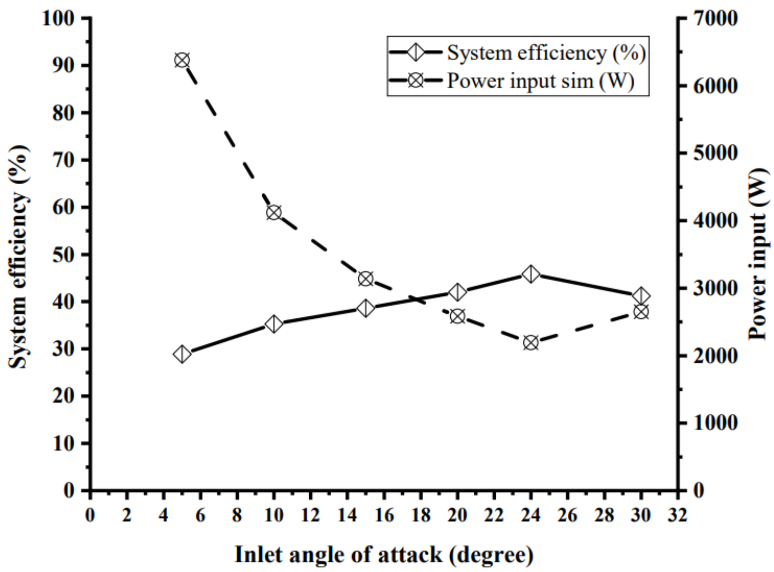


Fig. 11. The correlation between the power input system efficiency and the inlet angle of attack.

4.3 Experimental Results

Figure 12 shows the results of the system efficiency experiment of a pico-hydropower plant. By using a water turbine with 25 blades, the inlet angle of attack is 24 degrees. The experiment was conducted at a system head of 0.7 m because the canal can generate a maximum system head level of 0.7 m.

It was observed from this experiment that the system had been able to produce electricity starting from a system head level of 0.25 m onwards. At this head level, the generator rotated at 1,080 rpm, which is the rate at which electricity was generated. The amount of power output was found to increase by an increase in the system head level. Moreover, it was found that power output had increased as the head increased. It was found that the increases in power output would increase slowly and then curve. Finally, the highest power of 1,379.9 W occurred at a system head level of 0.7 m, which was the highest system head that could be provided by this canal. The system efficiency had also increased with any increases in the system head. The system efficiency was stable at a system head of 0.5-0.7 m, while at this head level range, the highest efficiency had been 48%. In the next section, this result was compared with and without a guide vane.

Figure 13 shows the system efficiency from the experiment of the vertical axes twin-turbine with and without a guide vane as compared to the simulation results. This result had the same experimental conditions: the system head was set at 0.7 m, the flow rate was 0.4 m^3/s, while both the mechanical efficiency and electrical efficiency were at 80% [19]. The simulation's system efficiencies and the experiments were 45.83% and 48.00%, respectively. In addition, the system efficiency for the vertical axis twin-turbine without the guide vane installation had been 34.96%. The power output in the experiment and simulation had been 1.378 kW and 1.258 kW respectively.

This was 0.120 kW (8.7%) less than the experiment. And found that the results of the vertical axis twin-turbine without the guide vane had been able to produce 960.28 W of electricity [18], which was 418.62 W (approximately 30.35%) less than the electricity that had been produced by the turbine with the guide vane.

The study focused on the optimal angle of attack and number of blades to optimize the pico hydroelectric power plants by using twin axis Banki turbines. The findings from the flow simulation and the experiments were then compared. It was found that system efficiency obtained from experiment was greater than the simulation at 4.73%. Moreover, it was observed that the turbines with guide vanes had shown greater levels of efficiency than those without guide vanes. It can, therefore, be concluded that the installation of a guide vane can increase the efficiency of vertical axes twin turbines. If the results from this research, which employed a pico-hydropower plant, are used for future commercial benefits, they could be beneficial for remote communities given the plant's small size and its ease of installation.

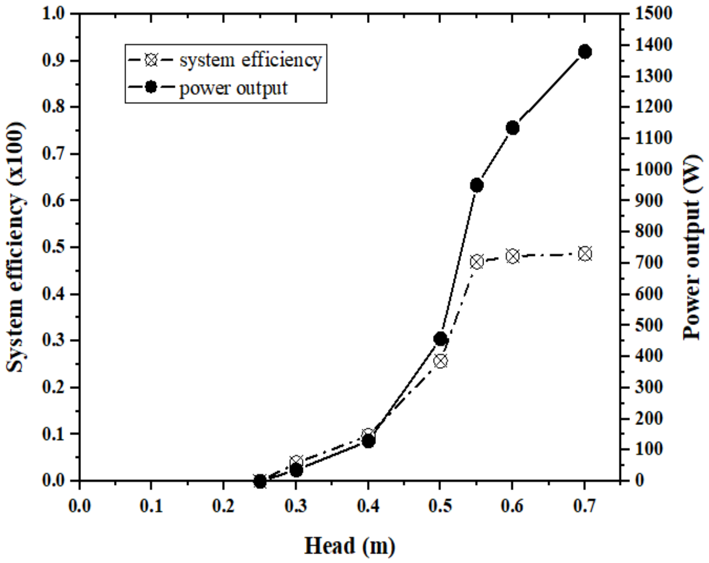


Fig. 12. The power output and system efficiency data from the experiment.

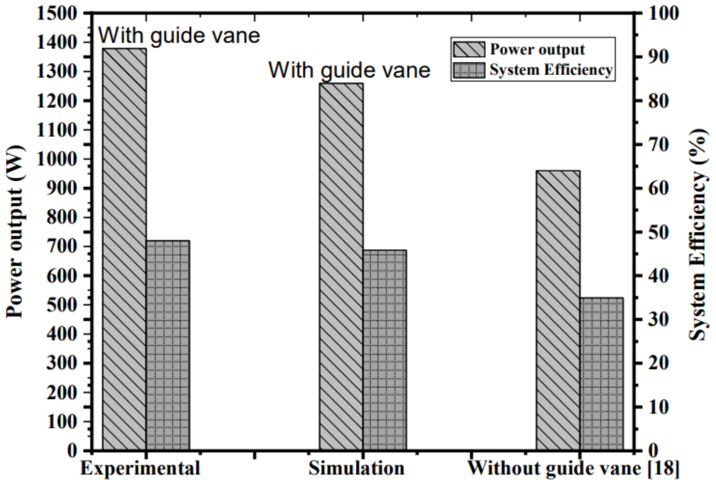


Fig.13. The system efficiency and power output of the vertical axis twin turbine.

5. CONCLUSIONS

This research investigated the factors that had affected the torque and system efficiency of a pico-hydropower plant, which uses cross flow-vertical axis twin turbines to increase the efficiency of the pico-hydropower plant that generates electricity from an irrigation canal with a head level of less than 0.8 meters and a high flow rate. It was found that the inlet angle of attack and the number of blades had affected the torque and system efficiency. Solid Work Flow Simulations were conducted using the computational fluid dynamic (CFD) method with inlet angles of attack of 5, 10, 15, 20, 24, and 30 degrees and with the number of blades at 15, 20, 25, 30, 35, and 40. It was revealed that the inlet angle of attack had demonstrated a higher effect on the torque than the number of blades, with P-values of 1.2×10^{-7} and 0.3915, respectively. The results showed that the 25 blades had exhibited the highest torque. In addition, it was also found that the torques at inlet angles of attack of 5, 10, 15, 20, 24, and 30 degrees, demonstrated that this set of angles had had torques of 195.0, 153.7, 128.1, 114.7, 106.2, and 115.7 Nm., respectively. Moreover, it was found that the installation of guides had affected the inlet velocity and the direction of the water flow. The inlet velocity had affected the turbine blades' input power, which directly affected the system efficiency of the hydropower plant. At the inlet angles of attack of 5-30 degrees, the system efficiency was found to increase with each higher inlet angle of attack. It was also found that the highest system efficiency of 45.83% had been observed at an inlet angle of attack of 24 degrees. The results showed that the number of turbine blades and the optimum angle of attack for the vertical axis dual turbine had been consistent with the results of the horizontal axis single turbine, which examined the efficiency of turbines for water heads of at least 5 meters [11].

The pico-hydropower plant was designed to have a maximum capacity of 3 kW. The system was designed for use in an irrigation canal with system head levels ranging from 0 to 0.7 meters. It was observed that the hydropower plant could produce more electricity when there were higher head levels. The highest power output of current was 1,378.9 W, which was observed at a head level of 0.7 meters. Similar patterns were also observed, as the system efficiency increased when the head level was higher. However, a more stable system efficiency of 48.0% was observed at a head level range of 0.5-0.7 meters. The results indicated that the system efficiency had been higher than the system without guide vane [17] and higher than commercial products [18], which have demonstrated system efficiencies of 32.36% and 34.96%, respectively.

Regarding the designation of turbines for very low heads, it is necessary to design guide vane to optimally control the inlet angle of attack. Moreover, the designation and installation of twin vertical axis turbines led to an increased cross-sectional area, which decreased the pressure back and, which, as a result, increased the system head. This is effective to the system of water management upstream of the electrical generating system. This system could also be implemented for the water resource where there are very low heads, such as irrigation canals, small rivers, and weirs in rural areas. However, in the future, if the design of the cross-sectional area of the nozzle and venturi are optimized, it will increase the efficiency of the system. This is due to the fact that the cross-section directly affects the water jet and turbine torque.

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