Comparing Efficiency between Dual and Single-Axis Vertical Turbine for Electrical Generating System

Kanisorn Thanutwutthikorn and Ratchaphol Suntivarakorn*

Department of Mechanical Engineering, Faculty of Engineering, Khon Kaen University, Khon Kaen, 40002, Thailand

* Corresponding author. E-mail address: ratchaphon@kku.ac.th

Received: 1 November 2022; Revised: 8 May 2023; Accepted: 29 May 2023; Available online: 26 August 2023

Abstract

This article reports an efficient comparison between 500W dual and single vertical axis cross-flow turbine for electrical generating systems. The studied parameters were the influence of the distance between dual vertical axes, then, comparing the efficiency with the single cross-flow turbine. From the designation of the L/D ratio as equal to 1, the diameter and height of the dual-axis vertical turbine was 0.3 m while the single-axis vertical turbine was 0.6 m. A chain was used for power transmission with a gear ratio of 1:18 and an induction generator was used as the electrical generating system. The results were that a dual-axis vertical turbine with a 0.8 m water head and at various distances of 3, 6, 9 and 12 cm had an efficiency of 32.36, 28.06, 20.44, and 14.44%, respectively. However, the efficiency decreased with increasing distance between the axes which resulted in a loss of water energy flowing through the axes. The water energy loss was variously 74, 150, 243 and 364 W. In the case of the single-axis vertical turbine, the efficiency was 20.73% which was closes to the dual-axis vertical turbine at a distance of 9 cm. The economic viability of dual-axis vertical turbines is 6.5 years but is 14.77 years for single-axis vertical turbines.

Keywords: vertical turbine, cross-flow turbine, electrical generating system

Introduction

Hydroelectric power generation systems produce clean energy without air pollution and have a lower cost of production than other power generation systems. In 2021, 1,330 GW of hydroelectric power was generated globally, which was 16% of total global energy generation (International Hydropower Association, 2021). Increases in the demand for electricity over recent decades have resulted in more hydroelectric power plants being constructed. However, the number of suitable water resources for large hydroelectric power generation systems has decreased which has led to a greater focus on the potential of electrical generating systems from small water resources such as irrigations ditches, canals, brooks, etc. This type of electricity generation is suitable for communities remote from large transmission lines.

Classification of power generation systems as being small or micro-hydro systems are based on generating capacity of 5 kW or less (Practical Action, 2013; Sopian & Razak, 2009). Hydro systems can also be classified according to their head level with low-head power generation systems having a head level of less than 10 m (Paish, 2002). There have been several studies on the development of low head power generation systems. A micro hydropower plant using Kaplan turbines with diameters between 3.5-5 m, heads between 1.4-4.5 m and flow rates of 10-30 m^3/s had an efficiency of 80-91% (Quaranta, Bahreini, Riasi, & Revelli, 2022). Archimedes screw turbines with a diameter of 4 m, head between 1-6 m and a flow rate of 0.1-5.5 m^3/s demonstrated efficiency between 75-85% (Lubitz, Lyons, & Simmons, 2014; Waters & Aggidis, 2000). However, large water turbines require large installation spaces and have a high cost, rendering them too costly and inappropriate for small, remote communities and low-income countries.

Cross-flow turbines, or Banki cross-flow turbines (Figure 1) are simple, low-cost water turbines with a simple design and construction. Designing a cross-flow turbine that meets the requirements requires an understanding of the operating principles and parameters for turbine production, such as blade angle (β_1), curvature of the blade (ρ) and central angle (δ) (Mockmore & Merryfield, 1949)), and the inlet angle of attack (α_1) on which output power depends. The design and control of the water with the proper inlet angle of attack will increase the turbine output power and efficiency (Vincenzo, Costanza, Armando, Oreste, & Tullio, 2013). Nano-hydraulic turbines are currently being used with small water resources or waterfalls (See Figure 1). Ikeda, Iio, and Tatsuno (2010) reported that the power coefficient (C_p) depends on the water flow rate and the maximum power coefficient is 0.58-0.66. This is an important consideration where the slope leading to the water resource has a very low head level, such as water resources with open flow channels and a low head level of < 3 m. Irrigation channels and canals, for example, are water resources with a low velocity which directly affects the efficiency of the turbine. However, where the irrigation canal has low head levels but high flow rates, the flow can compensate for the lower head level.

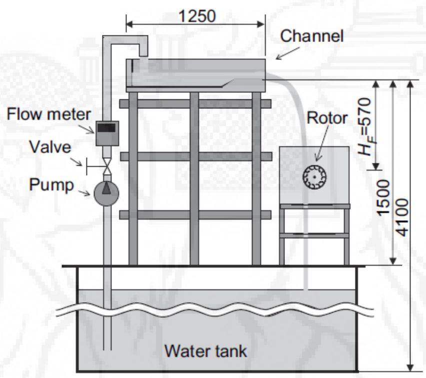


Figure 1 Experimental rig for Banki's water turbine. (source: Mockmore & Merryfield, 1949)

Cross-flow turbines are increasingly being used in low head level water resources. The cross-flow turbine can be installed in various configurations, such as a dual cross-flow horizontal axis turbine while installing a horizontal axis water turbine has been found to rotate the turbine at the same speed as the other turbine configurations. This can be explained by the lower turbine receiving more energy and having a higher rotational speed than the upper turbine which leads to an unequal power coefficient with the upper turbine having a power coefficient of 0.473 and the lower turbines having a power coefficient of 0.612, (Elbatran, Yaakob, Ahmed, & Shehata, 2018). Unequal power coefficients can be corrected by installing dual cross-flow vertical axis water turbines. The turbines of the dual cross-flow horizontal axis turbine will be installed at the same height which causes the water power to be divided equally for each turbine, maintaining same power output as achieved with the cross-flow turbine. Currently, commercial power generation systems are being developed that are equipped with dual cross-flow vertical axis turbines. It is designed to be installed in a canal with a head level between 0.7-3 m, flow rate of 0.5-5 m^3/s, power generation of 1.5-50 kW and average power generation of 35.2% (JAG Seabell). The dual cross-flow vertical axis turbine installation concept is suitable for water resources with open flow channels where the maximum velocity profile is located at the center of the channel. The water is then pressurized to flow through the nozzle to increase the speed and transfer the kinetic energy to the turbine blades.

The highest water speed will flow into the center of both turbines. This allows the turbine to receive the same amount of water energy, resulting in the turbine having the same power output. Few studies have compared the efficiency of the power generation system with a single cross-flow vertical axis turbine and a dual cross-flow vertical axis turbine. In addition, the installation of the dual cross-flow vertical axis turbine has a weakness in that it does not have proper control of the water inlet angle of attack.

The objective of the current research, therefore, was to identify the proper inlet angle of attack study that would greatly improve the efficiency of the power generation system. For this purpose, the efficiency of power generation systems equipped with a dual cross-flow vertical axis will be compared with the efficiency of single cross-flow vertical axis turbines.

Methods and Materials

The study of factors affecting cross-flow turbine efficiency requires knowledge of the working principles and design theory of cross-flow turbines (Mockmore & Merryfield, 1949). The design and construction of turbines include 3 important factors such as blade angle (β_1), curvature of the blade (ρ), and central angle (δ), as shown in Figure 2. All factors can be calculated from Eq. 1-3.

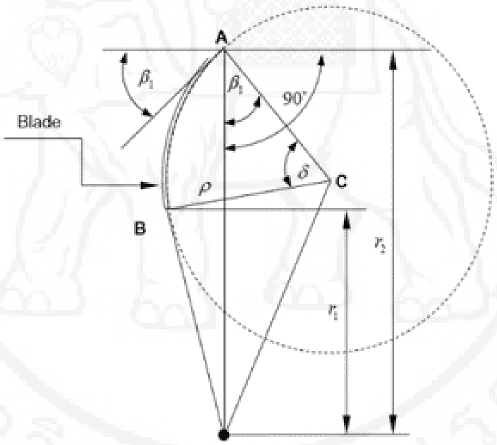


Figure 2 The characteristics of a blade

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

$$\rho = \left[\left(r_1^2 - r_2^2\right) \big/ \left(2r_1\cos\beta_1\right)\right] \quad (2)$$

$$\delta = 2\left[\tan^{-1}\left(\frac{\cos\beta_1}{\left(\sin\beta_1 + \left(r_2/r_1\right)\right)}\right)\right] \quad (3)$$

where α_1 is the inlet angle of attack (degree) and r_1 is the inside radius with r_2 the outside radius (radii measured in m). Water is forced to flow through the nozzle to increase speed, then flows into the turbine blades and converts to mechanical energy. The water flowing out of the nozzle will increase the speed corresponding to Eq. 4.

$$V_1 = C_d\sqrt{2gH} \tag{4}$$

where C_d is the nozzle coefficient (dimensionless), g is the gravitational constant (9.81 m/s^2) and H is the head (m) level. The input energy to the turbine entrance can be calculated by Eq. 5.

$$P_{input} = \rho gQH \tag{5}$$

where ρ is the density of water (kg/m^3) and Q is the volumetric flow rate (m^3/s). Therefore, the input energy can be reformatted by substituting Eq. 4 into Eq. 5 resulting in Eq. 6

$$P_{input} = \frac{\rho QV_1^2}{2C_d^2} \tag{6}$$

and output energy can be determined from Eq. 7

$$P_{output} = \rho Qu_1\left(V_1\cos\alpha_1 - u_1\right)\left(1+\psi\right) \tag{7}$$

where ψ is the empirical coefficient (about 0.98) and u_1 is the peripheral velocity (m/s) which can be calculated by Eq. 8

$$u_1 = \frac{\pi ND}{60} \tag{8}$$

where N is the turbine speed (rpm), D is the diameter of the cross-flow turbine (m) and, as cross-flow turbine efficiency is the ratio between output energy (Eq. 7) and input energy (Eq. 6), these can be written into Eq. 9.

$$\eta_{turbine} = \frac{\rho Qu_1\left(V_1\cos\alpha_1 - u_1\right)\left(1+\psi\right)}{\rho QV_1^2 \big/ 2C_d^2} \tag{9}$$

The electricity generated by the generating system installed as part of the current study $\left(P_{output,elec}\right)$ can be measured using Eq. 10

$$P_{output,elec} = VI \tag{10}$$

where V is voltage (V) and I is current (A). The practical power-generating system efficiency can be obtained from Eq. 11 (Practical Action, 2013)

$$\eta_{system} = \frac{VI}{\rho g Q H} \tag{11}$$

The factors affecting input and output power were examined and recorded, and the efficiency of the power generation system was calculated using Eq. 11.

Cross-flow turbine design theory

The designation of the cross-flow turbine diameter can be determined from the peripheral velocity of the turbine (u_1). From the velocity triangle (Mockmore & Merryfield, 1949) and applying Eq. 8, the diameter relationship of the cross-flow turbine is obtained as shown in Eq. 12

$$D = \frac{60}{\pi N}\left(\frac{1}{2}\left(C_d\sqrt{2gH}\right)\cos\alpha_1\right) \tag{12}$$

The water flow rate in the cross-flow turbine (Mockmore & Merryfield, 1949) gives the relationship between diameter and turbine height as shown in Eq. 13.

$$Q = k.D.L\left(C_d\sqrt{2gH}\right) \tag{13}$$

where L is the height of the turbine (m). Then, substituting the diameter from Eq. 12 into Eq. 13 where $C_d = 0.98$ and $k = 0.0875$ (Mockmore & Merryfield, 1949), the relationship between flow rate and head can be obtained in Eq. 14

$$L.D = \frac{0.478Q}{\sqrt{H}} \tag{14}$$

The economic cost-effectiveness of the system was calculated using Eq. 15.

$$\text{Economic cost} - \text{effectiveness} = \frac{\text{Production cost}}{\text{Profit}} \tag{15}$$

Design of cross-flow turbine and generation system

In this study, a power generation system was designed and then installed in an irrigation canal with a width of 2.5 m, depth of 1.8 m and water flow rate of 1 m^3/s, as shown in Figure 3. It was designed as a dual-axis vertical turbine power generation system with a capacity of 500 W, with each of the two turbines having a generating capacity of 250 W.

The ratio of height to diameter (H/D) was 1 which allowed the diameter and height of the turbine to be calculated from Eq. 14, which was equal to 0.3 m (see Figure 4). The nozzle cross-sectional area that suited for turbine size was calculated with a nozzle outlet area of 0.09 m^2 and outlet water velocity of 2.8 m/s. The design of the single-axis vertical turbine was similarly calculated, but the water flow rate was doubled, which was 0.250 m^3/s. The calculated ratio of the height and diameter of the turbine was 0.60 m.

Figure 3 Irrigation canal where turbines were installed and trialed

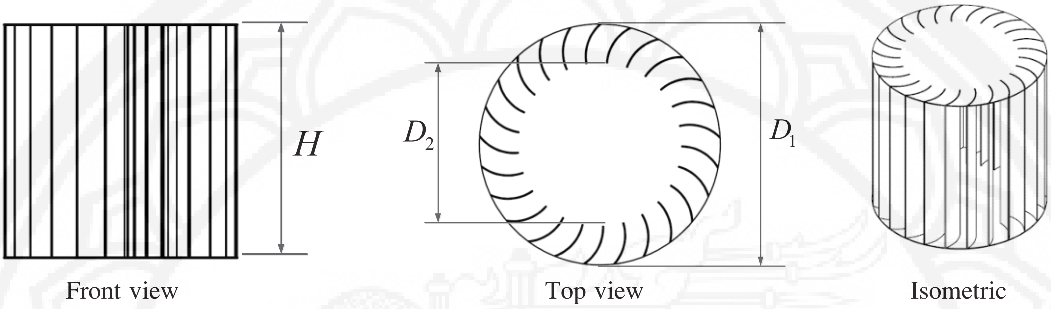


Figure 4 Characteristic of the turbine in this study

In this study, the optimum ratio of the water turbine diameter (D_2/D_1) was 0.68, the number of impellers was 25, and the incidence of water inlet of the turbine blades was 24° (Desai & Aziz, 1994). The turbine had a blade angle (β_1) of 41.68°, the curvature of the blade (ρ) was 0.0539 m and the central angle (δ) was 58°.

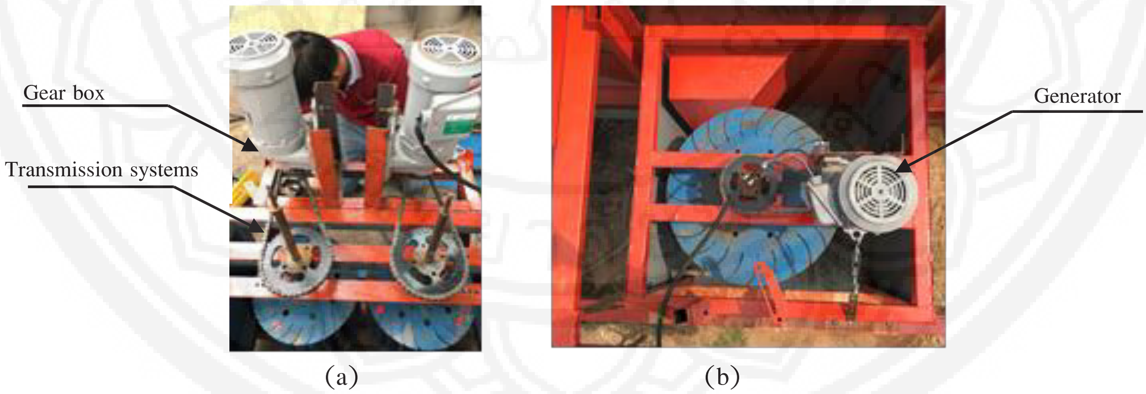


Figure 5 Installation of transmission and reduction system (a) dual-axis vertical turbine (b) single-axis vertical turbine

The irrigation canal had a very low head water resource and a low water velocity. This resulted in the turbine having a low speed as well. Therefore, the power transmission and reduction system was used to increase the speed around the generator shaft. It was calculated that the dual-axis vertical turbine had a peripheral velocity of 1.278 m/s, which resulted in a turbine speed of 81 rpm. This is a very low speed. Hence, the transmission system needed a gear reduction to increase the shaft axis speed sufficient to induce an electrical current. With a gear reduction ratio of 1:18, the generator rotated at a speed of 1,450 rpm. In this investigation, an induction generator was constructed by modifying an AC motor circuit of 1 HP (motor IP 55 which was unaffected by humidity) to transform the motor to a generator maximum capacity of 500 W (see Figure 5(a) - 5(b)). To ensure a valid comparison both turbine designs use the same transmissions, generators and load systems.

The data for the head level and water flow rate, the important parameters affecting input power were collected. Water velocity was measured using a propeller water velocity instrument, which has a measurement range of 0.1-6.1 m/s and an error of 0.1 m/s (see Figure 6). The output power was the measurement of the current that the system could produce. The energy data display system was built to continuously monitor and store the data (see Figure 7).

Figure 6 Water flow rate meter

FigureFigure

Figure 7 Output power meter and monitoring system

Installation and trial of the power generation system

The factors that need to be recorded for calculating the input power included the water flow rate (Figure 8(a)), and the head level (Figure 8(b)) The output power generated by the system was recorded as voltage and current (Figure 8(c)). The data was recorded when the head level increased by 0.1 m up to 0.8 m which was the highest head level that could be tested.

(a) (b) (c)

Figure 8 Installation and trial turbine system (a) measuring input water flowrate (b) measuring water head (c) display monitoring system

This study also investigated the optimum distance between the turbines. The installation of a turbine must allow to adjustment to the distance between the turbine shafts as shown in Figure 9. The experiment was performed at head levels between 0.1-0.8 m at turbine spacing of 3, 6, 9 and 12 cm.

Figure 9 Distance between turbines

Figure 10 shows the installation and trial characteristics of a single-axis vertical turbine power generation system. It was tested at head level 0.1-0.6 m because it was the highest head level that could be tested.

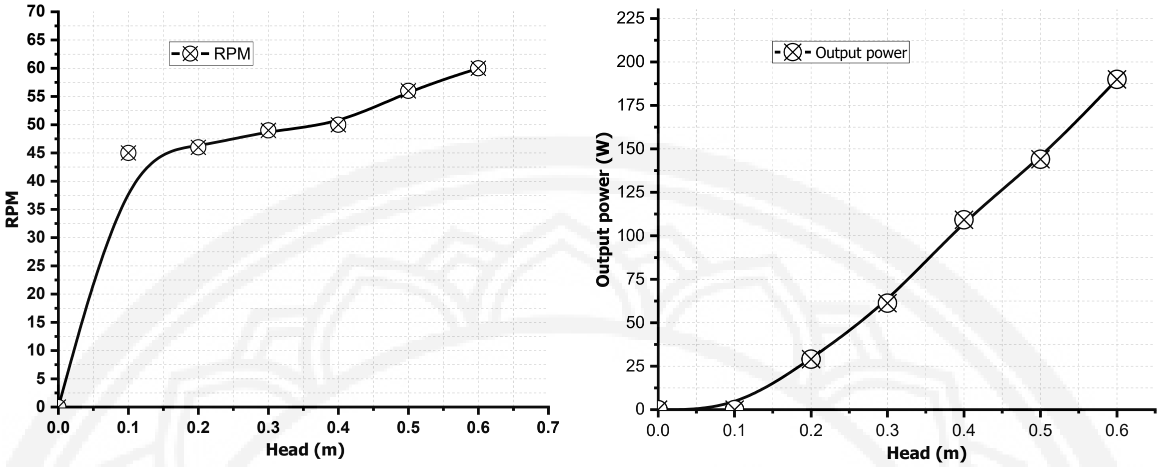
Figure 10 Measuring turbine speed

The data relating to input power and output power calculations such as flow rate, head level, and the current and voltage produced by the system was used to calculate the efficiency of the power generation system. The results from the dual-axis vertical turbine power generation system experiment with the appropriate water turbine spacing experiment were compared with the single-axis vertical turbine power generation system trial. The results of the comparison of the efficiency of the power generation systems were then used as a guideline for the further development of the power generation system. In the next section, the experimental results and discussions of the investigations are elaborated.

Results and Discussions

Single-axis vertical turbine

The effect of head level and turbine system speed is discussed. Figure 11(a) shows the speed of a single-axis vertical turbine investigated at the head level of 0.1-0.6 m. It was found that when the head level increased, the turbine speed increased. At head 0.1 m, the turbine had a speed of 45 rpm and at the head level of 0.6 m, the turbine had a speed of 60 rpm.



(a) (b)

Figure 11 (a) Effect of head-to-turbine speed and (b) effect of head -to- output power

Figure 11(b) shows the output power that the power generating system produced at head level 0.1-0.6 m. It was found that at a head level of 0.1 m, the turbine speed was insufficient to generate electricity. However, when the head level was increased to 0.2, 0.3, 0.4, 0.5 and 0.6 m, the power output was 29.0, 61.2, 109.2, 144.0 and 190.0 W, respectively.

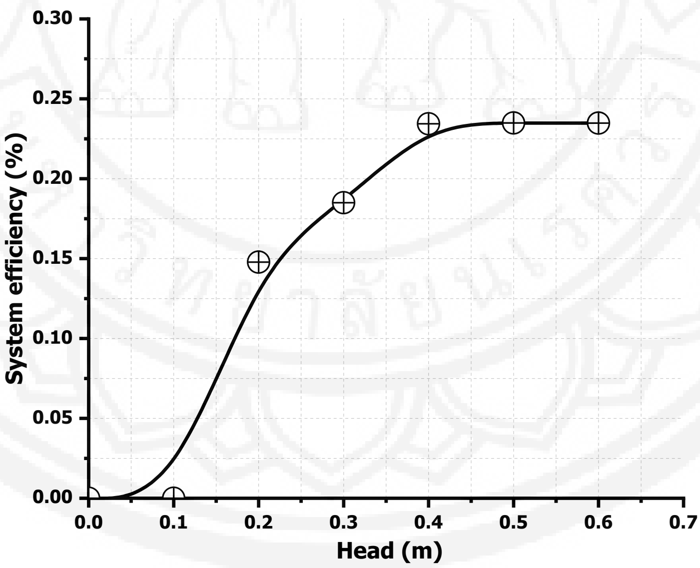


Figure 12 System efficiency of a single cross-flow vertical axis

Figure 12 shows the efficiency of a single-axis vertical turbine power generation system. It can be seen that at the head level of 0.2 m, the power generation system had an efficiency of 14.78%. At head level of 0.2-0.4 m, the efficiency trends to be linear and reached a constant value at head level 0.4-0.6 m with a constant efficiency of 23.50%. The average efficiency of the power generation system was 20.70%.

Dual-axis vertical turbine

Figure 13 shows the output power obtained from testing a dual-axis vertical turbine power generation system with adjustable gap margins of 3, 6, 9 and 12 cm. From the input power and output power data at a head level of 0.0-0.8 m, it can be seen that at 3 cm the system can generate the highest output power. It was also found that at head levels rising from 0.0-0.6 m (Interval A), the power output increased linearly, and the differential output power then increased (Interval B) at head levels of 0.6 - 0.8 m. As the gap increased, a loss of energy resulted because the water flowing through the gap between the turbines was greater, with increased water loss as the head level increased. It can be concluded that the higher the head level, the higher the water pressure.

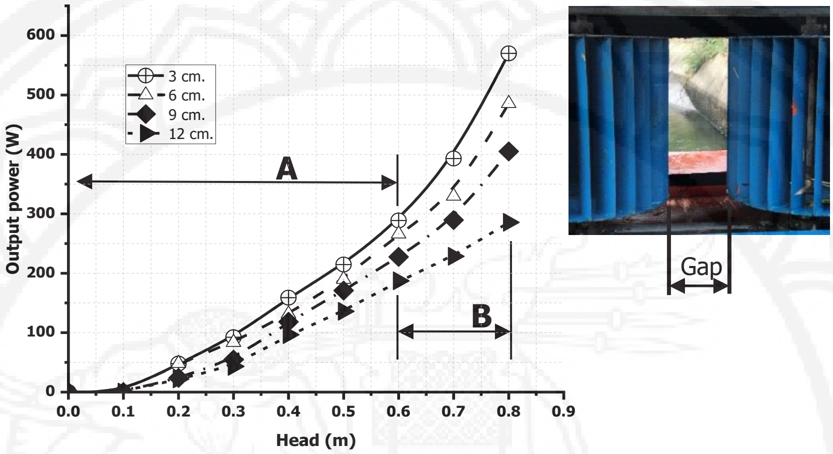


Figure 13 Comparing output power at difference gaps, 3 - 12 cm

Figure 14 shows the effect of gaps on the efficiency of the power generation system. By adjusting the distance of 3, 6, 9 and 12 cm, it was found that the average efficiency was 32.4, 28.1, 20.4 and 14.4%, respectively. Because the turbine with a narrow gap will be able to receive more water power than a turbine with wide gap. It has also been found that the wide gap will result in much water loss. Especially, the experiment at high head level will cause the system to have accumulated potential energy and increase the water pressure in the power generation system, resulting in increased water loss. In summary, turbines with a large gap will be less efficient than turbines with a small gap.

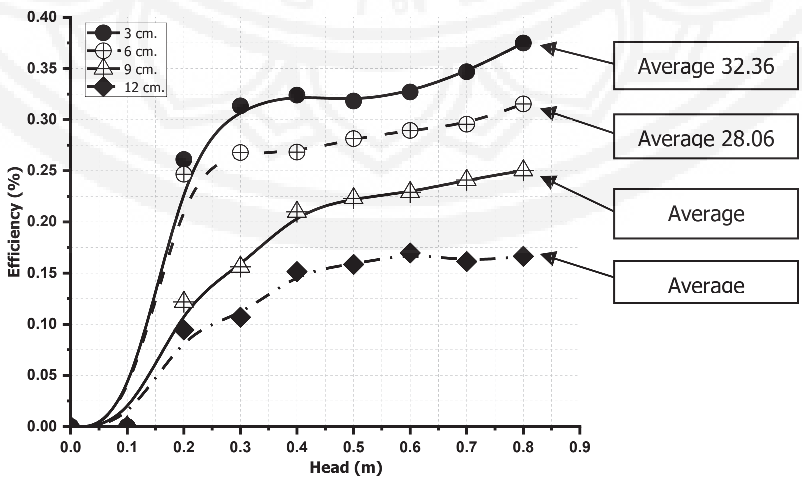


Figure 14 Comparing system efficiency at difference gaps, 3 - 12 cm, for dual-axis vertical turbine

Figure 15 shows the results obtained from the turbine spacing effect experiment. It was found that the water power will be divided into 2 parts: the part that flows into the turbine and the part that flows through the gap between the turbines, which is the part that causes the wasted work energy. Each distance had different water energy loss while the turbine spacing was 3, 6, 9 and 12 cm leading to the water loss being 0.014, 0.028, 0.045 and 0.069 m^3/s, respectively. At each turbine spacing, the loss of water power was 74, 150, 273.8 and 364 W, respectively.

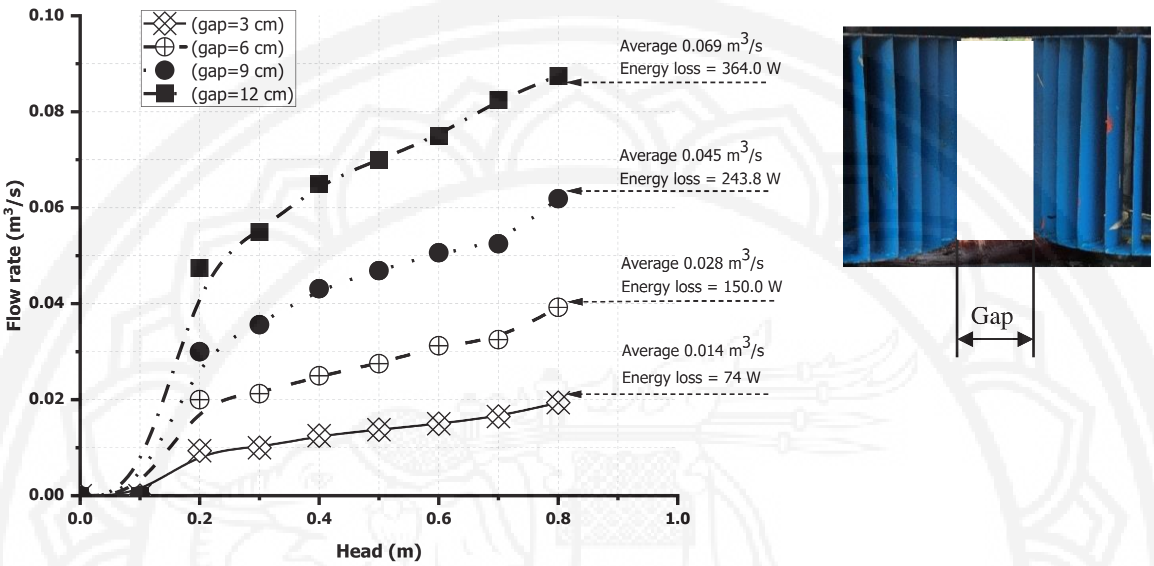


Figure 15 Energy loss due to water flow rate and turbine gap

Figure 16 shows a comparison of power generation system efficiency. It can be seen that the single-axis vertical turbine had an average efficiency of 20.73% which is similar to a dual-axis vertical turbine with a distance of 9 cm (20.44%). It was also found to be lower than that of a turbine with a distance of 3 and 6 cm, which had an efficiency of 32.36 and 28.06%. The amount of electricity produced depends on the generator's speed, so the turbine speed is the main factor affecting the output power. The single-axis vertical turbine has a larger diameter resulting in a lower speed than the smaller dual-axis vertical turbine. The dual-axis vertical turbine power generation system has two generators, resulting in a higher output power than a single-axis vertical turbine with only one generator. It was also found that the nozzle characteristics of the two turbines were different, which directly affected the nozzle values, which directly affected the turbine inlet water velocity.

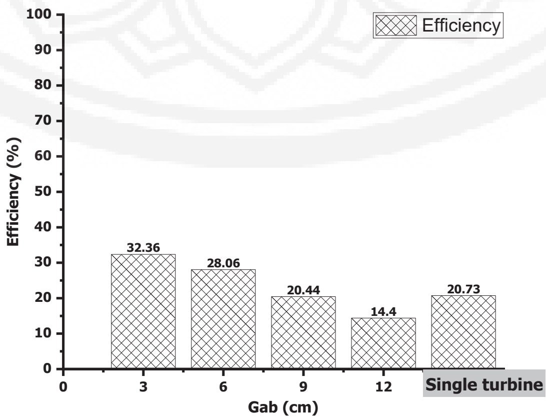


Figure 16 Comparing the average system efficiency of water turbine dual-axis vertical turbine and single-axis vertical turbine

The dual-axis vertical turbine power generation system has a total production cost of 99,000 Baht and a capacity of 3,995 kWh/year, equivalent to 17,663 Bath/year. A single-axis vertical turbine power generation system has a production cost of 87,000 Baht and can generate 1,332 kWh/year, or 5,888 Baht. Given the plant factor of 0.8, a dual-axis vertical turbine will be economically viable for 5.6 and a single-axis vertical turbine power generation system for 14.77 years.

Conclusion and Suggestions

This study compared the efficiency of hydroelectric power generation systems using a dual-axis vertical turbine and a single-axis vertical turbine. A Banki turbine or cross-flow turbine was selected as a prototype power generation system with a capacity of 500 W. It is easy to design this water turbine and construct it at a low cost, it is a suitable turbine suitable for low-head water sources. A cross-flow turbine was then designed to suit the water source potential and required capacity using the design theory of Mockmore and Merryfield (1948). The transmission system uses a chain and sprocket with a 1:18 reduction system to increase the speed sufficiently for the generator to generate electricity. The turbine design uses an L/D ratio of 1. The design results showed that the dual-axis vertical turbine had a diameter and height of 0.3 m while a single-axis vertical turbine had a diameter and height of 0.4 m. The turbine blade angle (β_1) was equal to 41.68°, the curvature of the blade (ρ) was equal to 0.0539 m and the central angle (δ) is 58°. The turbine was installed and tested in an irrigation water delivery canal. The results obtained from the trial of the dual-axis vertical turbine power generation system with adjustable spacing between turbines 3, 6, 9 and 12 cm found that the efficiency was 32.06, 28.06, 20.44 and 14.40%, respectively. It was also found that the loss of hydropower at each of these spaces between the turbines was 74, 150, 273.8 and 364 W, respectively. The efficiency of the single-axis vertical turbine power generation system was 20.73%, which was similar to a turbine with a distance of 9 cm but less than a turbine with a distance of 3 and 6 cm. The dual-axis vertical turbine power generation system has a production cost of 99,000 Baht and can produce 3,994 kWh/year of electricity, equivalent to 17,663 Baht/year. A single-axis vertical turbine power generation system has a production cost of 87,000 Baht and can generate 1,332 kWh/year, equivalent to 5,888 Baht/year. Thus, the dual-axis vertical turbine is cost-effective over 5.6 years and the single-axis vertical turbine power generation systems over 14.77 years.

Acknowledgements

The authors would like to express their gratitude to the National Research Council of Thailand, The Thailand Research Fund (TRF), the Energy Conservation Promotion Fund, Energy Policy and Planning, of the Ministry of Energy, for financial support, and Farm Engineering and Automation Technology Research Group (FEAT), Khon Kean University, for the tool and equipment necessary for the study. We also thank Mr Roy I. Morien for his editing of the grammar, syntax and general English expression in this manuscript.

References

Desai, V. R., & Aziz, N. M. (1994). Parametric evaluation of Cross-flow turbine performance. *Journal of energy engineering, 120(1)*, 17-34.

Elbatran, A. H., Yaakob, O. B., Ahmed, Y. M., & Shehata, A. S. *(2018).* Numerical and experimental investigations on efficient design and performance of hydrokinetic Banki cross-flow turbine for rural areas. *Ocean Engineering, 159*, 437-456.

Ikeda, T., Iio, S., & Tatsuno, K. (2010). Performance of nano-hydraulic turbine utilizing waterfalls. *Renewable Energy, 35*, 293-300.

International Hydropower Association. (2021). *Hydropower Status Report Sector trends and insights.* United Kingdom: IHA central office.

JAG Seabell. (2015). *Ultra-low head micro hydro turbine system STREAM Vertical Dual Cross-FlowTurbine.* Retrieved from https://www.seabell.jp/english/service/power.html

Lubitz, W. D., Lyons, M., & Simmons, S. (2014). Performance model of Archimedes screw hydro turbines with variable fill level. *Journal of Hydraulic Engineering, 140(10),* 04014050.

Mockmore, C. A., & Merryfield, F. (1949). *The Banki Water Turbine.* Oregon State College. Engineering Experiment Station, Bulletin series no. 25.

Quaranta, E., Bahreini, A., Riasi, A., & Revelli, R. (2022). The Very Low Head Turbine for hydropower generation in existing hydraulic infrastructures: State of the art and future challenges. *Sustainable Energy Technologies and Assessments, 51*, 101924.

Paish, O. (2002). Small hydro power: technology and current status. *Renewable and Sustainable Energy Reviews, 6*, 537-556.

Alison, D. (2009). *Micro-hydro power (Technical brief).* Retrieved from https://answers.practicalaction.org/our-resources/item/micro-hydro-power/

Sopian, K., & Razak, J. (2009). Pico hydro: clean power from small streams*: Proceedings of the 3rd WSEAS Int. Conf. on Renewable energy sources, 1 Jan 2009* (pp.414-419). Malaysia: Solar Energy Research Institute Universiti Kebangsaan Malaysia.

Vincenzo, S., Costanza, A., Armando, C., Oreste, F., & Tullio, T. (2013). Banki-Michell Optimal Design by Computational Fluid Dynamics Testing and Hydrodynamic Analysis. *Energies, 6,* 2362-2385. http://dx.doi.org/10.3390/en6052362

Waters, S., & Aggidis, G. (2015). Over 2000 years in review: Revival of the Archimedes screw from pump to turbine. *Renewable and Sustainable Energy Reviews, 51*, 497-505.