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A Comparison Study of Hydro-Compact Generators with Horizontal Spiral Turbines (HSTs) and a Three-Blade Turbine Used in Irrigation Canals

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Abstract: This study aimed to present the experimental results of two types of turbines and attachments used in a hydro-compact generator. Two Horizontal Spiral Turbines (HSTs) with blade angles of eighteen and twenty-one degrees, respectively, and a three-blade turbine were tested and experimented in a laboratory at five levels of water flow rate ranging from 1–2 m/s. After the efficiency and torque values of each turbine were identified, they were installed in two 200 W power generator systems: (1) with a “diffuser” attachment; and (2) with an “in-line+diffuser+nozzle chamber” attachment, and tested in a local irrigation canal with 1.2 m/s. The results from the laboratory indicated that the HST with a twenty-one degree blade angle had 38.10% efficiency at the water flow rate of 2 m/s. It could reach 120.0 rpm and produced 212 Nm of torque. The results from the field experiment revealed that the combination of the power generator with the twenty-one degree blade angle HST and the in-line + diffuser + nozzle chamber attachment was the most efficient, with 284 Nm of torque at 108 rpm and could generate 67.63 W of electrical power. When the water flow rate of the irrigation canal reached 1.5 m/s, it could reach 114 rpm and generate 129.2 W. This hydro-compact generator set is suitable for irrigation canals with a water flow rate ranging from 1–1.5 m/s.

Keywords: spiral turbine; electrical power; torque

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1. Introduction

Climate change causes incidents that challenge humankind to endure. The United Nation Office for Disaster Risk Reduction (UNDRR) states that some human activities have caused these drastic global disasters [1]. Global warming is one of the most serious problems faced by humankind, responsible for drastic weather changes caused by burning fossil fuels and population expansions. In the near future, there is expected to be a trend of power shortages that will lead to the increased usage of clean and renewable energy by every country in the world [2,3]. Clean and renewable energy usage is expected to have fewer effects on the environment than fossil fuels. However, clean and renewable energy from hydro-power plants can still harm the ecosystem, because their establishment requires immense areas of land [4,5].

In Thailand today, the capability of electrical power production from hydro-power plants throughout the country is 3107.51 megawatts (MW.), which accounts for 23.01% of Alternative Energy Consumption. Thailand aims to gather 3228 MW. from hydro-power plants by the year 2037 [6]. Although geographical limitations obstruct further establishment of large hydro-power plants, Thailand has other potential sources of hydrokinetic power, such as local irrigation reservoirs, irrigation canals, or local administration sectors, that can provide aid for villages and communities to produce electrical power from water sources [7].

Many studies indicate that there are plenty of irrigation canals in Thailand. However, most of them have the low water flow speed rate of about 0.52–2.0 m/s [8]. Thus, extracting electrical power from these canals requires a special hydro-power generator that is designed to operate under low water flow speed (less than 2.0 m/s) or low head pressure (less than 0.3 m). For ultimate performance, the generator requires an effective small-size turbine within the system. This kind of turbine must be eco-friendly, and must be well-accepted by the majority of people [9–11]. However, leaves, waste, or debris in the canals must be considered because, as they flow along, they might clog up the generator's water inlets [12,13]. Some living creatures in the water may also be trapped inside and injured [14]. Despite these concerns, this Pico power generator system can benefit houses or small villages [15,16]. The output wattage can be predicted if there is sufficient water in the system [17]. Moreover, this kind of generator has a positive environmental impact [18,19].

River Current Energy Conversion Systems (RCECS) is a system that was proven to be able to convert the kinetic energy of water flow in rivers into other forms of useful power effectively. One key factor that makes RCECS successful is the cost of power production, including operation and maintenance costs. Moreover, the design, applications, capability, and practicality of RCECS have created accountability [20]. Thus, the adaptation of RCECS in this study will strengthen the proof of the system to be a powerful and effective alternative of gathering renewable energy.

The principle of water current power indicates that most of the water volume flowing horizontally in any natural source must have direction and speed. This can be a source of electrical power harvest [21,22] when a turbine hydro-power generator is installed [23]. The electricity is generated from a transformation of water flow power into kinetic power at the axle of the generator's turbine; still, there is a power loss in the system [24]. There are many types of water turbines in hydro-power generator systems, largely divided into two groups according to their axle configurations (vertical and horizontal). Horizontal-axle turbines are further divided into two types according to their applications; vertical and horizontal installations [25]. Turbines in whirlpool hydro-generator systems, as well as Induced Vibration (VIV) turbines [26], have also been developed. Therefore, to achieve the most practical and effective goal of extracting renewable energy from local irrigations requires choosing the right applications that suits the water flow characteristics and the size of the power generator. Betz's law indicates that the extracted peak power coefficient value from a turbine is 59 percent. However, in reality, the extracted power values are lower because of the loss from the turbine's characteristics. Therefore, the power loss value in the system must be included in the experiments [27]. A proper turbine type selection for this circumstance must be carefully selected for the highest potential and the lowest eco-impact, as well as for low production cost. Moreover, there are studies concerning different types of turbines used in hydro-generator systems in irrigation canals with water flow rates from 0.6–3 m/s, as shown in Table 1 [28].

Table 1. Turbine specifications [28].

Manufacturers	Device Name	Turbine Type	Min./Max. Speed	Power Output
Lucid Energy Pty., Ltd. (Dallas, TX, USA) [29]	Gorlov Helical turbine	Helical Darrieus cross-axis	(0.6 m/s)/no limit	Up to 20 kW, depends on size
Thropton Energy Services (Northumberland, UK) [30,31]	Water current turbine	Axis flow propeller	(0.6 m/s)/depends on diameter	Up to 2 kW at 240 V
Tidal EnergyPty., Ltd. (Canberra, Australia) [32]	Davidson–HillVenturi (DHV) Turbine	Cross-flow turbine	Min. 2 m/s	From 4.6 kW
Seabell Int.Co., Ltd. (Tokyo, Japan) [33]	Steam	Dual, cross-axis	(0.6 m/s)/no limit	0.5–10 kW models
New Energy Corporation Inc. (Calgary, AB, Canada) [34]	En Current Hydro Turbine	Cross-axis	Max. 3 m/s for maximum power	5 kW (and 10 kW)
Eclectic Energy Ltd. (Nottinghamshire, UK) [35]	DuoGen-3	Axial flow propeller	Min. (0.93 m/s)/(4.63 m/s) max.	8 amps at 3.09 m/s
Alternative Hydro Solutions Ltd. (Toronto, ON, Canada) [31]	Free-stream Darrieus water turbine	Cross-axis	(0.5 m/s)/depends on diameter	Up to 2–3 kW
Energy Alliance Ltd. (Ural region, Russia) [30]	Sub-merged hydro unit	Cross-axis	Min 3 m/s	1–5 kW (and 410 kW)

A properly designed Horizontal Spiral Turbine (HST) can achieve the highest efficiency. Its key feature is the ability to reduce the turbulence generated by the impact of high-pressure water flow with the surface of the blade. This is obviously a benefit to the generator's efficiency and performance. Another obvious unique feature is that HST can be applied to wind and water generators with low-speed flow. HST's advantages are the low cost of production, compactness, and an ability to operate effectively under low pressure head. A hydro-generator system with an HST application can be properly used in rivers, canals, and irrigation canals without doing serious harm to living creatures in the water. It can be harmlessly blended with ecosystems; moreover, the construction materials are not expensive [36]. HSTs have been designed based on Fibonacci functions [37] and the golden ratio [38]. They are an arithmetic series of natural phenomena according to Fibonacci sequence principles. One round of rotation (360 degree) of an HST axle is equal to a length. Thus, the angle of the blades alters the length. The last characteristic of efficient HST relates to the number of blades. If the number of blades is insufficient, the surface area for converting force will cause the HST to generate low torque. On the other hand, if the number of blades is too high, the HST will create a solid wall state. Too many blades also increase the HST mass and inertia that reduce the overall torque [39]. Ratchapol et al. (2016) discovered that, under low water velocity and with between two and six blades, an HST with three blades could achieve the maximum torque and most optimal performance [40].

Yasukuni Nishi Okubo and Norio Kikuchi designed a new hydro-compact generator system that had "a runner" and "a collection device" including "a diffuser section" to enhance the water flow through the turbine. This increased power extracting ability and flow rate by 2.76% in a hydroelectric power generator with a three-blade turbine. At 456 rpm and a water flow rate of 1.72 m/s, 156.4 watts of electric power could be generated [41,42]. Hidayat et al. (2020) proved that a hydro-spiral turbine could spin faster (90 rpm) than other types at the same water volume [43]. Ratchapol et al. (2016) used the golden ratio function to enhance the efficiency of spiral turbines by extending the blade's radius and adjusting the diameter/length (D/L) ratio to 2/3. They proved that a spiral turbine had proper efficiency when compared with the a three-blade turbine. A hydro-generator with a proper spiral turbine could effectively generate electrical power at water flow rate ranging from 0.5 to 2 m/s [40]. Wiroon and Ratchapol (2017) also proved that a horizontal spiral turbine in a hydro-generator system with a nozzle chamber inlet was more efficient than one with a free flow inlet. Moreover, the blade angle also significantly affected the system's performance and efficiency [44]. Uday Y. Bhenede (2015) had designed and developed a turbine in a hydro-generator system that could effectively operate under low water pressure. It was a small-size turbine in a generator system that could operate under variant head pressure [45].

Today, HST research and development is focused on identifying the best values of different blade angles, length/axis radius ratio, blade number, or torque. Therefore, in this study, two Horizontal Spiral Turbines (HSTs) with blade angles of eighteen and twenty-one degrees, respectively, and a three-blade turbine, were tested in a laboratory at five levels of water flow rate ranging from 1–2 m/s. After the efficiency and torque values of each turbine were identified, they were installed in two 200 W power generator systems: (1) with a "diffuser" attachment; and (2) with an "in-line+diffuser+nozzle chamber" attachment, and tested in a local irrigation canal with a water flow rate of 1.2 m/s.

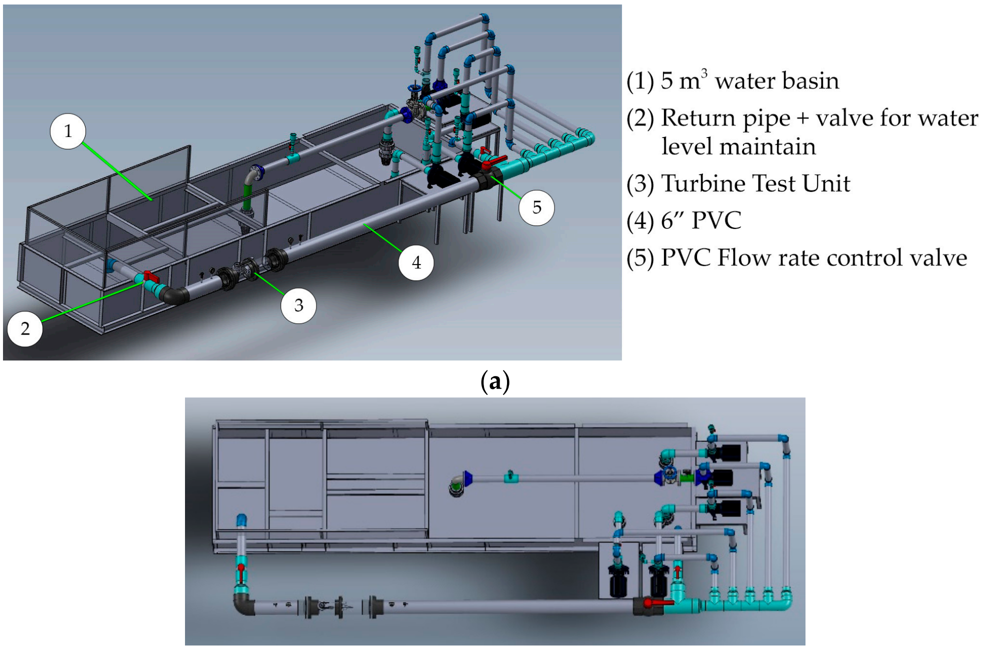
2. Materials and Methods

Laboratory experiments and related equations

This study aimed to design 3-blade Horizontal Spiral Turbines with blade angles of 18 and 21 degrees used in a hydro-generator system [40]. The simulation was set as displayed in Figures 1 and 2 and was simulated in a laboratory. The generator was fitted with 6 inches of spiral turbine. It was attached with 6 inches of PVC pipes and its body was a clear acrylic for better performance observations. The simulator system could generate 5 levels of water flow speed ranging from 1–2 m/s, which represented the actual current in local irrigation canals with a flow speed rate of 0.5–2.0 m/s throughout the region [8]. The initial torque power and torque power was identified using Equation (1) [46–48]. Later, in the field experiments, the turbine size was increased to 15 inches.

$$P_{t,out} = \frac{2\pi\tau N}{60} \tag{1}$$

$$P_{t,out} = \text{Power Output (kW)}$$
$$\tau = \text{Torque (Nm)}$$
$$N = \text{Revolutions per minute (RPM)}$$



(**a**)

(**b**)

Figure 1. Sketch of the experimental setup. (**a**) Isometric view; (**b**) top view.

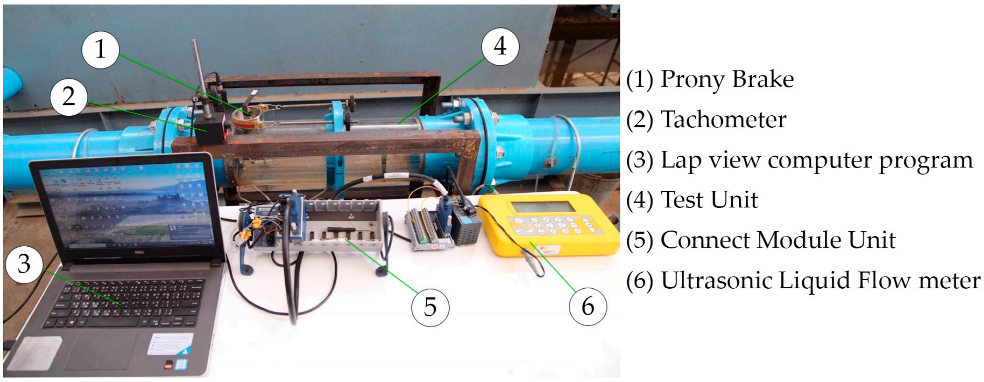


Figure 2. Simulation set.

Value measurements in the laboratory were operated by using: (1) an Ultrasonic Liquid Flow Meter; Micronics Portaflow PF300 for water flow rate (m/s), (2) a Tachometer Light Sensor Module for RPM, and (3) a Local Cell Module for torque at turbine axles. These values were processed by Lab View NATIONAL INSTRUMENTS NI cDAQ-9178 to identify the generated power and turbine efficiency. This laboratory simulation was carried out according to Gianluca Zitti et al. (2002) [49]. Torque values from each turbine model were studied and evaluated for appropriate uses in real contexts.

Power and efficiency of turbines at different water volumes and flow speeds were identified using Equations (2) and (3). The peak power of turbines was identified using Equation (4) [50,51].

$$P_{t,in} = \rho g Q H_n \tag{2}$$

$$\eta = \frac{P_{t,in}}{P_{t,out}} \tag{3}$$

$$P_{t,out} = \left[\frac{16}{27}\right]\left[\frac{1}{2}\right]\rho A v^3 \tag{4}$$

$P_{t,in}$ = Power input (kW)

ρ = Water Density $\left(\mathrm{kg/m^3}\right)$

g = Gravitational of mass $\left(\mathrm{m/s^2}\right)$

Q = Water Volume $\left(\mathrm{m^3/s}\right)$

H_n = Head Pressure (m)

η = Efficiency

$\frac{16}{27}$ = Max Power Coefficient (CPmax)

A = Turbine Surface $\left(\mathrm{m^2}\right)$

v = Water Flow Speed (m/s)

One rotation of the HST axle (360 degree) determined the width and the length of the turbine. The fixed pitch (L) and fixed diameter (D) are displayed in Table 2. HSTs with 18 and 21 degree blade angles, and the three-blade turbine, are displayed in Figures 3 and 4.

Table 2. Turbine specifications.

Turbine	Blade Area (mm^2)	Pitch (mm)	Length (mm)	Width (mm)
18-degree	12,653.72	49	233	150
21-degree	10,587.91	49	197	150
3-blade	754.96	-	-	10

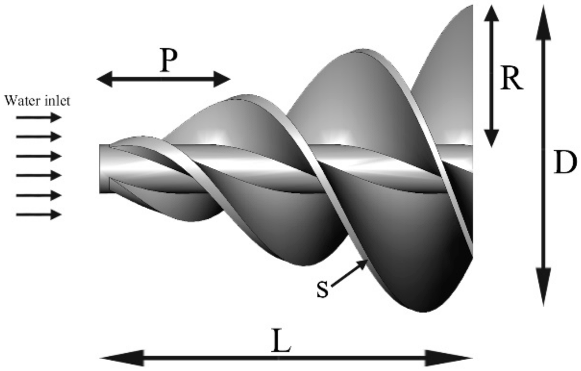
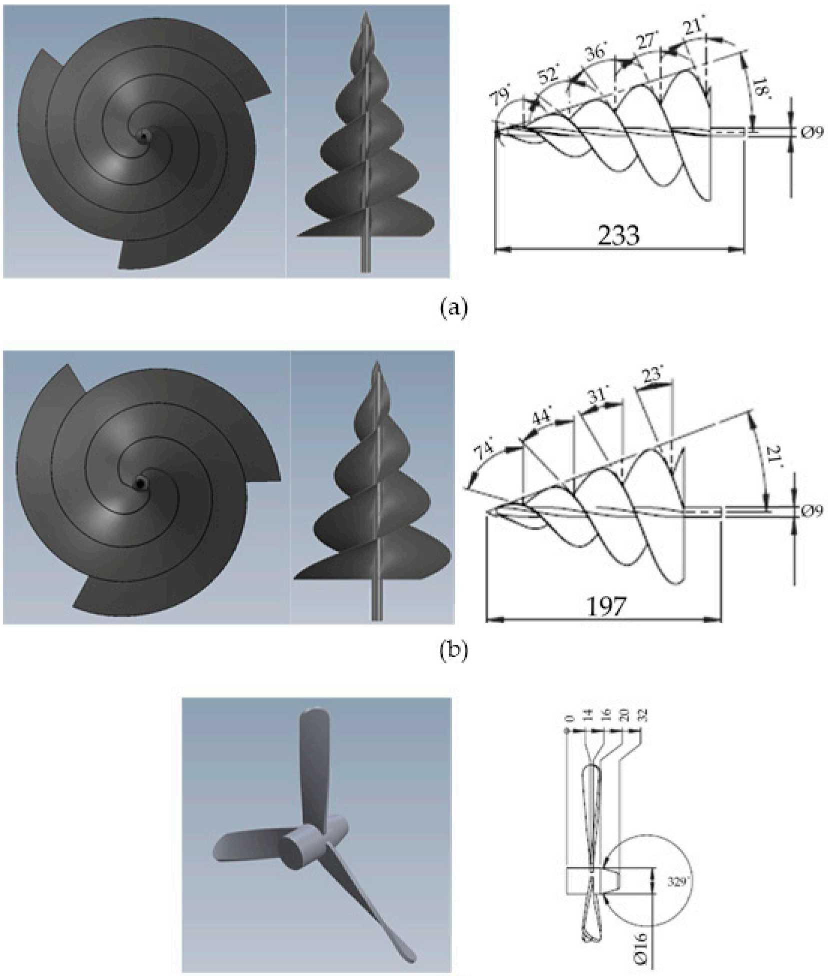


Figure 3. Horizontal spiral turbine design.



(a)

(b)

(c)

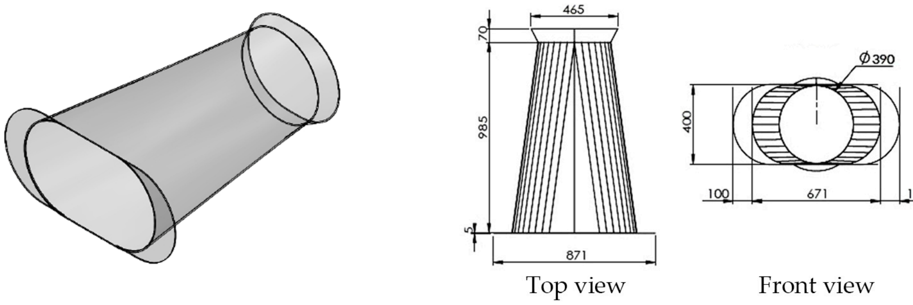
Figure 4. Turbines to be tested in the simulations. (**a**) 18-degree, (**b**) 21-degree, (**c**) 3-blade.

"L" represents the height at one round of rotation. "s" represents the peripheral length of the HST. "R" represents the HST radius. "N" represents the number of rounds of rotation. All the variables were used in Equations (5) and (6) for the design.

$$r'(t) = -\frac{2\pi NR}{L}\sin\left(\frac{2\pi Nt}{L}\right)i + \frac{2\pi NR}{L}\cos\left(\frac{2\pi Nt}{L}\right)j + k \tag{5}$$

$$s = \sqrt{4\pi^2 N^2 R^2 + L^2} \tag{6}$$

The collective chamber (see Figure 5) was designed according to Yasuyuki [41] to regulate the inlet fluid pressure of the system [52]. It was also attached with a rudder to enhance the water flow rate.



(a) (b)

Figure 5. Diffuser/collective chamber. (a) Three-dimensional representation; (b) drawing view.

Power Output (η)

The power output was identified using Equations (7) and (8) [53].

$$\eta = \frac{P_e}{P_m} \tag{7}$$

$$P_e = \mathrm{EI} \tag{8}$$

E = Voltage (V)

I = Current (A)

P_e = Power Output (W)

P_m = Power Output from Water Power (W)

3. The Field Experiment

A diffuser was attached to the turbine housing of a 200 W electrical power generator (Table 3) as displayed in Figure 6. A 15-inch-diameter HST with an 18-degree blade angle, a 15-inch-diameter HST with a 21-degree blade angle, and a three-blade turbine 15 inches in diameter were tested in this generator system. There were two generator systems used in the experiment: (1) a generator system with a diffuser as a trumpet-shaped collective chamber attachment (see Figure 7a), and (2) a generator system with an in-line pipe + diffuser + nozzle chamber attachment (see Figure 7b). They were tested in an irrigation canal in Baan Kota, Tambol Sila, Amphoe Muang, Khon Kaen Province (see Figure 8) with water velocity ranging from 0.8 to 1.2 m/s and a water volume of 2.10–3.15 m^3/s. They were planted using a rigid structure as a scaffold to set them in the middle and along the canal. The data of (1) water velocity, (2) the turbines' RPM, (3) the turbines' torque, and (4) the power output were analyzed using measuring devices, and this data reading process was carried out exactly as in the laboratory.

Table 3. Axial flux generator specification.

Rated Power	0.2 kW
Rated Rotation Speed	200 rpm
Rated Voltage	12VAC
Efficiency	90%
Start Torque	<0.05 Nm
Phase Type	3 Phase

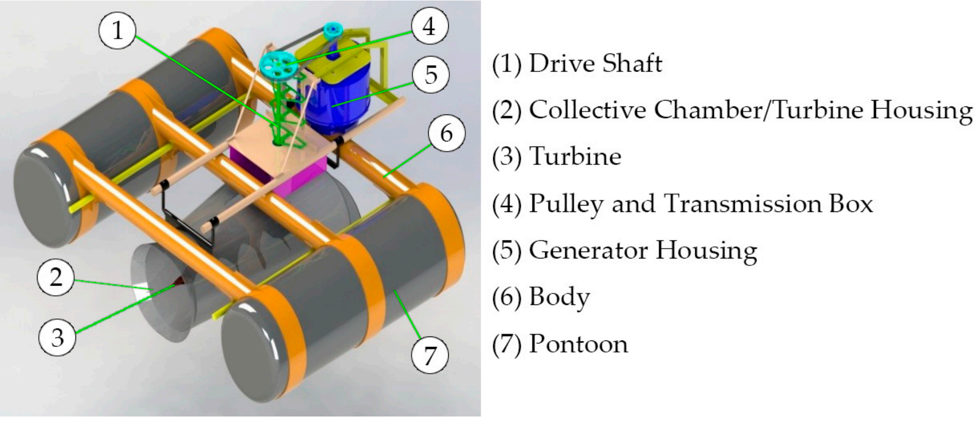
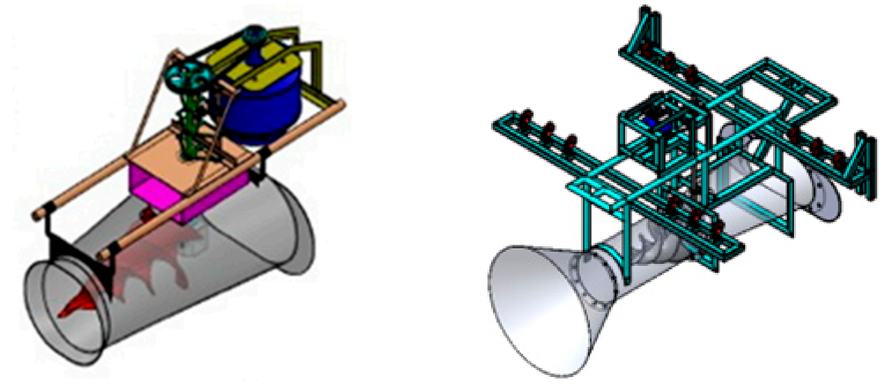


Figure 6. The prototype and its components.



(**a**) (**b**)

Figure 7. Two generator systems. (**a**) The generator system with a diffuser as a trumpet-shaped collective chamber. (**b**) The generator system with an in-line pipe + diffuser + nozzle chamber.

(**a**) (**b**)

Figure 8. Field experiments. (**a**) The generator system with a diffuser as a trumpet-shaped collective chamber. (**b**) The generator system with an in-line pipe + diffuser + nozzle chamber.

4. Results and Discussions

Turbines' efficiency and torque from laboratory simulator

The comparison results of efficiency of the three turbine types with 6-inch diameters at different water velocities from the laboratory simulation are displayed in Figure 9. As shown below, the HST with the 21-degree blade angle reached the highest efficiency at all water flow speeds. The HST with the 18-degree blade angle's efficiency was lower than that of the 21-degree HST. However, the efficiency of the three-blade turbine could not be determined under water velocities ranging from 1 to 2 m/s. It needed higher water flow speed to be practical, so it had the lowest efficiency in this experiment. The HST with the 21-degree blade angle had 38.10% efficiency at 120.00 rpm of 2 m/s water velocity. It reached 39.05% at 156.63 rpm of 1.5 m/s water velocity. The results revealed that the operations of the HST with 21-degree blade angle at 1, 1.25, 1.50, 1.75, and 2.0 m/s indicated 1100, 1300, 1630, 1850, and 2100 L/s of water, respectively. Figure 10 displays the torque values generated from the HSTs and the three-blade turbine. All torque values were altered by water flow speed. The 21-degree HST generated the most torque at 212 Nm at 2 m/s water flow speed. This created data that can be used as a reference in enhancing systems for practical field applications.

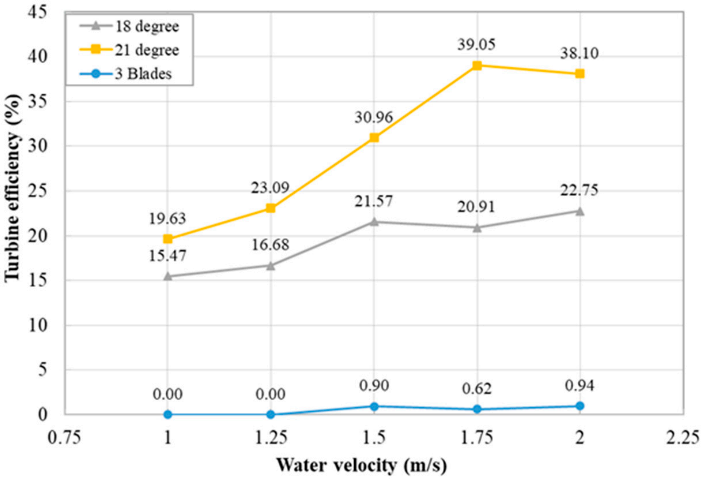


Figure 9. Comparison results of efficiency of the three turbine types in laboratory simulation at water flow speed of 1, 1.25, 1.50, 1.75, and 2.00 m/s.

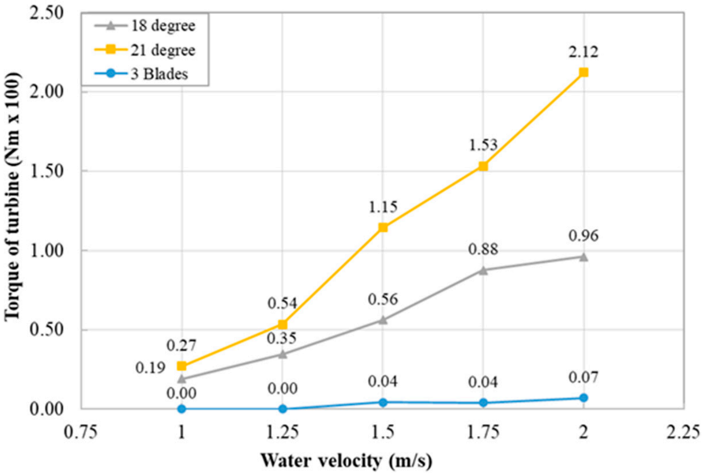


Figure 10. Comparison results of torque values of the three turbine types in laboratory simulation at water flow speed of 1, 1.25, 1.50, 1.75, and 2.00 m/s.

Field Experiments

The torque values of the three turbine types with 15-inch diameters are shown in Table 4. From the field experiments in an actual irrigation canal with the average water velocity of 1.2 m/s, the best turbine type was the HST with the 21-degree blade angle in a generator system with an in-line + collective chamber + inlet nozzle. It had a peak torque of 284 Nm. The HST with the 21-degree blade angle in a generator system with only the diffuser/collective chamber could only generate a torque value of 217.2 Nm.

Table 4. Torque results.

Turbine		Speed of Turbine (rpm)	Torque (Nm × 100)
Water velocity (m/s)		1.2	1.2
Spiral turbine + collective chamber	18-degree	28	13.65
	21-degree	41	21.72
	3-blade	26	4.56
Spiral turbine + inline + collective chamber + inlet nozzle 100 cm	18-degree	102	20.06
	21-degree	108	28.40
	3-blade	58	7.04

When torque values generated from the 6-inch-diameter turbines used in the laboratory simulation and the 15-inch-diameter turbines used in the field experiments from both generator systems were compared, it was obvious that the generator system with the additional modifications of collective chamber + inlet nozzle 100 cm could generate more torque. In the laboratory simulation, at a water flow speed of 1.2 m/s, the 21-degree HST with 6-inch diameter produced about 49 Nm of torque, but when the turbine diameter was increased to 15 inches, the torque values increased to 217.2 and 284.0 Nm in both generators. Obviously, the generator with higher torque could generate more power.

Power output

From the field experiments in an actual irrigation canal with the average water velocity of 1.2 m/s, the best turbine type among the rest that could generate the most power output (67.63 watts) was the HST with the 21-degree blade angle in a 200 W generator system with an in-line + collective chamber + inlet nozzle (as shown in Table 5). After the long-run operations at different water flow speeds, the results were as shown in Figures 11 and 12. These results were analyzed and compared with related studies as displayed in Table 6.

Table 5. Power output results.

Turbine		Electric Power (Watt)
Water velocity (m/s)		1.2
Spiral turbine + collective chamber	18-degree	21.90
	21-degree	28.43
	3-blade	6.92
Spiral turbine + inline + collective chamber + inlet nozzle 100 cm	18-degree	26.85
	21-degree	67.63
	3- blade	7.15

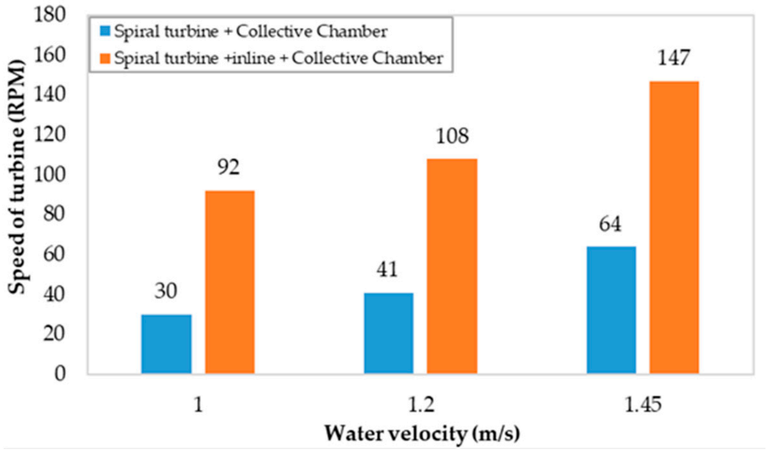


Figure 11. Comparison results of rpm generated by HST with 21-degree angle blade in the generator system with diffuser/collective chamber and the generator system with in-line + diffuser + nozzle chamber at water velocities of 1.0, 1.2, and 1.45 m/s.

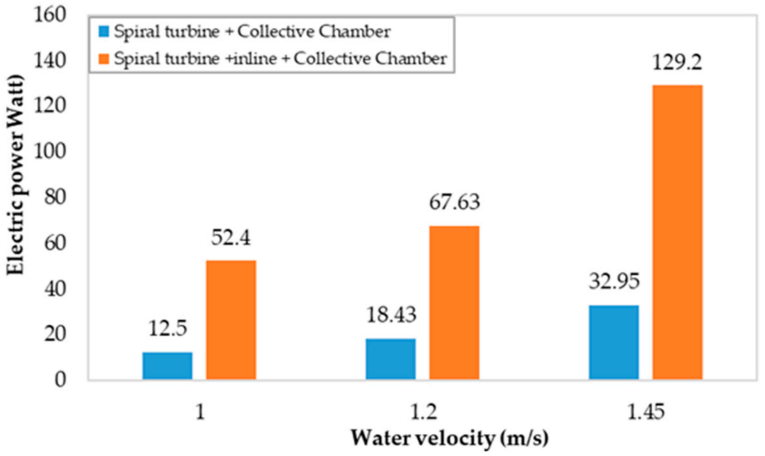


Figure 12. Comparison results of power output generated by HST with 21-degree angle blade in the generator system with diffuser/collective chamber and the generator system with in-line + diffuser + nozzle chamber at water velocities of 1.0, 1.2, and 1.45 m/s.

Table 6. Comparing results with related studies.

Ref.	Turbine	Water Velocity (V)	Section Inlet Area (A)	Work Output (Watt)
Wiroon	21 deg spiral Turbine + diffuser	1.45 m/s	0.16 m^2	67.63
Yasukuni Nishi et al. [41]	3-blades + diffuser	1.72 m/s	0.16 m^2	154.00
Erinofiardi [54]	Screw Turbine	0.077 m/s	0.0088 m^2	0.28
Tomomi Uchiyama [12]	Guide vane	0.159 m^3/s	0.005 m^2	222.00
Joel Titus [55]	Turbine blades	0.009 m^3/s	0.005 m^2	212.00
Budiarso [56]	Turgo turbine	n.d.	0.038 m^2	5.34
C.H. Achebe [57]	Crossflow turbine	0.0015 m^3/s	0.015 m^2	35.00
Gianluce Zitti et al. [49]	Screw turbine	1–2 m/s	0.003 m^2	500.00

5. Summary and Conclusions

The golden ratio function had the most important role in this study in order to verify the proper HST's blade angles. There were three turbines (an HST with an 18-degree blade angle, an HST with a 21-degree blade angle, and a three-blade turbine) designed to be tested in two generator systems in this study. Firstly, all turbines were tested in a simulation set in the laboratory. The simulator revealed that the HST with the 21-degree blade angle had the highest efficiency (38.10%) at all water flow speeds. When the two sets of generator systems (one with a diffuser/collective chamber attachment and another one with an in-line + diffuser + nozzle chamber) were tested in an actual irrigation canal at the average natural water flow speed of 1.2 m/s, the results revealed that the HST with the 21-degree blade angle in a generator system with an in-line + diffuser + nozzle chamber could generate the highest power input of 67.63 watts. In the long-run operation experiment, when the water velocity reached 1.5 m/s, it could generate electrical power up to 129.2 watts.

The turbines used the in laboratory and field experiments were different in size because the bigger turbine size employed in the actual irrigation canal had more inertia. Thus, the transmission set attached to the generator system had to be properly designed to fulfill the turbine's performance.

This study showed that a Horizontal Spiral Turbine (HST) in a hydro-compact generator system could effectively operate under low water flow speed. The HST blade angle could also generate high torque from low water flow speed. In conclusion, an HST in a generator system with an in-line + diffuser + nozzle chamber could significantly generate high torque and high power output in any actual irrigation canal with low water flow rate at the average of 1.5 m/s throughout the country.

6. Break-Even Point and Investments

From this study, the conditions that must be considered in order to meet the break-even point for investors are:

- 1.5 m/s average water flow speed;
- 24 h operation;
- 365 days production length;
- 0.8 (9.6 months) plant factor value;
- USD 0.13 per one power unit selling price.

The maximum cost of production of a 200-watt hydro-compact generator with an HST and attachments is USD 2434.83 and the break-even point is 22.86 years. Details are displayed in Table 7.

In conclusion, it is obvious that the main issue of applying this kind of technology is the correlation between the cost of production and the break-even point. However, the production cost of this compact hydro-generator system is still high, whereas the low-speed water flow rate of local irrigation canals provides "not much" renewable energy. Nicolas D et al. (2016) stated that the main concerns of using HSTs were lowering the production costs, enhancing the turbines' efficiency, environmental awareness, and public relations campaigns [58].

Table 7. A 200-watt hydro-compact generator with HST cost of production.

Inventory	USD per Unit
1. Turbine Cost of Production	429.31
2. Materials Cost	572.41
3. Generator Cost of Production	857.67
4. Labor Cost	572.41

Remark: There will be variations in production cost since the cost has been converted from THB to USD (updated 15 December 2020).

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