Feasibility Analysis of a Pico-Scale Turgo Turbine Bucket using Coconut Shell Spoons for Electricity Generation in Remote Areas in Indonesia

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ARTICLE INFO	ABSTRACT
	Until 2018, 1396 villages in Indonesia, deemed as remote areas, still did not have access to the national grid electricity. To resolve this issue, the use of independent power plants is an appropriate solution. The use of a pico-scale Turgo turbine, which is an independent power plant, is recommended in Indonesia due to its mini-, micro-, and pico-scale water energy potential of 19 GW. As the Turgo turbine is intended for use in remote areas, the use of local materials, e.g., coconut shells, is proposed as the bucket material. From static compressive strength tests revealed that the maximum pressure points a coconut shell proportional to the water pressure with a potential power of 3300 W. The size of a coconut shell spoon, which is not uniform, can be overcome by its curvature angle. The curvature angle represents the relative angle of the incoming and outgoing jets, while this is a represents of the depth and length of the spoon. Thus, to ensure the performance of the Turgo turbine under maximum conditions, the curvature angle of the coconut shell spoon is ~90°. Moreover, the total efficiency of the turbine is 34.94%, with a possibility of reaching higher values.

1. Introduction

Until 2018, 1396 villages, corresponding to 1.7% of the total number of villages, in Indonesia still did not have access to electricity [1], where a majority of these villages are located in remote areas. Generally, the remote areas in Indonesia are hilly regions, which still do not have adequate access to the infrastructure, leading to the difficult in expanding the electricity grid. In addition, the high costs associated with the expansion of the electricity grid to remote areas are a limitation. The electricity grid expansion is expensive because it is difficult to obtain licenses to open up land for expansion electricity grid in protected forest areas or nature reserves and to provide compensation

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commensurate to the loss experienced by those affected by grid expansion. Furthermore, each remote location comprises a small number of residents (implying low electricity utilization), and their income is less than those of urban communities, also leading to unecomonic electricity costs during grid expansion [2]. Thus, independent electricity plants constitute a technological solution to satisfy the needs of electricity in remote areas [3,4]. Pico hydro is an independent electricity plant that may be appropriate for remote areas in Indonesia due to its small-, micro-, and pico-scale water energy potential of up to 19 GW under low head conditions (<5 m) [5].

It is a hydroelectric power plant with a capacity of less than 5 kW [6]. In terms of investment and operational costs (life-cycle costs), pico hydro is more cost-effective than wind turbines and solar photovoltaics [7,8]. This has been demonstrated in Cameroon [7], Kenya [9], Nepal [10], Laos [11], Rwanda [12], Honduras [13], and Peru [14], which have used pico hydro for the generation of electricity in remote areas.

Typically, under low head conditions, the maximum efficiency is only achieved if reaction turbines such as a propeller, Archimedes, overshot, and undershot are utilized [15]. The use of an impulse turbine (Turgo and/or Pelton turbine) under low head conditions is not favourable, and it is not recommended for pico-scale applications. However, hydropower on the micro, small, mini, and large scale is typically used for commercial purposes; hence, it is crucial to select an appropriate, efficient turbine. While, the case for the use of pico hydro wherein the selection of the turbine is considered in accordance to several factors: maintenance, operational, modularity, portability and investment cost [8]. Based on the assessment by multi-criteria analysis, an impulse-type pico-scale Turgo turbine is recommended for applications in remote areas [15]. Turgo turbines are suitable in remote areas due to their low investment costs, portable, easy to operate and easy maintenance [15,16].

Since the Turgo turbine is an impulse-type turbine, the low rotation velocity produced under low head conditions is an issue [17]. Therefore, a direct current (DC)-type generator is used because it can produce electricity under low rotations [18]; it is cost-effective, and it exhibits a capacity of less than 2 kW [19]. In addition, several electrical appliances, such as lighting lamps, use DC currents. Moreover, by using electrical equipment with an alternating current (AC), the generated DC current can be stored using batteries and supplied to the AC electrical equipment using an inverter [20].

The performance of the Turgo turbine is affected by its bucket shape because the conversion of water energy to the turbine occurs in a bucket [21]. The bucket shape of the Turgo turbine is curved. The curvature of the Turgo turbine bucket is designed to deflect the flow of water [21]. To achieve the maximum efficiency of a Turgo turbine, a bucket with a flow deflection curve must be manufactured with high precision. However, it is difficult and expensive to make a bucket with good flow deflection [22]. Considering that pico hydro is an independent power plant owned by a person or a group of people, a simple shape as well as construction, low investment and operational costs, as well as maintenance, and easy access to component materials are the main characteristics for the application of a pico-scale Turgo turbine.

The use of materials that are widely available in the market as raw materials for the Turgo turbine buckets has been carried out. For example, stainless-steel spoon materials have been used for making Turgo turbine buckets due to their cost-effective [16,23]. Such examples provide new ideas from local Indonesia people for the application of pico hydro. The use of natural raw materials, namely coconut shells, has long been used by the Indonesian people as spoons for eating and cooking. When it comes in contact with water, a coconut shell spoon is strong and durable, although its strength is still less than that of a stainless-steel spoon. Owing to its cost-effectiveness, non-corrosiveness, and abundance throughout Indonesia, coconut shell spoons can be used as the bucket for a Turgo turbine runner. Thus, in this study, the curvature angle of a commercially available coconut shell spoon is

examined in accordance with the water outlet direction to achieve the maximum efficiency of the turbine.

2. Theoretical Hydraulic Efficiency of the Turgo Turbine

The difference between the Turgo turbine and the Pelton turbine is the direction of the jet from the nozzle (Figure 1).
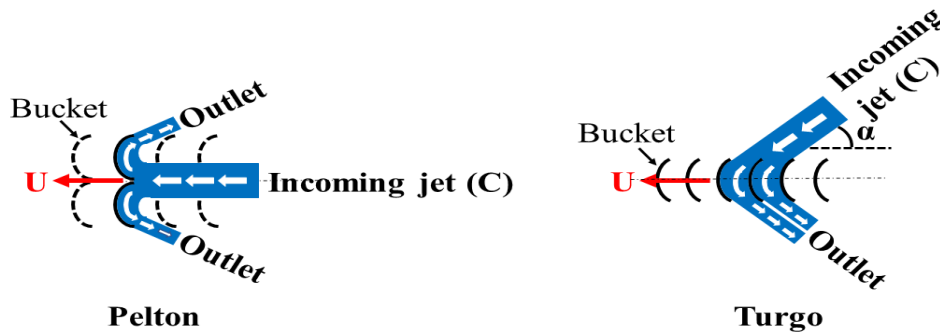

Fig. 1. Difference in the angle of the incoming jet of the Pelton and Turgo turbines

The kinetic energy of the water absorbed by the runner is expressed by changes in the inlet and outlet velocities of water (Figure 1). The angle of the relative velocity at the water inlet (β_1) is made parallel to the edge of the inlet side of the bucket; hence, water can smoothly enter to avoid the occurrence of a hydraulic shock (water hammer) [24]. The calculation of the Turgo turbine design begins by the determination of the actual velocity of the incoming jet or absolute velocity (C_1) based on the head (H) and coefficiency of friciton (C_d) of the nozzle [25] using Eq. (1).

$$C_1 = C_d\sqrt{2gH} \tag{1}$$

Generally, the C_d value for the Turgo turbine nozzle is 0.96.

From Figure 2, C is the absolute velocity of water, W is the relative velocity of water, U is the rotation velocity of the wheel, β is the angle of the relative velocity, α is the angle of the absolute velocity, 1 is the inlet position, and 2 is the outlet position.

The amount of the absorbed water energy (E) depends on the change in the momentum of the flow of water after passing through the bucket, which is determined using Eq. (2) [26].
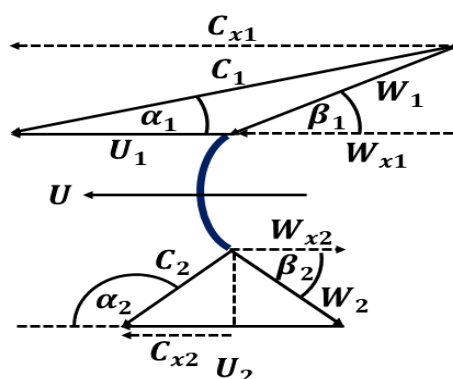

Fig. 2. Vector of velocity triangle in the Turgo turbine [17]

$$E = \frac{(U_1 C_{x1} - U_2 C_{x2})}{g} \tag{2}$$

where $C_{x1} = W_{x1} + U_1$; $C_{x2} = W_{x2} + U_2$; $\cos \alpha_1 = (W_{x1} + U_1)/C_1$; $\cos \alpha_2 = (W_{x2} + U_2)/C_2$; $U = r \cdot \omega$. β_1 can be expressed as follows

$$\beta_1 = \tan^{-1}\left(\frac{\sin \alpha_1}{\cos \alpha_1 - \varphi}\right) \tag{3}$$

where φ is the ratio of the rotational velocity of the wheel (U) and the absolute velocity at the inlet (C_1)

$$\varphi = \frac{U}{C_1} = \cos \alpha_1 - \frac{\sin \alpha_1}{\tan \beta_1} \tag{4}$$

To achieve the maximum efficiency, φ is 0.46 [27], while α_1 varies between 20° and 40° [24]. Hence, the power produced by the turbine (P_M) is expressed as follows

$$P_M = \rho Q (U_1 C_{x1} - U_2 C_{x2}) \tag{5}$$

Then, the theoretical hydraulic efficiency (η_H) is expressed as follows

$$\eta_H = \frac{P_M}{P_h} = \frac{P_M}{\rho g Q H} \tag{6}$$

where P_h is the power potential of water. By using the velocity triangle, the theoretical hydraulic efficiency is as follows [27]

$$\eta_H = 2 C_d{}^2 \left(\varphi \cos \alpha_1 - \varphi^2 + \frac{k \varphi \sin \alpha_1 \cos \beta_2}{\sin \beta_1}\right) \tag{7}$$

where k is the coefficient of friction in the bucket with a value between 0.90 and 0.95.

3. Coconut Shell Spoon Bucket

Coconut shells are natural materials that are easily obtained and widely used as household furniture in Indonesia. They are also used as vegetable spoons (Figure 3). The use of the hereditary coconut shell material indicates that this material is extremely resistant to water. The coconut shells spoon in Figure 3 is sold in Indonesia both in cities and villages.

Prior to the application of a coconut shell material for the bucket of the Turgo turbine, it is crucial to perform geometrical analysis. Geometrical analysis is performed to estimate the change in momentum that occurs due to changes in the jet direction. The changes in the jet direction are caused by the curvature of the spoon. In addition, the strength of the coconut shell spoon material needs to be estimated as it will come in contact will pressurized water. The strength is estimated to determine the limit of water pressure that the bucket can withstand.

Fig. 3. Shape of the coconut shell spoon from the Indonesian market

3.1 Geometry of Coconut Shell Spoon

The geometrical analysis of the coconut shell spoon is carried out to determine the shape of the spoon (Figure 3) that can absorb the highest amount of water energy. Geometrical analysis is performed by the measurement of the length (L), width (B), depth (T), and angle of curvature (Figures 4 and 5, and Table 1).

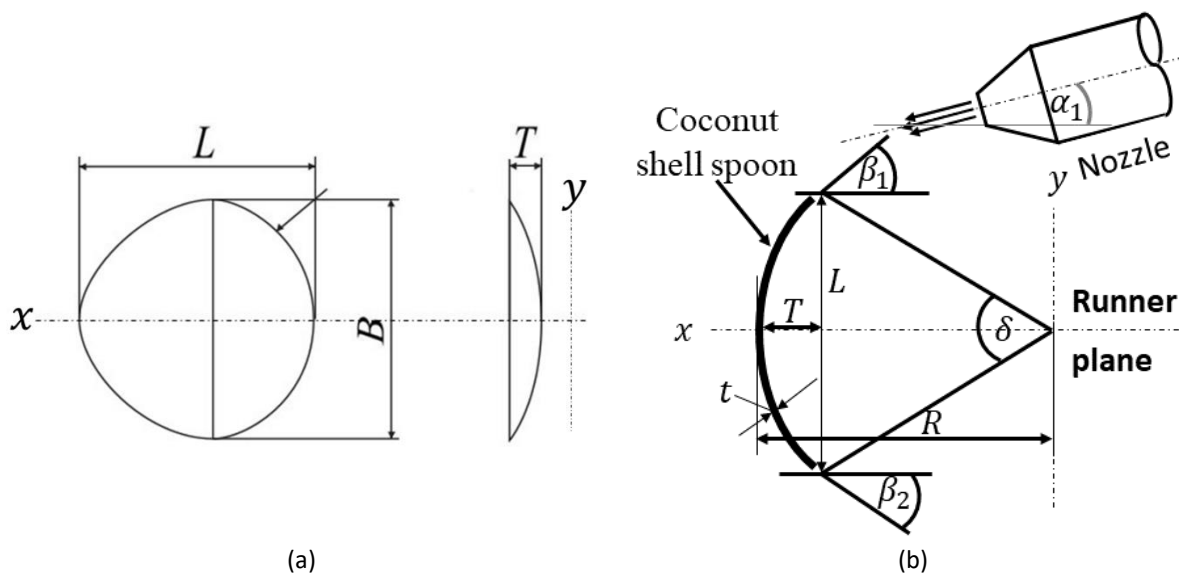(a)   (b)

Fig. 4. Geometry of the spoon (a) Transverse dispay of the spoon (b) Dimension of the spoon

Table 1
Dimensions of the coconut shell spoon from the Indonesian market

Type	L (mm)	T (mm)	R (mm)	B (mm)	t (mm)	δ (°)
Spoon A	95	20	66	8.0	1.5	92
Spoon B	90	12	90	7.5	1.5	60
Spoon C	85	10	95	7.5	1.5	53
Spoon D	80	11	78	6.2	1.5	62

3.2 Geometrical Positions of the Coconut Shell Spoons towards the Runner Plane

If α_1 and φ are fixed, then β_1 will not change (Eq. 3). However, η_H will change because of changes in β_2 (Eq. 7). β_2 depends on the position of the blade towards the plane parallel to the axis. Geometrical analysis is performed by positioning the four spoon models (i.e., A, B, C and D, respectively) with the same α_1 value. The α_1 values are varied in the range of 10°, 20°, 30°, and 40°. Although the α_1 value for all four spoons are the same, the β_2 value will vary. By rotating the blade (changing the blade position) towards the runner plane until the desired α_1 value is obtained, β_1 and β_2 can be determined using the analysis shown in Figure 5 and Eq. (3), (8) and (9). Thus, η_H for each bucket or spoons model can be determined using Eq. (7).

$$\delta = 2 \, \arcsin \frac{L}{2R} \tag{8}$$

$$\beta_2 = 180° - \delta - \beta_1 \tag{9}$$
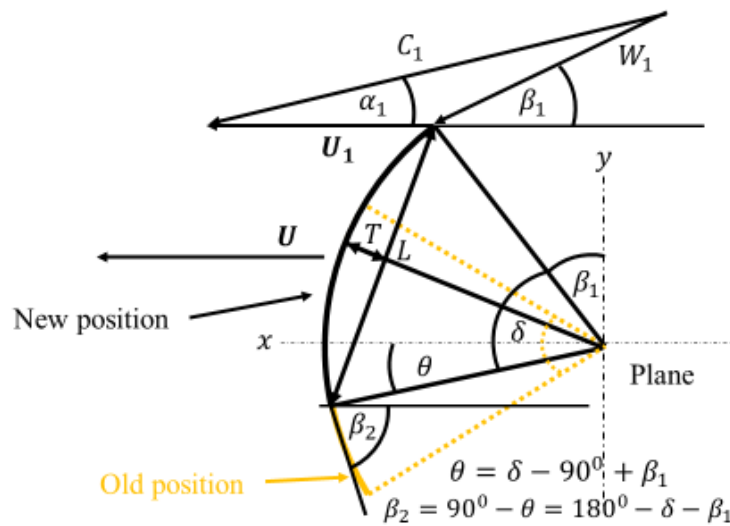

Fig. 5. Concept of the vector velocity triangle analysis on coconut shell spoons

4. Static Test Pressure of the Coconut Shell Spoon

The strength of the coconut shell spoon is estimated by static compressive strength tests to determine the maximum static load that it can withstand until it undergoes cracks or breakage. This test is carried out using Marshall's test equipment and the Marshall test (Figure 6a).

The strength test is carried out using 30 samples comprising models A (0) and C. The spoon sample is pressed using a steel ball (pounder) (Figure 6b). The surface of the sample that meets the steel ball is measured using Vernier callipers. The deformation depth is measured using a dial gauge (µm). The measured depth values are converted to force, which is first multiplied by a calibration factor of 0.3979 kgf/div. Then, to calculate the total force that can damage the coconut shell spoon, the results from the calibration product are converted into Newton (N), with a conversion of 1 kgf ≈ 9.81 N, and added to 7.3637 N. The value of 7.363 N is the total weights of the steel ball, nuts and bolt. Furthermore, the surface pressure of the sample is determined by dividing the total force that can damage the sample with the surface area of the sample that meets the steel ball. Figure 7 shows the results obtained from the static compressive strength tests using the Marshall test. The static

compressive strength of the coconut shell spoon affords a large standard deviation, with an uncertainty percentage of greater than 20% (Figure 7). Such a high uncertainty value is related to the different thicknesses of the sample. The average static compressive strengths of model A and C spoons are 19.023 ± 3,9 MPa and 19,104 ± 5,1 MPa, respectively.
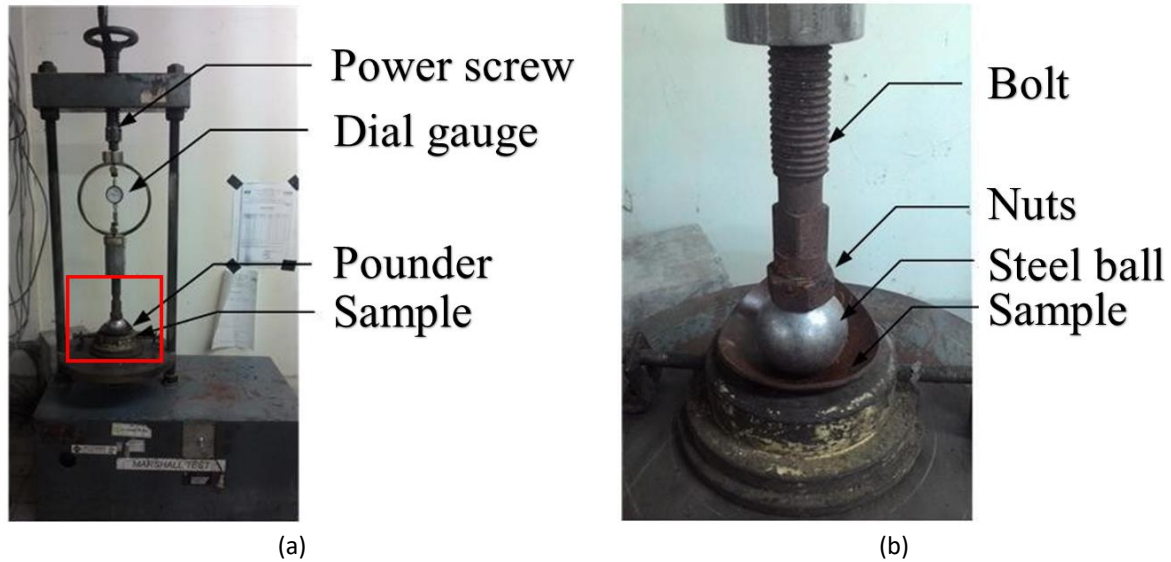

(a) (b)

Fig. 6. Marshall text method (a) Static pressure test equipment (b) Sample testing
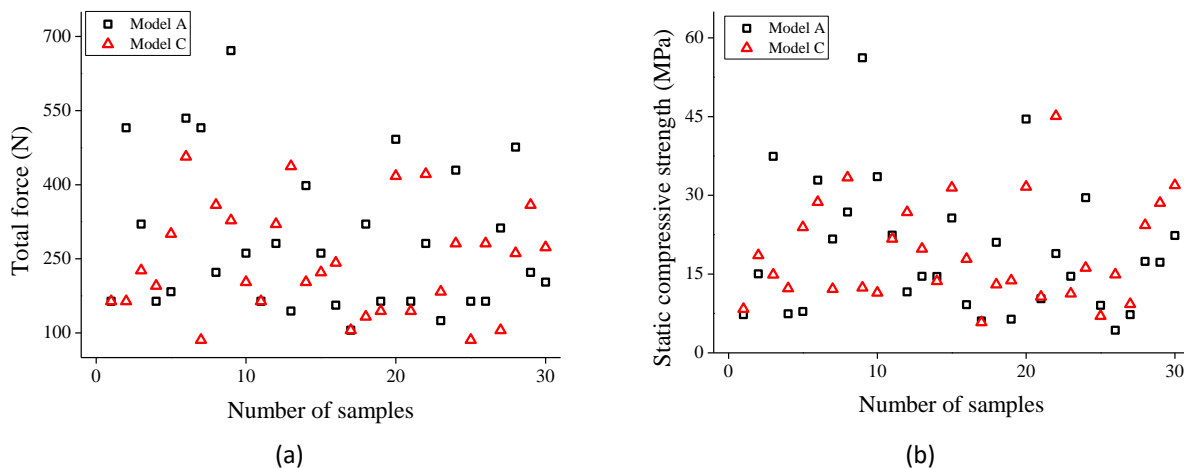

(a) (b)

Fig. 7. Static compressive strength test results (a) Total force (b) Static compressive strength

If the Turgo turbine exhibits a capacity of 500–2500 W with an efficiency of 45–55%, then the maximum force of water to the bucket can be determined as follows. Based on the Euler concept in Eq. 5, the maximum efficiency can be attained if C_{x2} is assumed to be 0. Furthermore, the power produced by the turbine (P_M) is calculated using Eq. 10

$$P_M = \tau \cdot \omega \tag{10}$$

where τ is the torque, and ω is the rotational speed of the wheel. τ is determined using Eq. (9)

$$\tau = \rho \cdot Q(r_1 C_{x1} - r_2 C_{x2}) \tag{11}$$

where r is the radius of the wheel. Hence, the force of water to the bucket is expressed by $\rho \cdot Q \cdot C_{x1}$ or

$$F = p_{jet} \cdot A \tag{12}$$

where p_{jet} is the pressure of the jet, and A is the bucket area. The determination of A is adapted from the circle area equation; hence, $A = \pi \cdot d^2/4$. d is the nozzle diameter, which is equal to L/(2 until 3) or T $\cdot$ (0.8 until 1.2). Hence, d for the bucket model A is 0.032 m. Table 2 summarizes the calculation using Eq. 12.

Table 2
Analysis of the pressure received by the bucket at a potential power of 1100–3300 W

P_h (W)	η_H (%)	P_u (W)	Q (m³/s)	F (N)	p_{jet} (MPa)
1100	45	495	0.056	342.00	0.42
1700	45	765	0.087	528.54	0.66
2200	45	990	0.112	684.00	0.85
2750	45	1238	0.140	854.99	1,06
3300	45	1485	0.168	1025.99	1,28

Based on Table 2, for a P_h of 3300 W, p_{jet} is 1.28 MPa. On the other hand, the bucket model A can withstand loads up to 19.023 ± 3,9 MPa. Thus, coconut shells can be used as the bucket for the pico-scale Turgo turbine.

5. Calculation Results

Eq. 7 is utilized to determine the η_H values for each spoon model, where α_1 is varied from 10° to 40° [28], C_d is set at 0.97, k is set at 0.92 [24], and the optimum φ value depends on the α_1 value (See Table 3 for more details) [28].

Table 4 summarizes the results obtained from the calculations using Eq. 7. Based on Table 4, spoon type A is the good choice as a blade because it has a higher efficiency than other types. Thus, type A is used as a blade (see Figure 8).
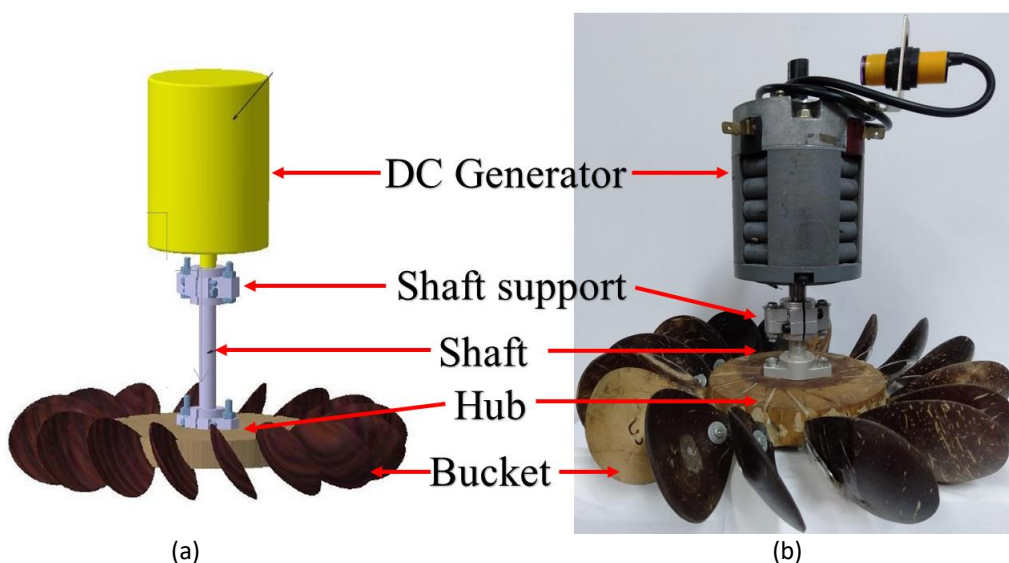

(a)   (b)
Fig. 8. Turgo turbine (a) Schematic of the Turgo turbine (b) Top-view of runners

Table 3
Relationship of φ and α_1

Parameter	Value			
α_1	10°	20°	30°	40°
φ optimum	0.62	0.58	0.53	0.52

Table 4
Effect of α_1 on η_H based on analytical calculation

Spoon model	L (mm)	T (mm)	R (mm)	T/L	φ	δ (°)	α_1 (°)	β_1 (°)	β_2 (°)	η_H (%)
A	95	20	66	0.21	0.62	92	10	25	63	62
B	90	12	90	0.13	0.62	60	10	25	95	38
C	85	10	95	0.12	0.62	53	10	25	102	33
D	80	11	78	0.14	0.62	62	10	25	93	49
A	95	20	66	0.21	0.58	92	20	44	44	73
B	90	12	90	0.13	0.58	60	20	44	76	49
C	85	10	95	0.12	0.58	53	20	44	83	43
D	80	11	78	0.14	0.58	62	20	44	74	51
A	95	20	66	0.21	0.55	92	30	58	30	81
B	90	12	90	0.13	0.55	60	30	58	62	59
C	85	10	95	0.12	0.55	53	30	58	69	53
D	80	11	78	0.14	0.55	62	30	58	60	60
A	95	20	66	0.21	0.53	92	40	70	18	85
B	90	12	90	0.13	0.53	60	40	70	50	67
C	85	10	95	0.12	0.53	53	40	70	57	61
D	80	11	78	0.14	0.53	62	40	70	48	68

6. Manufacturing of Turgo Turbine Runners

During the manufacturing process of the Turgo turbine runner, a readymade material is possibly used to reduce manufacturing costs. However, wood and stainless-steel spoons must be processed first. The wood must be formed in a circle, which will be used as a hub that functions as a stainless-steel spoon holder, and the stainless-steel spoon handle must be cut and used as a connector between the coconut shell spoon and hub. Then, the bucket (coconut shell spoon) is placed into the formed hub gap (Figure 8).

7. Experimental Method

As the Turgo turbine will be used in remote areas, the used measuring instruments must be cost-effective, albeit exhibit a good accuracy and low uncertainty [29]. A micro-controller with a capacity of 8 bits is used with three sensors: A DC current and voltage measuring device, flow measuring device, and rotational speed device.

The DC current and voltage measuring device uses an INA129 sensor with an operational range of 0–26 Vdc. The flow measuring device uses the YF-DN40 sensor with an operational range of 0–150 lpm. The rotational speed device uses the proximity E18-D80NK sensor. All measuring instruments are built and verified using commercial measuring instruments. The DC current and voltage measuring device and the rotational speed device are verified using a commercial measuring device, while the flow measuring device is verified using a measuring cup and rotameter. Based on the verification results, the percentage of accuracy for the built measuring instruments is divided into two categories: full scale and reading. The full scale for the current DC measuring devices exhibits an accuracy of 0.8% and a DC voltage of 4.5% [29]. The reading for rotational speed measuring devices

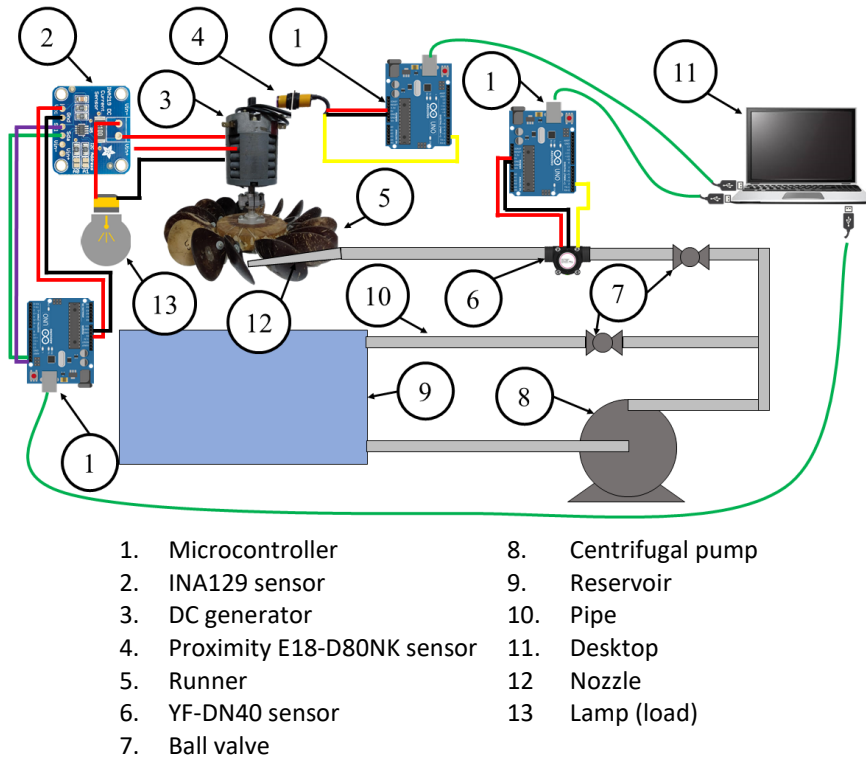exhibits an accuracy of ±2.74 rpm and a flow rate of ±0.76 lpm [29]. Figure 9 shows the experimental setup.

1. Microcontroller
2. INA129 sensor
3. DC generator
4. Proximity E18-D80NK sensor
5. Runner
6. YF-DN40 sensor
7. Ball valve
8. Centrifugal pump
9. Reservoir
10. Pipe
11. Desktop
12. Nozzle
13. Lamp (load)

Fig. 9. Experimental setup

The electric power (P_e) produced by the turbine is estimated by the following Eq. 13

$$P_e = v \cdot i \tag{13}$$

where v is the DC voltage, and i is the DC current. Hence, the total efficiency can be determined using Eq. 14

$$\eta_t = \frac{P_e}{P_h} \tag{14}$$

8. Experimental Results

Tests are carried out using a lamp with a load of 12 Vdc and with five sizes for the nozzle diameter (d): 19 mm, 16 mm, 15 mm, 10 mm, and 8 mm. The nozzle size is varied to estimate the appropriate D/d ratio in the pico-scale Turgo turbine. Figure 10 shows the test results. Based on Figure 10, the size of the nozzle affects the performance of the Turgo turbine, where a D/d ratio of 22 (d = 19 mm) affords a higher total efficiency than those of the others, with the peak of the total efficiency observed at 34.94% at a rotation speed of 404.25 rpm. Based on the results, a D/d ratio of 22 is recommended for use in the pico-scale Turgo turbine.

Based on the measurement, there is a minimum flow required for the turbine to produce electrical power: For a D/d ratio of 11.6, the minimum flow is 48 ± 0.05 lpm, for a D/d ratio of 13.7, it is 33.52 ± 0.16 lpm, for a D/d ratio of 14.67, it is 31.7 ± 0.14 lpm, for a D/d ratio of 22, it is 19.17 ±

0.18 lpm, and for a D/d ratio of 27.5, it is 15.06 ± 0.01 lpm because the used DC generator will generate current (i) if the minimum rotational speed is 190 rpm (Figure 10).
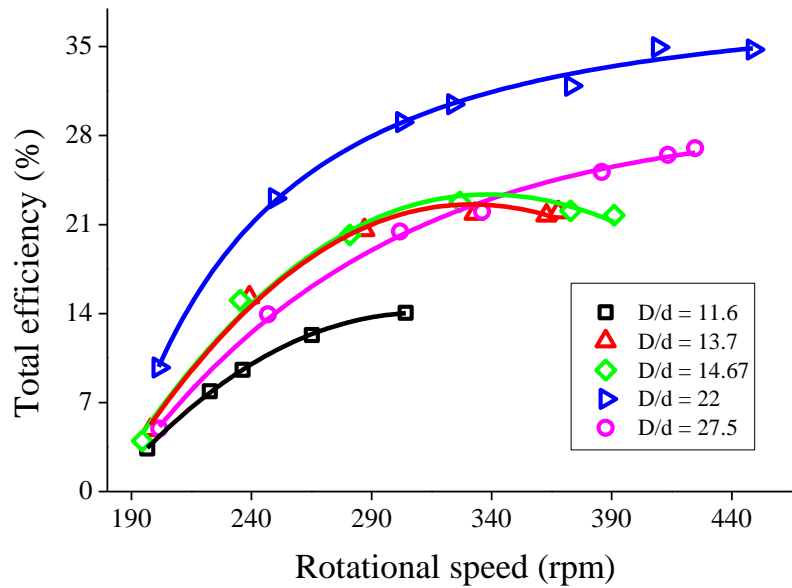

Fig. 10. Experimental results

9. Discussion

This study is a follow-up study conducted by Budiarso *et al.,* [16], and it verifies the study conducted by Gaiser *et al.,* [23]. The Turgo turbine designed by Budiarso *et al.,* [16] exhibits a hydraulic efficiency of 44.3% and an investment cost of USD 48. On the other hand, the turbine designed by Gaiser *et al.,* [23] exhibits a hydraulic efficiency of 63.4% and an investment cost only of USD 30. However, the reliability of the Turgo turbines designed by Budiarso *et al.,* [16] and Geiser *et al.,* [23] for applications is still doubtful because the reported efficiency is the hydraulic efficiency and not the total efficiency (electrical power). To clarify this doubt, the design of the runner dimension utilizes the boundary conditions proposed by Gaiser *et al.,* [23], with the only difference being the bucket material, and this turbine is connected to the DC generator. Hence, the boundary conditions proposed by Gaiser *et al.,* [23] are appropriate for use in the design of a pico-scale Turgo turbine. Moreover, the investment cost required to manufacture a Turgo turbine using coconut shell material is USD 29, which is more cost-effective than those reported by Budiarso *et al.,* [16] and Gaiser *et al.,* [23] (see Table 5). This price does not include all of the cost, if the including the DC generator and piping system the total price for manufacture is USD 85. Furthermore, if it is assumed the effiency of the DC generator used is 60 %, then the mechanical efficiency of the tubrine that builds is 58.3 % (35% devided 60%).

Table 5
Comparison investment cost and efficiency this study with previous studies

Authors	Price	Efficiency Mechanics	Total Efficiency
Budiarso *et al.,* [16]	USD 48	44.3 %	-
Gaiser *et al.,* [23]	USD 30	63.4 %	-
This study	USD 29	58.3 %	35 %

There is a significant difference in the D/d ratio for maximum operational conditions, where Gaiser *et al.,* [23] have recommended an optimum D/d ratio from 6.99 to 18.25. On the other hand, the results obtained herein are similar to the recommendations reported in the study by Cobb *et al.,* [30]. The results obtained herein and those reported by Cobb *et al.,* [30] are presumably correct because the total efficiency is reported; hence, the minimum rotation required to produce power is also accumulated. Thus, based on previous study [30], it can be said that the test carried out is valid and verified.

10. Conclusions

The theoretical hydraulic efficiency of the Turgo turbine is the maximum due to the large ratio between the depth and length of the spoon (T/L ratio) and the absolute angle of the incoming jet (α_1). The depth and length of the spoon affect the magnitude of the angle of the relative incoming (β_1) and outgoing jets (β_2). β_1 and β_2 represent the curvature angles of the coconut shell spoon (δ), and a $\delta \approx 90°$ is required to achieve a high hydraulic efficiency.

Coconut shells can be used as the Turgo turbine bucket material because the pressure received by the blade with a potential power of 3300 W is less than the maximum pressure that the coconut shell can withstand. Based on the results, the total efficiency of the turbine is 34.94%, with a possibility of achieving higher values if tested with a head above 5 m.

To increase the level of technological readiness, the as-built Turgo turbine will be tested under actual conditions to investigate the issues experienced by the turbine under real conditions.

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