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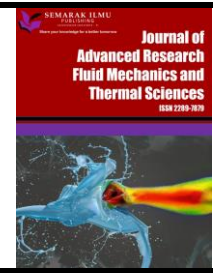


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ISSN: 2289-7879



# Feasibility of Pico Scale Turgo Turbine Blade Manufacturing Method Using Three-Dimension Printer Technology

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### ARTICLE INFO

### ABSTRACT

#### Article history:

Received 26 February 2023

Received in revised form 4 June 2023

Accepted 11 June 2023

Available online 25 June 2023

#### Keywords:

Turgo turbine; triangle velocity; blade; 3D printer

This study proposed the design of pico-scale Turgo turbine blades using triangle velocity and printing blades using three-dimensional (3D) printer technology. Then, describe the testing method of Pico scale Turgo turbines in laboratory conditions. The velocity triangle analysis accommodates backflow where it is affected by blade angle; this is relevant to the Turgo turbine because the flow and blades have an angle so that the estimated change in momentum approaches real conditions. Based on calculation results, the geometry of the pico-scale Turgo turbine blades that produce maximum performance is as follows: angle of attack is 20°, inlet blade angle is 40°, outlet blade angle is 10°, and radius blade angle is 15°. Then, simulation results determine the potential water power that the blade is capable of receiving is 17.5 W. The experimental setup has a potential water power of 14.81 W, lower than the mechanical strength simulation results. From the experimental results, the performance maximum is 0.092; the average deviation between the analytical and experimental is 4%. Therefore, the manufacture of pico-scale Turgo turbine blades using 3D printer technology is considered because of the ease of the manufacturing process, the time needed in the manufacturing process is short, and the cost is low.

## 1. Introduction

The Turgo turbine is categorized as an impulse turbine, and the blades absorb the kinetic energy of the water into mechanical power [1]. The Turgo turbine is a development of the Pelton turbine, so its approaches are widely adapted using the Pelton turbine concept [2]. Turgo turbines are considered an alternative to independent power plants in remote areas because of their simple shape and easy maintenance and operation; it is the pico scale for remote areas [3-7].

Pico scale Turgo turbine research development continues so that it can be applied in low head conditions (<5 m). Williamson *et al.*, [8] recommend designing a Turgo turbine with a two-

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dimensional (2D) quasi-steady state analysis, and the resulting efficiency ( $\eta$ ) increased by up to 20% ( $\eta$  becoming 87%). Cobb and Sharp [9] test results recommend that the pico scale Turgo turbine's angle of attack ( $\alpha_1$ ) is 20°. Warjito *et al.*, [2] utilized the curvature concept to design blades that can be manufactured using PVC pipes; follow-up research by Aaraj *et al.*, [10]. Aaraj *et al.*, [10] conceptualized the blade using the velocity triangle and elaborated on curvature; this proposal is difficult to manufacture in remote areas based on an engineering assessment by Warjito *et al.*, [2].

Saeed *et al.*, [6], Williamson *et al.*, [8], and Gaiser *et al.*, [11] explain the Turgo turbine performance ( $\eta$ ) of 90%, 83%, and 91%, respectively; the performance is above 80% but use different geometries. Table 1 shows the details of the geometry. Table 1 shows no final agreement regarding the optimum parameter  $\alpha_1$ , blade angle in the inlet ( $\beta_1$ ), and outlet ( $\beta_2$ ) for the pico scale Turgo turbine.

**Table 1**  
 Geometry of Turgo turbine blade and its performance in previous studies

Authors	$\alpha_1$ (°)	$\beta_1$ (°)	$\beta_2$ (°)	$\Upsilon$ (°)	$P_{mech}$ (W)	$\eta$ (%)
Gaiser <i>et al.</i> , [11]	30	79	19	11	83	90
Saeed <i>et al.</i> , [6]	20	34	30	56	85.98	83
Williamson <i>et al.</i> , [8]	20	60	30	20	89.69	91

Furthermore, several applied research was carried out to determine the reliability of the Turgo turbine at the pico scale with simple materials. The use of tablespoons for Turgo turbine blades to reduce manufacturing costs was proposed by Budiarmo *et al.*, [12]. Budiarmo *et al.*, [12] compared a tablespoon Turgo turbine with a Pelton turbine (precision blade). From an economic and performance, the Turgo turbine is more profitable than the Pelton turbine for the low-head [12]. Then, Adanta *et al.*, [13,14] utilized coconut shells as a Turgo turbine blade material, resulting in better performance than the Pelton turbine and Turgo turbine with a tablespoons blade.

The coconut shell does not have precise geometry, so the  $\beta_2$  of each blade is different (although not significant). The Turgo turbine with coconut shell blade has better performance because it uses  $\beta_1$  of 40° and  $\alpha_1$  of 20° which is the optimum condition based on analytical results [15]. Consequently, the difference  $\beta_2$  of each blade is the wheel rotation looks unbalanced [13,14]; this condition should be avoided because it shortens generator life. Hence, the challenge for the Turgo turbine is how to manufacture precise, cheap, and fast blades. Three-dimensional (3D) printer technology is the suitable choice in Turgo turbine blade manufacturing to produce precise geometry, and fast. Therefore, this study aims to investigate the feasibility study of 3D printer technology to produce precise and fast Turgo turbine blades for pico scale.

## 2. Method

### 2.1 Analytical Method

Figure 1 shows the Turgo turbine design flowchart where a is the velocity triangle schematic, and b is the algorithm. From Figure 1, the specified boundary conditions are  $\alpha_1$ ,  $\beta_1$ , H, and Q. Magnitude of  $\alpha_1$  from 15° to 25°; this is to verify mathematically  $\alpha_1$  of 15° is optimum. Then, the  $\beta_1$  of ~40° satisfies the  $U/C_{1x}$  of 0.5. Then, discharge (Q) of 2.5 lps and head (H) of 5 m is based on experimental or site conditions.

At inlet (Figure 1), H determines  $C_1$ ,  $C_1$  and  $\alpha_1$  for  $C_{1x}$  and  $C_{1r}$ ,  $\beta_1$  and  $C_{1r}$  for  $W_1$ . Then,  $W_1$ ,  $C_1$ , and  $\alpha_1$  for U. At the outlet, the losses percentage due to shear between water to blade wall of 5%, expressed  $W_2=0.95 \cdot W_1$ . Further, U,  $W_2$ , and  $\beta_2$  for determine  $C_2$ ;  $\beta_2$  are from 10° to 80°. Next, using trigonometry concepts,  $C_2$ , U, and  $W_2$ , for determining  $\alpha_2$  and  $C_{2x}$ .

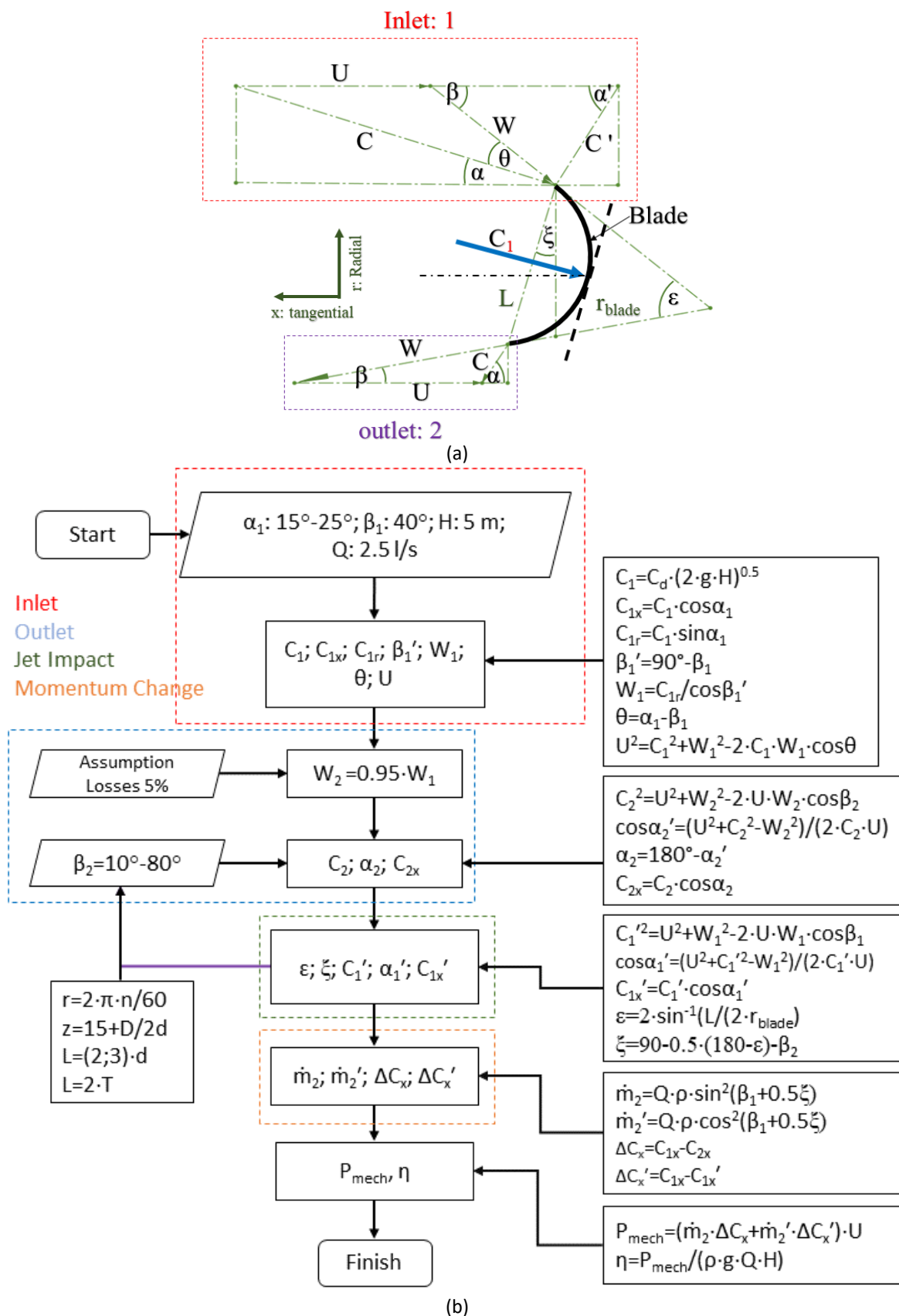


Fig. 1. Flow chart Turgo turbine design: (a) Velocity triangle schematic, (b) Algorithm

After the inlet and outlet are defined, the next step is to analyze the backflow, represented by  $C_1'$ ,  $C_{1x}'$ , and  $\alpha_1'$ . The backflow depicts the mass flow toward the inlet side ( $\dot{m}_2'$ ).  $C_1'$  and  $\alpha_1'$  are determined by  $W_1$ ,  $U$ , and  $\beta_1$  using the Pythagorean theorem. Then, using the trigonometry concept,  $C_{1x}'$  is determined by  $C_1'$  and  $\alpha_1'$ . The backflow is affected by the blade radius angle ( $\xi$ ) and blade angle ( $\epsilon$ ); their formula can be seen in study by Syofii *et al.*, [16]. Therefore, the mass balance analysis is absorbed ( $\dot{m}_2$ ) and considered as losses ( $\dot{m}_2'$ ), which becomes

$$\dot{m}_2 = Q \cdot \rho \cdot \cos^2 \left( \frac{90 - \alpha_1 - \xi}{2} \right) \quad (1)$$

$$\dot{m}_2' = Q \cdot \rho \cdot \sin^2 \left( \frac{90 - \alpha_1 - \xi}{2} \right) \quad (2)$$

And the changes in velocity are  $\Delta C_x$  (energy extraction) and  $\Delta C_x'$  (losses)

$$\Delta C_x = C_{1x} - C_{2x} \quad (3)$$

$$\Delta C_x' = C_{1x}' - C_{1x}' \quad (4)$$

Therefore, the mechanical power ( $P_{\text{mech}}$ ) is adapted from the Euler equation and becomes

$$P_{\text{mech}} = (\dot{m}_2 \cdot \Delta C_x + \dot{m}_2' \cdot \Delta C_x') \cdot U \quad (5)$$

Then, the Turgo turbine performance is a function of  $P_{\text{mech}}$  and  $P_{\text{avai}}$ , becomes

$$\eta = \frac{P_{\text{mech}}}{\rho \cdot g \cdot Q \cdot H} \times 100\% \quad (6)$$

The runner radius ( $r$ ) is the geometry determined first using  $U = \omega \cdot r$ . Angular velocity ( $\omega$ ) is a function of wheel rotation ( $n$ ). Then, determine the blade number ( $z$ ) using  $z = 15 + (D / (2 \cdot d))$ ;  $D$  is the wheel diameter, and  $d$  is the jet diameter. Ratio of  $d/D$  from 11 to 16 is optimum. Next, the calculation of blade radius ( $L$ ) and blade depth ( $T$ ) using  $L = (2/3)d$ , and  $T = 0.5L$ , respectively.

## 2.2 Experimental Method

The data logging system uses a microcontroller with an 8-bit capacity. Four instruments are used: a tachometer, DC current ( $I$ ) and voltage ( $V$ ) multimeter, and flowmeter. Determination of electric power ( $P_e$ ) using

$$P_e = V \cdot I \quad (7)$$

Infrared sensor type E18-D80NK is used as a tachometer (measuring runner rotation). E18-D80NK sensor works by detecting objects and then reflecting light from infrared to the receptor. The amount of light reflected in unit time is processed by the microcontroller. The tachometer system using the E18-D80NK sensor has an uncertainty ( $U_{0.95}$ ) of 0.04% and an error to the commercial device of 0.05%.

The discharge meter uses a YF-DN40 sensor mounted on a pipe with a diameter of 1.5 inches. YF-DN40 sensor specification is 0 to 150 lpm. The sensor consists of a valve body, water rotor and hall effect sensor. The YF-DN40 sensor activates when water flows through it, causing the rotor to rotate; the change in rotational speed is proportional to the discharge. Then, the hall effect sensor sends a pulse signal to the microcontroller, which processes it into discharge data measured in lpm. The flowmeter system using the YF-DN40 sensor has an error of 9.13%.

The multimeter is designed using the ACS 712 sensor to measure amperes and a 24V VCC sensor to measure direct voltage current (Vdc). The ACS712 sensor is a sensor capable of detecting AC and DC currents. This sensor has high accuracy by being supplied with 5V DC and 4.5V output voltage. Signals and voltages are sent to the microcontroller to be processed into currents and voltages to determine the measured DC power. Figure 2 depicts a schematic of the setup apparatus. The multimeter system using the ACS712 sensor has an uncertainty of 4.38% and using a 24V VCC sensor of 1.37%.

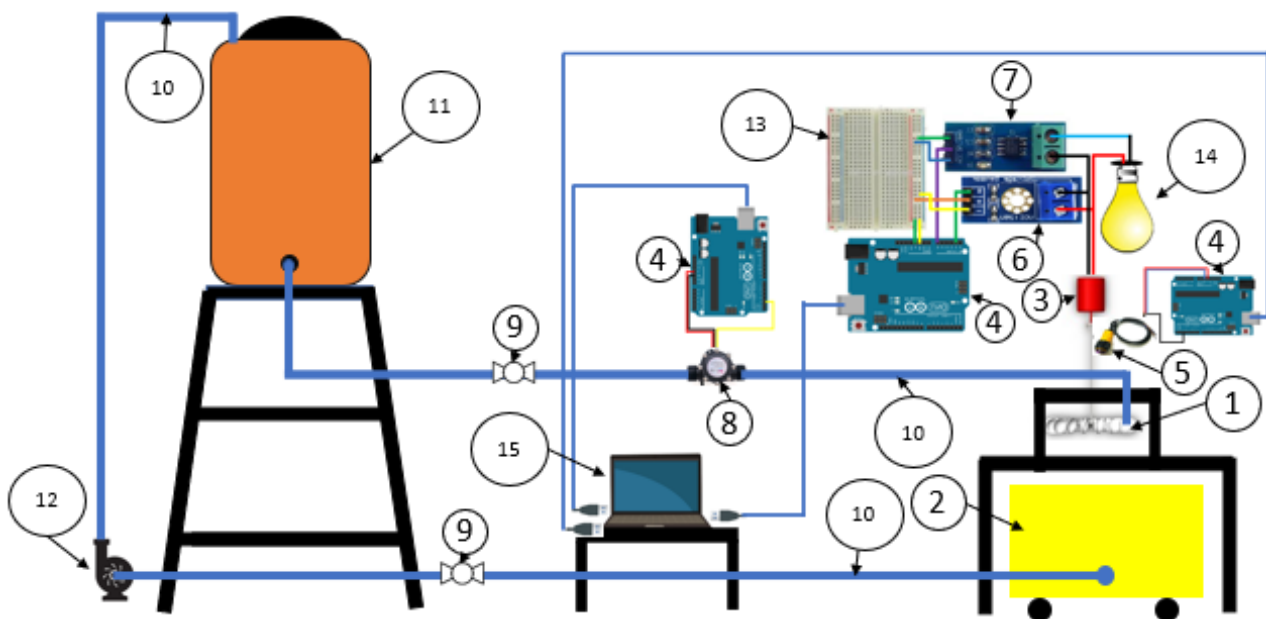
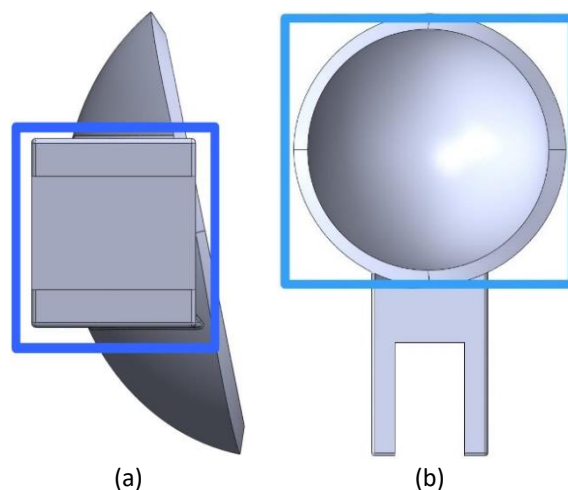


Fig. 2. Experimental setup of a pico-scale Turgo turbine

Information in Figure 2 is (1) Turgo turbine, (2) Reservoir, (3) DC Generators, (4) Arduino Uno, (5) E18-D80NK sensor, (6) ACS712 sensor, (7) 24V VCC sensor, (8) YF-DN40 sensor, (9) Valve, (10) Pipe, (11) Water tank, (12) Pump, (13) Writing Board, (14) Lights, and (15) Laptops

### 2.3 Blade Mechanical Strength Simulation Method

Mechanical strength simulation to predict acceptable Pp for blades using SOLIDWORKS for Students software. Figure 3 is a boundary condition set in the simulation, where the support is on the blade arm, and a static impact is applied to the blade. The static impact received by the blade is 100 N to 400 N.



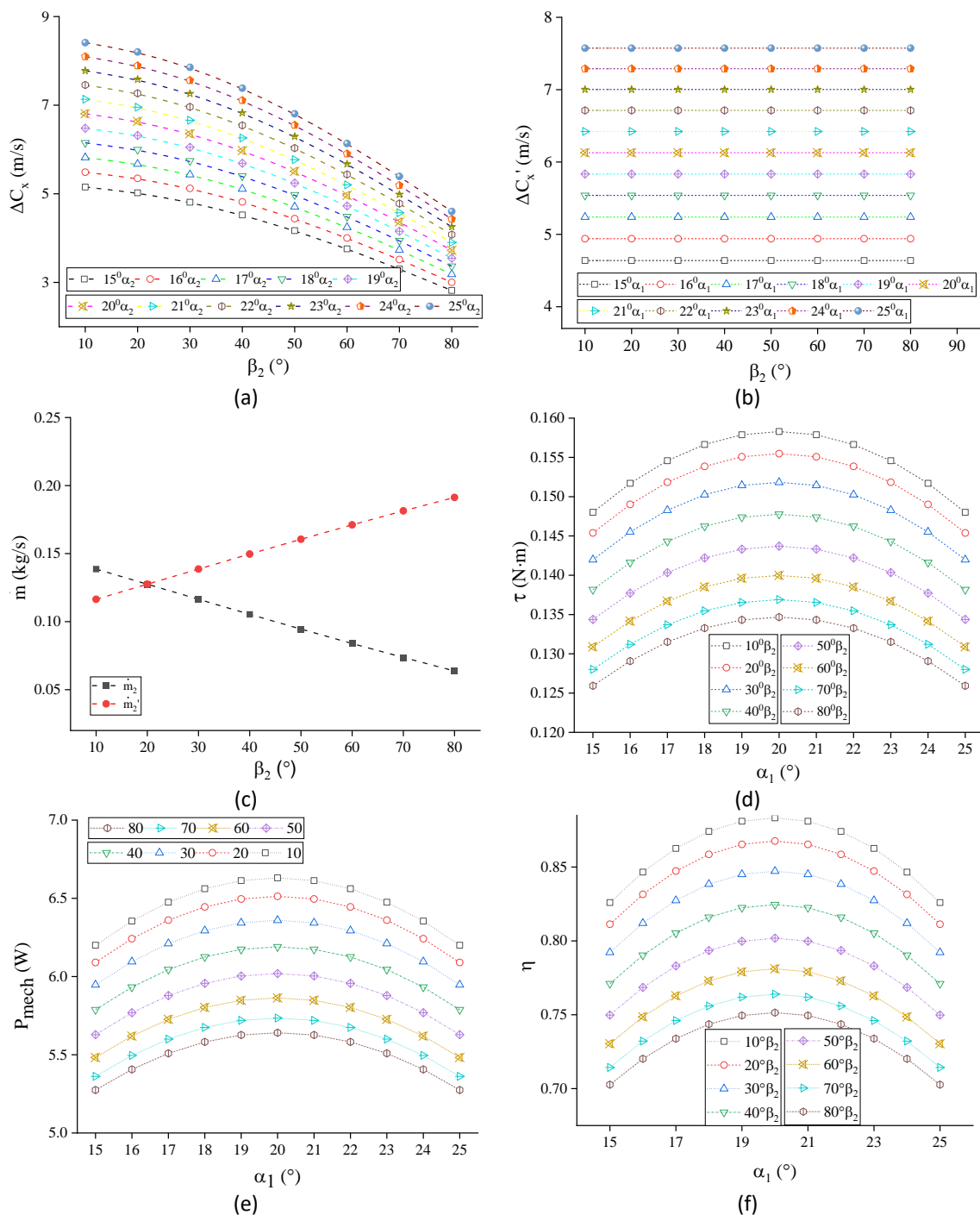
**Fig. 3.** The boundary conditions of the mechanical strength simulation: (a) Support, (b) Static impact

### 3. Results and Discussion

#### 3.1 Analytical Results

Figure 4(a) is the relationship between  $\beta_2$  and  $\alpha_1$  to  $\Delta C_x$ . From Figure 4, the higher the  $\beta_2$ , the smaller the  $\Delta C_x$ .  $\Delta C_x$  the smallest is at  $\beta_2$  of  $10^\circ$  and  $\alpha_1$  of  $25^\circ$ . Based on Figure 4, the greater the  $\beta_2$  and  $\alpha_1$ , the greater the  $\Delta C_x$ . Figure 4(b) is the relationship between  $\beta_2$  and  $\Delta C_x'$ . From Figure 4(b), the relationship between  $\beta_2$  and  $\alpha_1$  to  $\Delta C_x'$  is linear; increasing  $\beta_2$  and  $\alpha_1$  then  $\Delta C_x'$  rising. The  $\alpha_1$  of  $15^\circ$  produces the lowest  $\Delta C_x'$ . Figure 4(c) is the relationship between  $\beta_2$  to  $\dot{m}_2$  and  $\dot{m}_2'$ . From Figure 4(c), the relationship between  $\beta_2$  to  $\dot{m}_2$  is inversely proportional to the relationship between  $\beta_2$  to  $\dot{m}_2'$ . From the calculation results, the more significant the  $\beta_2$ , the  $\dot{m}_2'$  increases and  $\dot{m}_2$  decreases. The ratio of  $\dot{m}_2$  and  $\dot{m}_2'$  of 0.5 occurring at  $20^\circ \beta_2$ ; the water energy is converted into mechanical energy and becomes losses has a ratio of 50%. Figure 4(d) is the relationship between  $\alpha_1$  and  $\beta_2$  to  $\tau$ , where their relationship is a parabola. Based on Figure 4(d),  $\alpha_1$  of  $15^\circ$  and  $25^\circ$  produces a lower  $\tau$  than the others. Furthermore,  $\alpha_1$  of  $20^\circ$  has a higher  $\tau$  than the others, where this condition occurs in all variations of  $\beta_2$ . Based on the calculation results, the smaller  $\beta_2$  has a better  $\tau$  than the larger  $\beta_2$ , and vice versa.

Figure 4(e) is the relationship of  $\alpha_1$  and  $\beta_2$  to  $P_{\text{mech}}$ , where their relationship is a parabola. Figure 4(f) is the relationship between  $\alpha_1$  and  $\beta_2$  to  $\eta$ . The pattern of the  $P_{\text{mech}}$  and  $\eta$  curves is similar to Figure 4(d) because it is influenced by  $\dot{m}_2$  and  $\dot{m}_2'$ , which varies, while  $P_{\text{avai}}$  is constant. Table 2 shows the Turgo turbine blade dimensions obtained from the calculation results, and Figure 5 shows the Turgo turbine runner.

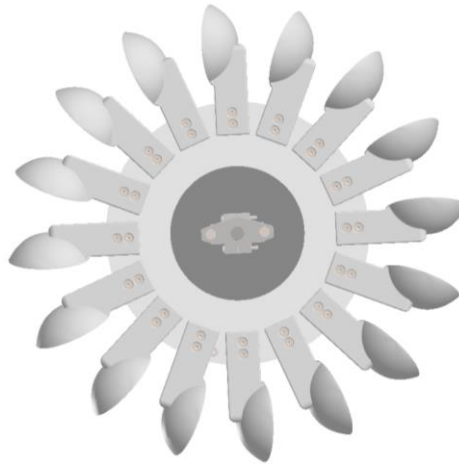


**Fig. 4.** Analytical results: (a) Relation of  $\beta_2$  and  $\alpha_1$  to  $\Delta C_x$ , (b) Relation of  $\beta_2$  and  $\alpha_1$  with  $\Delta C_x'$ , (c) Relation of  $\beta_2$  to  $\dot{m}_2$  and  $\dot{m}_2'$ , (d) Relation of  $\alpha_1$  and  $\beta_2$  to  $\tau$ , (e) Relation of  $\alpha_1$  and  $\beta_2$  to  $P_{mech}$ , and (f) Relation of  $\alpha_1$  and  $\beta_2$  to  $\eta$



**Table 2**  
Turgo turbine blade dimensions calculated results

Parameters	Unit
$\beta_1$	40°
$\beta_2$	10°
$\alpha_1$	20°
Z	16
$r_{blade}$	2.86 mm
D	274.53 mm
$\xi$	50°
$\epsilon$	15°

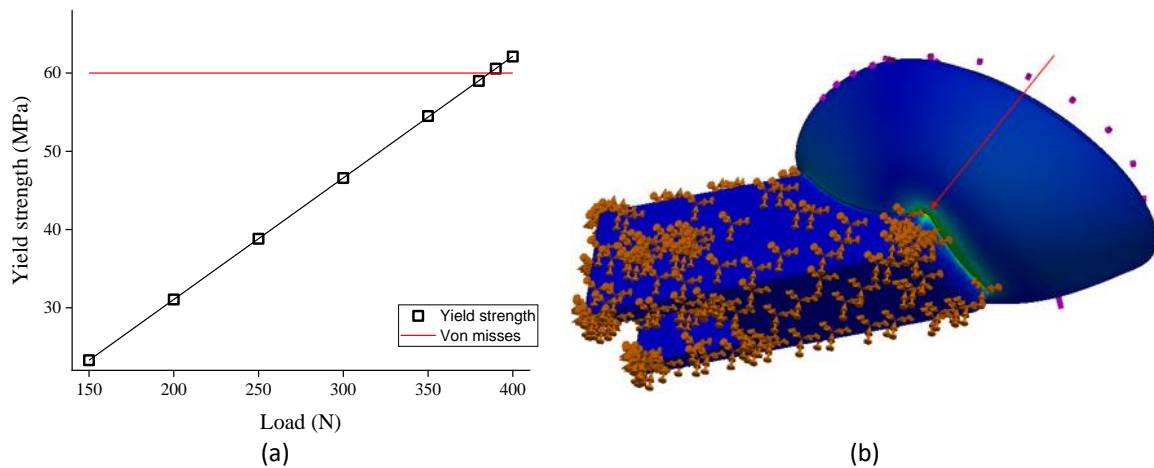


**Fig. 5.** Turgo turbine runner designed

### 3.2 Blade Mechanical Strength Simulation Results

The boundary conditions shall define the properties of the test material. Material properties similar to polylactic acid (PLA) with a maximum yield strength of 60 MPa are considered blade materials [1]. Static conditions mechanical strength tests are divided into Figure 6(a): 100 N, 150 N, 200 N, 250 N, 300 N, 350 N, 380 N, and 400 N. Visualization of the simulation of the results for 400 N in Figure 6(b).

Figure 6(a) is the result of a static mechanical strength simulation. From the simulation results, the maximum Von Mises load on the Turgo turbine scale pico blades designed using PLA material is 60 MPa. From Figure 6(a), the yield strength under loads of 390 N and 400 N exceeds the Von misses, which are 60.56 MPA and 62.11 MPa, respectively. Meanwhile, 380 N to 100 N loads yield strength does not exceed Von misses. Figure 6(b) is a visualization of the mechanical strength simulation results at a load of 400 N. Figure 6(b) shows blade areas with red conditions where the area is damaged.



**Fig. 6.** Mechanical strength simulation results: (a) Relation of load to yield strength, and (b) Visualization of 400 N load simulation results

Then, convert the load to  $P_{avai}$ . Table 3 is the result of converting the load into  $P_{avai}$ . From the conversion results (Table 3),  $P_{avai}$  that the blade can receive 17.5 W.

**Table 3**

Convert load to  $P_{avai}$

F (N)	Q (lps)	Q (m <sup>3</sup> /s)	H (C <sub>1</sub> 1 m/s)	$P_{avai}$ (W)
100	10	0.01	0.051	5
150	15	0.015	0.051	7.5
200	20	0.02	0.051	10
250	25	0.025	0.051	12.5
300	30	0.03	0.051	15
350	35	0.035	0.051	17.5
380	38	0.038	0.051	19

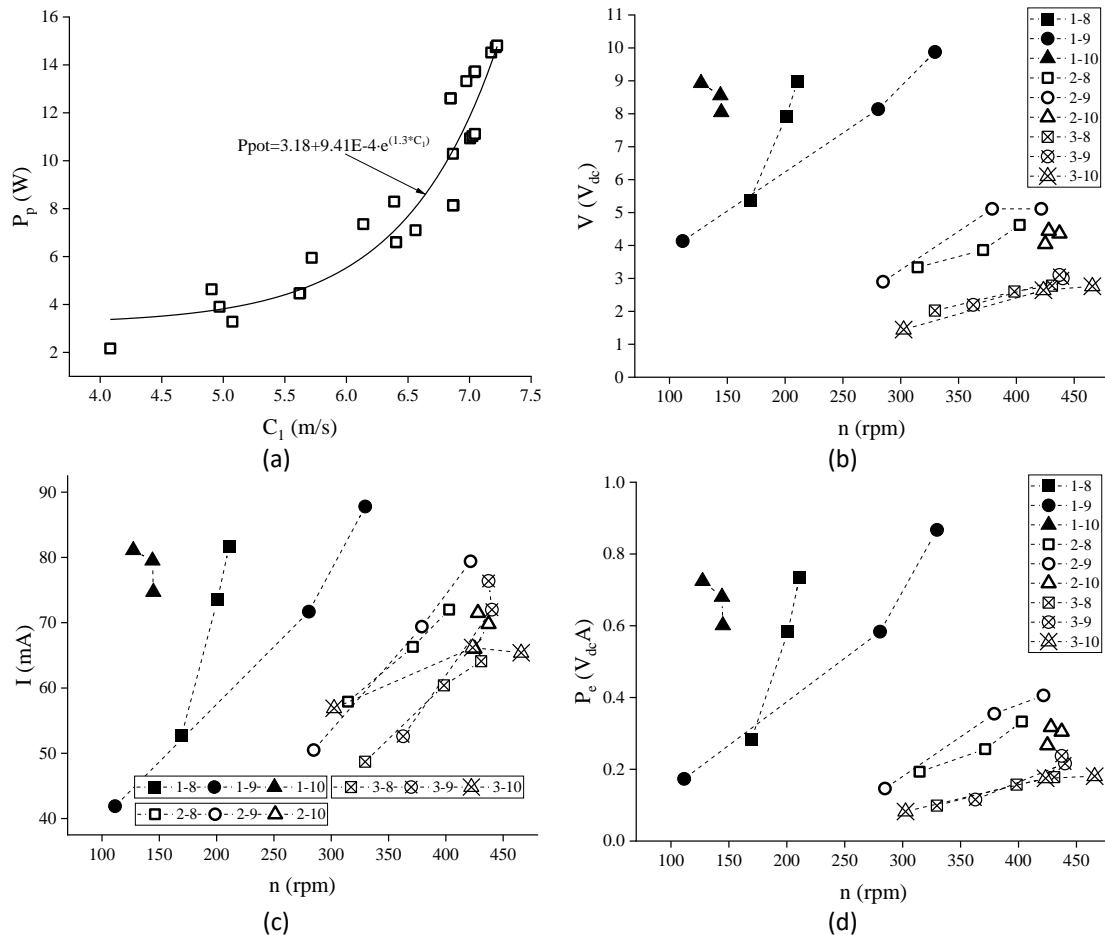
### 3.3 Experimental Results

Figure 7(a) shows the relation of  $P_{avai}$  to the absolute velocity of water ( $C_1$ ) with the expression exponential. The experimental setup has the highest  $C_1$  of 7.22 m/s with a  $P_{avai}$  of 14.81 W, the  $P_{avai}$  of the experimental setup is lower than that recommended by the mechanical strength simulation results.

Figure 7(b) shows the relation of  $n$  to  $V$  generated by the DC generator. From Figure 7(b), all variations in jet diameter (8, 9, 10 mm) increase in  $n$  and  $V$ . For a load of 1 lamp, the 9 mm jet produces the highest  $n$  of 329.67 rpm with a  $V$  of 9.87  $V_{dc}$ . For a load of 2 lamps, a 10 mm jet produces the highest  $n$  of 437.29 rpm with a  $V$  of 4.37  $V_{dc}$ . Then, for 3 lamps, a 10 mm jet produces the highest  $n$  of 465.68 rpm with a  $V$  of 2.76  $V_{dc}$ .

Figure 7(c) shows the relation of  $n$  to  $I$  generated by the DC generator. From Figure 7(c), all variations in jet diameter (8, 9, 10 mm) experience an increase in  $n$  and  $I$ , similar to the graph in Figure 7(b). For a load of 1 lamp, the 9 mm jet produces the highest  $n$  of 329.67 rpm with  $I$  of 87.8 mA. For a load of 2 lamps, a 10 mm jet produces the highest  $n$  of 437.29 rpm with an  $I$  of 69.8 mA. Then, for 3 lamps, a 10 mm jet produces the highest  $n$  of 465.68 rpm with a  $V$  of 65.4 mA.

Figure 7(d) shows the relation of  $n$  to  $P_e$ , similar to Figure 7(b) and Figure 7(c). The patterns are similar because  $P_e$  is a function of  $V$  and  $I$ . Based on Figure 7(d), the highest  $P_e$  of 0.87  $V_{dc}$  occurs at  $n$  of 329 rpm with 1 lamp load and 8 mm jet. Then, the lowest  $P_e$  of 0.08  $V_{dc}$  occurred at  $n$  of 302.46 rpm with a load of 3 lamps and a 10 mm jet.



**Fig. 7.** Experimental results: (a) Relation of  $C_1$  to  $P_{avail}$ , (b) Relation of  $n$  to  $V$ , (c) Relation of  $n$  to  $I$ , and (d) Relation of  $n$  to  $P_e$

### 3.4 Discussion

Figure 8 shows a relation of the tip speed ratio ( $U/C_1$ ) to the performance of the turbine ( $\eta$ ), where the relationship is a parabola with an equation of the order 2. From Figure 8, the highest performance of the designed pico-scale Turgo turbine is 0.092 at  $U/C_1$  of 0.5. The 0.5  $U/C_1$  showed similar test results to the Pelton Impulse turbine concept. Thus, the experimental test results can be said to be verified.

From the results of the velocity triangle analysis and experimental tests, the maximum conditions for the design of the pico-scale Turgo turbine blades are obtained. From the analytical results,  $\alpha_1$  is  $20^\circ$ ,  $\beta_1$  is  $40^\circ$ ,  $\beta_2$  is  $10^\circ$ ,  $r_{blade}$  is  $15^\circ$ . From the experimental results, the maximum  $\eta$  is 0.092 (9.2%), which is the electrical efficiency. Therefore, manufacturing pico-scale Turgo turbine blades using 3D printer technology is better than previous studies using coconut shells as the blade material [13]. Therefore, pico-scale printing of Turgo turbine blades using a 3D printing machine is recommended because of the ease of the manufacturing process, the time needed in the manufacturing process is short, and the cost is low.

Furthermore, from the results of calculations and experimental data, the average deviation between the analytical and experimental is 4%. Thus, the mathematical analysis using the velocity triangle approach has been verified and validated.

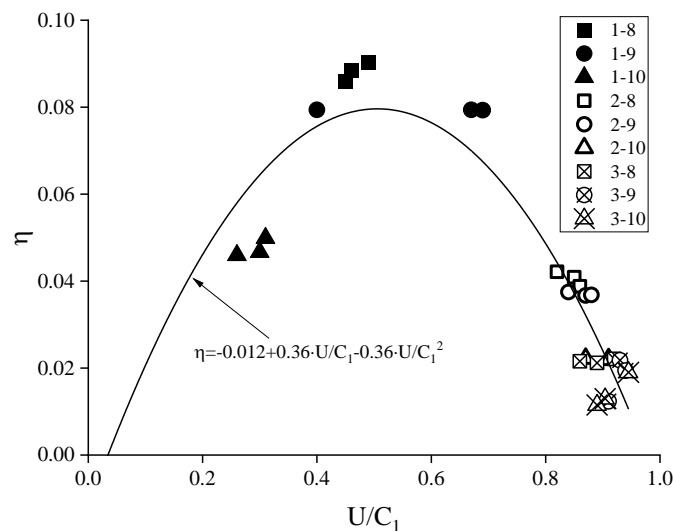


Fig. 8. Relation of  $U/C_1$  to  $\eta$

#### 4. Conclusions

The Turgo turbine blade manufacturing method using 3D printer technology can be recommended because, from the mechanical strength simulation results, the maximum  $P_{\text{avail}}$  that can be received by Turgo turbine blades made from PLA is 17.5 W (35 lps). Then, from the experimental results, the maximum performance of the Turgo turbine made from PLA is 0.092 (9.2%). Furthermore, the geometry of the pico-scale Turgo turbine blades that produce maximum performance is as follows:  $\alpha_1$  is  $20^\circ$ ,  $\beta_1$  is  $40^\circ$ ,  $\beta_2$  is  $10^\circ$ ,  $r_{\text{blade}}$  is  $15^\circ$ .

#### Acknowledgement

The research/publication of this article was funded by DIPA of Public Service Agency of Universitas Sriwijaya 2022. SP DIPA-023.17.2.677515/2022, on December 13, 2021.

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