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Triangle Velocity Analysis of the Pelton Turbine Design in Microhydro Power Plant

Dibyo Setiawan[1*], Yowando Putro Wicaksono[2], Herbert Hasudungan Siahaan[2], Cahyo Wibowo[2], Fisika Prasetyo Putra[3]

[1]*Department of Mechanical Engineering, Politeknik Negeri Bandung, West Java, 40559, Indonesia.*
[2] *Department of Mechanical Engineering, Universitas Mpu Tantular, Jakarta, 13410, Indonesia.*
[3] *Department of Civil Engineering, Universitas 17 Agustus 1945, Jakarta, 14350, Indonesia.*
* Corresponding Author. E-mail : dibyo.setiawan@polban.ac.id

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Abstract

During the period of 29 years, the Central Java Provincial Government has implemented strategic research formulation for flood reduction efforts. One solution for flood management is building a dam. The built dam has the potential to generate electricity. The purpose of the activity is to analyze the turbine speed triangle from the results of the technical design. The method used is the analysis of the turbine speed triangle at an entry angle of 12-14°. The results of the triangle analysis obtained show the F value at 14-12° of 34695.5, 34761.6, and 34847.7 N.m. Torque at 14° were 5313, 5320, and 5330 N.m. Torque at 13° were 5363, 5370, and 5380 N.m. Torque 12° were 5401, 5409, and 5418 N.m. P at 14-12° were 641.5, 642.9, and 644.1 kW. The efficiency of η_o and η_m is 0.90 % and 0.95 %. The conclusion of the application of the turbine speed triangle analysis at an angle of 4-6° is that the optimum turbine efficiency is at an opening angle of 12° with the ability to increase turbine power by 14.79 % and efficiency by 14.66 %.

Keywords: discharge; Pelton turbine; triangle velocity.

1. Introduction

For 29 years, the Central Java Province Government and the Semarang City Government have conducted strategic research on flood reduction efforts, which were implemented from 1960-1990. The area of Semarang City, precisely Kaligarang, has flooded frequently. After the flooding, the government synergized to implement flood reduction activities by collaborating with the Japanese nongovernmental organization. It then was conducted through the XYZ planning agency in order to develop a long-term flood reduction plan. In addition, the formulation of a master plan, the study of national strategic activities and collaboration was carried out for 1 year, starting in 1992 to1993 [1]. The master plan for the development of water resources and the feasibility study [2] was selected to reduce flooding and organize urban drainage in Semarang City. The study resulted in the recommendation that a multifunctional dam design program was needed. Although the dam is used for flood management [3], it is also used for other functions, such as irrigation systems, power plants [4], and tourist attractions [5]. The dam has a capacity of up to 53 km^2, an inundation area of 189 Ha, the ability to hold water in the pool up to 20.4 million m^3, and the elevation above the foundation can reach 77 m and the highest elevation reaches 157 m [6].

The following are the results of relevant studies conducted by several researchers in the development of the dam, among others: J. Planchot, et al., reviewed the flooding plan controlled by Jatibarang dam. Approximately 270 m^3/s of flooding in the 50-year return period and the discharge will be reduced to 100 m^3/s. Important components of dam engineering include diversion tunnels, dam structures, spillway channels, and power generation channels [1], then D. Setiawan et al., with the results obtained in the application of variation of guide blade opening and the full factorial optimization method, the simulation results obtained a value of F 7.53 N.m, T 1.61 kg.m, P 424.83 kW, ηo 0.88 %, the conclusion with the application of this approach can improve performance 11 % [5].

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Based on the dam technical data showing that mainstay discharge is in the range of 0.75 m^3/sec paired with the turbine selection curve [7], this figure allows for the selection of more than one type of turbine [8]. The range can be used for the types of francis, pelton, and cross-flow turbines [9]. In this sense, with the existence of several choices of turbine types from the curve, the availability of water in the dam and the height difference, the dam has potential as a power plant [10]. It is considered to be important to compile a study of the design of a power plant with a choice of Pelton turbine types [11] in order to support efforts to handle the energy transition in the government program. This activity is carried out to contribute to the design of renewable energy [12] and to maximize water resources to increase energy security in power plants [13]. The purpose of this research is to conduct another turbine triangle velocity analysis and to compile a Pelton turbine design draft. Its novelty emphasizes on the examining the implementation scheme of the Pelton turbine, whereas the previous study examined the implementation of the Francis turbine design. The choice of more than one turbine refers to the results of the turbine selection, in which the curve shows a discharge of 0.75 m^3/second, three types of turbines used; Francis, Pelton and cross-flow [14].

2. Experimental Methods

This study uses a triangular velocity analysis method approach from the technical design results. The stages of the activity are shown in the activity flow diagram as follows.

2.1. Flowchart of Activities

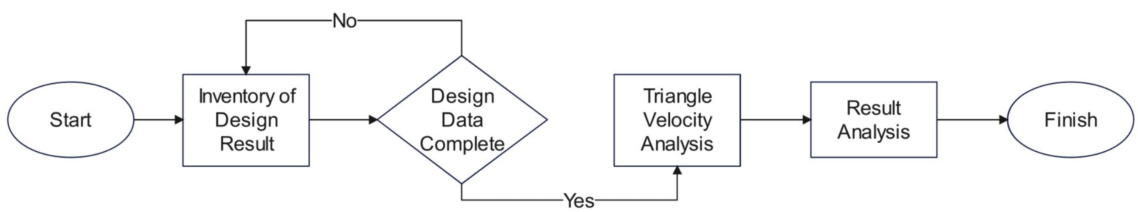

Figure 1. Turbine Velocity Triangle

The flow chart in Figure 1 can be described as follows:

a. Inventory of design results in previous research activities, where data such as dam specifications and turbine design results are described, so that the basic components of the triangle velocity calculation can be known.
b. If the design has been arranged, then the triangle velocity analysis is carried out, the triangle velocity is analyzed to determine all forms of velocity that occur at the stage of water starting to enter, the force process with the response of rotating turbine blades until the water comes out.
c. Furthermore, in addition to being able to comprehend all forms of velocity in the force process, there are further responses such as hydraulic power, torque and efficiency.
d. The next step after obtaining the results, it is then further analyzed, summarized, and curve images are displayed, so that the data presented can be more informative.

2.2. Application Usage

The applications used in present study are Microsoft Excel 2013, 2D CAD Autocad 2021 and 3D CAD onshape open source.

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2.3. Results of Turbine Design

Table 1 presents the results of the Pelton turbine design.

Table 1. Pelton turbine design inventory results

Description	Notation	Values	Units
Effective water fall height	H_e	68.03	m
Mainstay discharge	Q	1.02	m^3/s
Power generated	P	680.72	kW
Rapid pipe diameter	D	727	mm
Rapid pipe thickness	T	3.07	mm
Nominal turbine efficiency	H_t	82.5	%
Maximum turbine efficiency	η_{tmax}	83.3	%
Generator loss	P_{gloss}	27.757	kW
Power of generator	P_g	533.243	kW
Generator efficiency	η_g	95	%
Nominal generator power	$\eta_{g'}$	561.3	kW
Inlet valve	-	Butterfly Valve	-
Turbine specific speed	N_s	25.72	rpm
Number of nozzles	Z	2	pieces
Turbine rotation	N	350.41	rpm
Generator specific speed	N_o	300	rpm
Specific velocity based on flow	n_q	14.94	rpm
Jet absolute velocity	c_1	35.8	m/s
Optimal jet diameter	D	134.7	mm
Optimal circumferential velocity	U_1	17.9	m/s
Stitch circumference diameter	D	976.1	mm
Turbine wheel diameter	D_o	1315	mm
Number of turbine bowls	Z	26	pieces
Bowl width	B	431.04	mm
Bowl height	H	282.87	mm
Bowl opening width	A	161.64	mm
Bowl depth	T	121.23	mm
Bowl mold clearance	K	97.61	mm
Casing inside diameter	L	3290	mm
Height of casing above nozzle	H_r	592	mm
Material of shaft	-	AISI 1055	-
Shaft diameter	d_s	70	mm
Shaft allowable shear stress	τ_a	12.95	kg/mm^2
Shear stress occurring in the shaft	T	7.17	kg/mm^2

Based on the calculation of the mainstay discharge, effective falling height, generator system design and triangle velocity analysis, the turbine design is obtained as shown in Figure 2.

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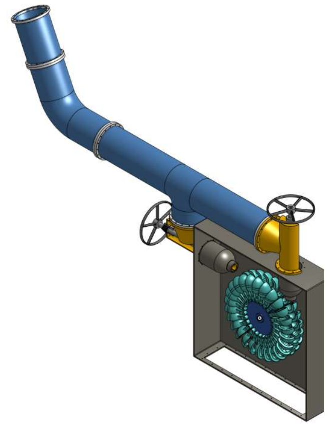

Figure 2. Design and analysis of turbine velocity triangle

2.4. Velocity Triangle Analysis

The dimensions of the turbine bowl obtained have a rotation angle of 168° [15], the profile of the bowl water inlet angle is set between 12-14° and the bowl exit angle between 4-6°. Furthermore, calculations are carried out covering the following areas as seen in Figure 3.

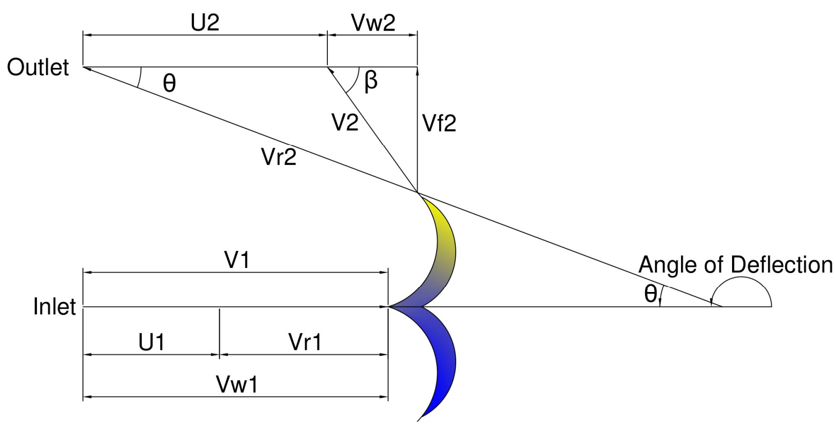

Figure 3. Triangular cycle turbine velocity

Based on Figure 3, the notations listed in the performance of the triangle velocity analysis are described. V_1 is inlet water absolute velocity (m/s). Meanwhile, V_{r1} is relative velocity of the nozzle to the inlet side bowl (m/s). V_{w1} is inlet side vortex velocity (m/s), where U_1 is inlet side tangential velocity (m/s). V_2 is outlet water absolute velocity (m/s), while V_{r2} is relative velocity of the nozzle to the exit side bowl (m/s). V_{w2} is outlet side vortex velocity (m/s). U_2 is outlet side tangential velocity (m/s). V_{f2} is outlet side flow velocity (m/s). α is the angle made by the velocity relative to the direction of motion of the outlet side blade (°), and β is the angle made by the absolute velocity to the direction of motion of the outlet side blade (°).

Tangential velocity of inlet side bowl could be calculated using following equation [16].

$$U = K_u\sqrt{2gH} = U_1 \quad (1)$$

where, U is tangential velocity (m/s), U_1 is tangential velocity of inlet side bowl (m/s), K_u is speed ratio, assumed (0.46), g is gravity acceleration (9.81 m/s^2), and H is effective falling height (m). According to equation (1), tangential velocity is found around 16.8 m/s.

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Absolute velocity on the inlet side could be calculated using following equation [16].

$$V_1 = C_v\sqrt{2gh} \tag{2}$$

where, C_v is Coefficient of velocity (0.98 ~ 0.99), g is gravity acceleration (9.81 m/s^2), and H is effective falling height (m). According to equation (2), absolute velocity on the inlet side is found around 35.8 m/s.

Inlet side vortex velocity could be calculated using following equation [16].

$$V_{w1} = V_1 \tag{3}$$

where, V_{w1} is inlet side vortex velocity (m/s), and V_1 inlet water absolute velocity (m/s). According to equation (3), inlet side vortex velocity is found around 35.8 m/s.

Relative velocity of the nozzle to the inlet side bowl could be calculated using following equation [16].

$$V_{r1}=V_1 - U_1 \tag{4}$$

where, V_{r1} is relative velocity of the nozzle to the inlet side bowl (m/s), V_1 is inlet water absolute velocity (m/s), and U_1 is Inlet side tangential velocity (m/s). According to equation (4), the relative velocity of the nozzle to the inlet side bowl is found around 19 m/s.

Outlet side bowl tangential velocity could be calculated using following equation [16]

$$U_2=U_1 \tag{5}$$

where, U_2 is outlet side tangential velocity (m/s) and U_1 is inlet side tangential velocity (m/s). According to equation (5), outlet side bowl tangential velocity is found around 16.8 m/s.

Relative velocity of the nozzle to the inlet side bowl could be calculated using following equation [16].

$$V_{r2} = K \text{ x } V_{r1} \tag{6}$$

where K is bowl friction coefficient, assumed (1.0) and V_{r1} is relative velocity of the nozzle to the inlet side bowl (m/s). According to equation (6), the relative velocity of the nozzle to the inlet side bowl is found around 19 m/s.

Outlet side vortex velocity could be calculated using following equation [16].

$$V_{w2} = V_{r2} \text{ Cos } \phi - U_2 \tag{7}$$

where V_{w2} is an outlet side vortex velocity (m/s), V_{r2} is relative velocity of the nozzle to the exit side bowl (m/s), and U_2 is outlet side tangential velocity (m/s). According to equation (7), the outlet side vortex velocity is found around 1.78 m/s.

Outlet water absolute velocity could be calculated using following equation [16].

$$\text{Cos } \beta = \frac{V_{w2}}{V_2} \tag{8}$$

where V_2 is outlet water absolute velocity (m/s). According to equation (8), the outlet water absolute velocity is found around 1.77 m/s.

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Outlet side flow velocity could be calculated using following equation [16].

$$Sin\ \alpha = \frac{V_{f2}}{V_{r2}} \quad (9)$$

where V_{f2} is outlet side flow velocity (m/s). According to equation (9), the outlet side flow velocity is found around 3.95 m/s.

Force based on velocity triangle could be calculated using following equation [17].

$$\mathrm{F} = \rho \mathrm{Q_d}(\mathrm{V_{w1}} - \mathrm{V_{w2}}) \quad (10)$$

where F is force based on velocity triangle (N), ρ is water density (1000 kg/m^3), Q_d is flow rate (m^3/s), V_{w1} is Inlet side vortex velocity (m/s), and V_{w2} outlet side vortex velocity (m/s). According to equation (10), the force based on velocity triangle is found around 34700.4 N.

Power based on velocity triangle could be calculated using following equation [18].

$$\mathrm{P} = \rho \mathrm{Q_d}(\mathrm{V_{w1}U_1} + \mathrm{V_{w2}U_2}) \quad (11)$$

where P is turbine power based on velocity triangle (W), ρ is water density (1000 kg/m^3), Q_d is flow rate (m^3/s), V_{w1} is inlet side vortex velocity (m/s), V_{w2} is outlet side vortex velocity (m/s), U_1 is inlet side tangential velocity (m/s), and U_2 outlet side tangential velocity (m/s). According to equation (11), the power based on velocity triangle is found around 643.97 kW.

Torque based on velocity triangle could be calculated using following equation [18].

$$\mathrm{T} = \rho \mathrm{Q_d}(\mathrm{r_1 U_1 Cos}\ \beta_1 - \mathrm{r_2 U_2 Cos}\ \beta_2) \quad (12)$$

where T is turbine torque from the velocity triangle (N.m), ρ is water density (1000 kg/m^3), Q_d is flow rate (m^3/s), r_1 is outer radius of runner (m), r_2 is inner radius of runner (m), U_1 is inlet side tangential velocity (m/s); U_2 is outlet side tangential velocity (m/s), β_1 is angle of water enter bowl (°), and β_2 is angle at which water leaves the bowl (°). According to equation (12), the torque based on velocity triangle is found around 5406 N.m.

Hydraulic efficiency could be calculated using following equation [18].

$$\eta_\mathrm{h} = \frac{\mathrm{V_{w1}\ x\ U_1}}{\mathrm{g\ x\ H}} \quad (13)$$

where ηh is hydraulic efficiency (%), V_{w1} is inlet side vortex velocity (m/s); U_1 is inlet side tangential velocity (m/s), g is gravity acceleration (9.81 m/s^2), and H is falling height (m). According to equation (13), the hydraulic efficiency is found to be around 90 %.

Mechanical efficiency could be calculated using following equation [18].

$$\eta_m = \frac{P}{\rho Q V_{w1} U_1} \quad (14)$$

where η_m is mechanical efficiency (%), P is turbine power based on velocity triangle (W), Q is water flow rate (m^3/s), ρ is water density (1000 kg/m^3), V_{w1} is inlet side vortex velocity (m/s), and U_1 is inlet side tangential velocity (m/s). According to equation (14), the mechanical efficiency is found to be around 95 %.

Turbine operation efficiency could be calculated using following equation [18].

$$\eta_\mathrm{o} = \eta_\mathrm{h}\ \mathrm{x}\ \eta_\mathrm{m} \quad (15)$$

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where η_o is the turbine operation efficiency (%), η_h is hydraulic efficiency (%), and η_m is mechanical efficiency (%). According to equation (14), the turbine operation efficiency is found to be around 95 %.

3. Results and Discussion

Table 2. Results of triangle velocity analysis

Description	Notation	Values	Units
Inlet side bowl tangential velocity	$U=U_1=U_2$	16,8	m/s
Inlet absolute velocity	$V_1=V_{w1}$	35.8	m/s
Relative velocity of the nozzle to the inlet side bowl	V_{r1}	19	m/s
Relative velocity of the nozzle to the exit side bowl	V_{r2}	19	m/s
Outlet side vortex velocity	V_{w2}	1.78	m/s
Outlet water absolute velocity	Cos β	1.77	m/s
Outlet side flow velocity	Sin α	3.95	m/s
Force	F	34.700	N
Power	P	634,97	Watt
Torque	T	5406	N.m
Hydraulic efficiency	η_h	90	%
Mechanical efficiency	η_m	95	%

The results of triangle velocity analysis are presented in Table 2. The vortex velocity at the water outlet side is affected by the angle profile of the inlet bowl. The velocity is shown in Figure 4.

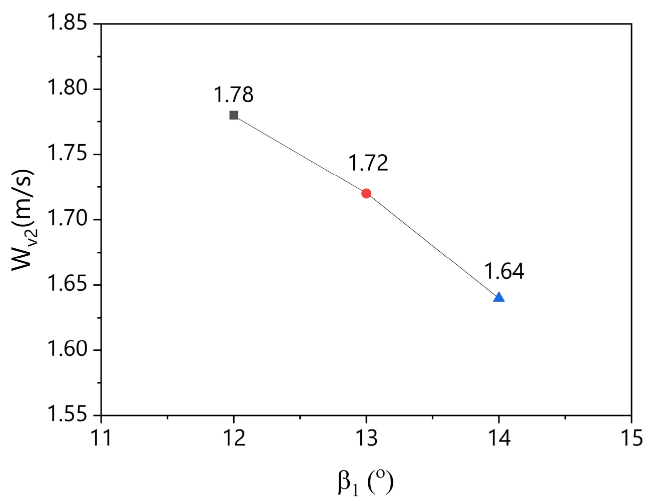

Figure 4. Effect of bowl entry angle on outlet side vortex velocity

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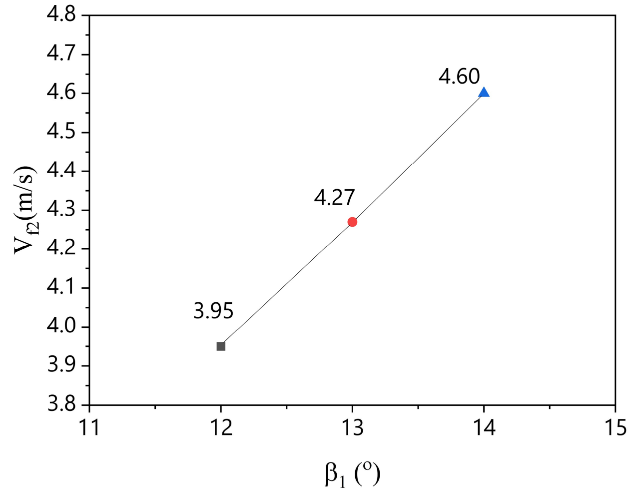

Figure 5. Effect of bowl entry angle on outlet side flow velocity

Figure 4 shows that there is a relationship between the absolute velocity and the velocity on the exit side. Therefore, it can be seen that the smaller the β value, the more the velocity value of water increases on the outlet side of the water. The flow velocity on the outlet side is also affected by the angle profile of the inlet bowl (seen Figure 5), is inversely proportional to the previous result, where the higher the β value, the more velocity flow on the outlet side increases.

The turbine force affected by the outlet side vortex velocity (V_{w2}) is affected by the bowl entry angle. It can be seen in Figure 6 below that the higher the value of β, the more force generated.

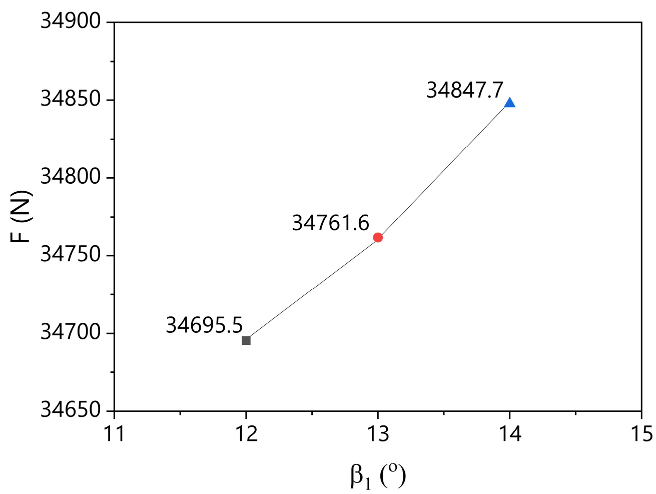

Figure 6. Effect of bowl entry angle on force

The turbine power affected by the vortex velocity on the outlet side (V_{w2}) is affected by the entry angle of the bowl in Figure 7. In contrast to force, in Figure 7 the increase in the power value is in the position of a small β value [19].

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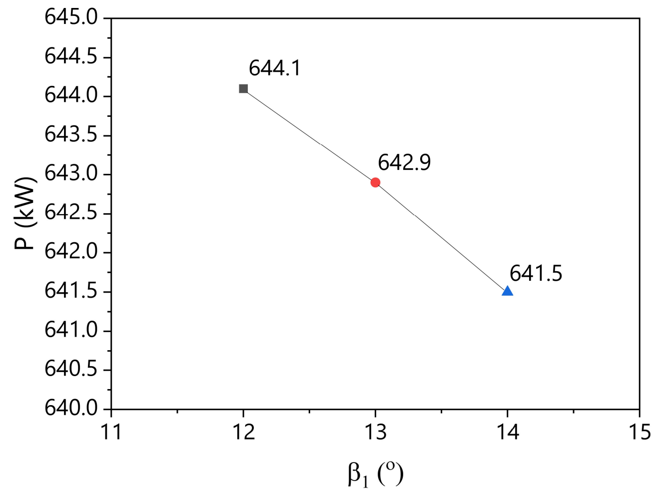
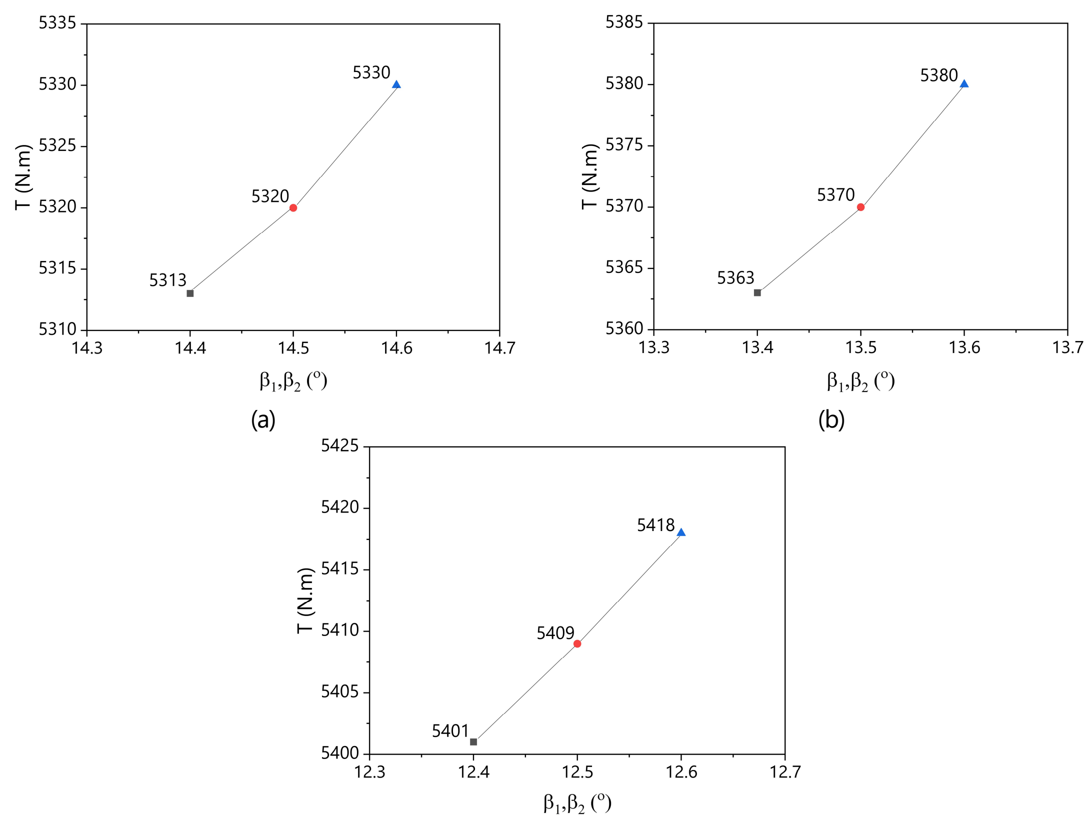


Figure 7. Effect of bowl entry angle on power

The turbine torque is affected by the entry and exit angles of the bowl, shown in Figures 6, 7 and 8. From the results of the Pelton turbine triangle velocity analysis, a profile of 12° entry angle and 6° exit angle of the bowl is selected, which can increase the turbine power and turbine torque. The profile of the entry angle of the bowl and the exit angle of the bowl enhances the turbine power by 14.79 % and the efficiency by 14.66 %.



(c)

Figure 8. Effect of the bowl entry angles of (a) 14°, (b) 13°, and (c) 12° with bowl exit angles of 4, 5, and 6° on the torque

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4. Conclusion

The analysis of the Pelton turbine's velocity triangle concludes with the bowl profile, which yields a turbine force of 34700 N, a turbine power of 643.97 kW, and a turbine torque of 5406 N.m based on the triangle velocity. Hydraulic efficiency is achieved at 90 %, mechanical efficiency at 95 %, and turbine operating efficiency at 95 %. The results of the triangle analysis obtained show the F value at 14-12° of 34695.5, 34761.6, and 34847.7 N.m. Torque at 14 ° were 5313, 5320, and 5330 N.m. Torque 13° were 5363, 5370, and 5380 N.m. torque 12° were 5401, 5409, and 5418 N.m. P at 14-12° were 641.5, 642.9, and 644.1 kW. Efficiency η_o and η_m is 0.90 and 0.95. The conclusion of the application of the turbine speed triangle analysis at an angle of 4-6° is that the optimum turbine efficiency is at an opening angle of 12° with the ability to increase turbine power by 14.79 % and efficiency by 14.66 %.

5. Acknowledgments

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