Cutout Types Analysis on Pico Hydro Pelton Turbine

Budiarso[#], Warjito[#], Dendy Adanta[#], Nesen Syah Puta[#], Hans Vohra[#]

[#]*Department Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus Baru UI, Depok, 16424, Indonesia*
E-mail: dendyadanta@ymail.com

Abstract— **Pico hydro is a simple electricity generation technology and can be applied in remote areas that do not have access to electricity. Pico hydro systems produce power less than or equal to 5 kW. Pelton turbine is an impulse turbine frequently used in a pico hydro system. Pelton turbine has a cut-out in its buckets that prevent the water jet leak from the tip of the bucket into the next bucket. The study has been done to explain the effects of bucket geometry on energy conversion from water flow into kinetic energy. Four different types of cutouts namely ω, v, w and u were used. This study aims to find the best cutout geometry, which can convert the most water energy. The computation method is utilized to study in detail the flow of the fluid. In this study, there is two principal analysis performed, first is ANOVA blocking design for torque analysis, and the second is a qualitative analysis of the flow passing the cutout. The results indicate that the cutouts of the buckets have a significant influence on generated torque. The analysis revealed that u type cut-out buckets give the best performance among others type of buckets and are the easiest to manufacture.**

Keywords— **pelton turbine; cut-out; pico hydro; ANOVA block design; remote area.**

I. INTRODUCTION

Electricity in this era is a primary need for everyone including the people of Indonesia. Every year, the demand for electricity rises by 8.1% while the supply does not match the demand. [1]. Apart from the need for electricity, several regions in Indonesia do not have access to electricity. This can be seen from the electrification ratio, which is 87% in 2015. [2]. Many efforts have been done to expand the national grid. However, many people felt unsatisfied with the result. Out of the challenges that are faced in the efforts of electrification, the most difficult is the geographical condition of Indonesia which is made up of many islands that are spread along the archipelago, and it is mountainous terrain. This condition requires a large amount of-of funds or investments to develop and build new electric grids [3].

Utilization of local resources can be a solution to electrify remote areas. By doing so, off-grid systems can be used, and the remote areas can be self-sustained and thus can function without the need for a national grid.

Since water energy is in abundance, pico hydro systems can be a solution for electrifying remote areas [4]. The application of pico hydro turbine for electrifying remote areas has been implemented in several countries such as Cameroon, Nepal, Laos, Rwanda, Honduras, Bolivia and Peru [5]–[11]. One of the main issues that disturb the functionality of the pico hydro turbine is garbage. Indonesia is a developing and tropical country where the rivers are usually filled with garbage in the form of dry leaves from trees, household waste, and others. Due to this reason, Pelton turbines are considered to be the best option since impulse turbines are resistant toward garbage when compared to reaction turbines [11], although at a lower head a Pelton turbine has low efficiency.

There many parameters that affect Pelton turbine performance namely bucket geometry and number, cutout type and turbine diameter. Thus, these parameters determine the turbine efficiency. Previous works have revealed many important facts regarding the parameters and have built our good understanding of this turbine. However, there are still some doubts about the effects of cutout type in a pico hydro system environment. Thus, it becomes a fascinating, relevant and demanding topic to study the effects of cutout bucket on turbine performance. Cutout types of the bucket maximize energy conversion from water energy into kinetic energy. This is because cutouts have a function to prevent the flow from hitting the tip of the bucket during the transition of jet between the first bucket and the next bucket. The right bucket type also results in a more stable and uniform torque, which will then increase the life of the generator, as there is a smooth production of torque instead of a sudden one.

II. MATERIAL AND METHOD

A. The Material

Cutout refers to the cut at the top side of the bucket. Cut-out has a function to prevent the water from hitting the tip during the transition of the jet from a particular bucket to the following bucket [13]. Pelton turbine has four types of cutout ω type, v type, w type and u type. Each has their effects. The sketches are shown in Fig. 1:

<center>ω type   v type</center>

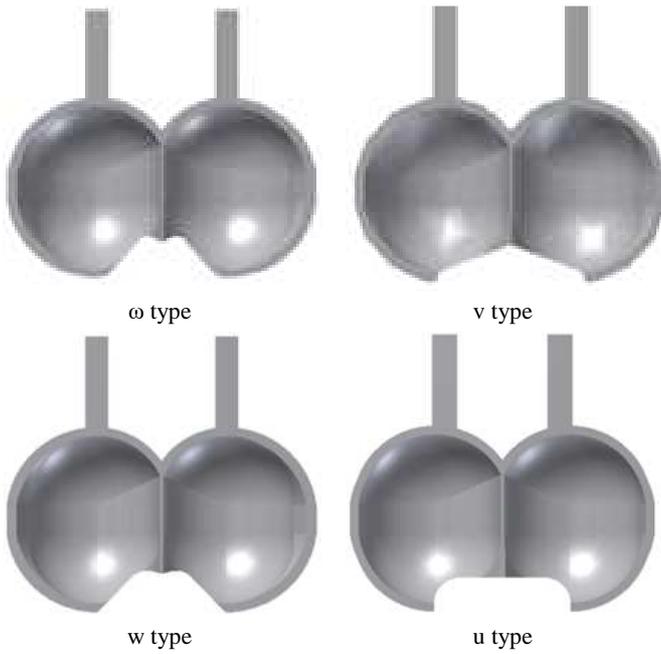<center>w type   u type</center>

<center>Fig. 1   Geometry cutout in Pelton turbine</center>

This study is done to find the type of cutout that is suitable for pico hydro Pelton turbine. There are no geometrical differences on the bucket of the Pelton turbine. Fig. 2 shows the sketch of the Pelton turbine.

The dimension of the bucket was found by employing the following relation [13]: $A = 4 * d$; $B = 0.9 * d$; $C = 2.5 * d$; $E = 0.95 * d$; and $F = (1.2 * d) + 5\text{mm}$. Where A is the bucket width, B is the distance from the center to the cutout axis, C is bucket length, E is bucket depth, and F is cutout width.
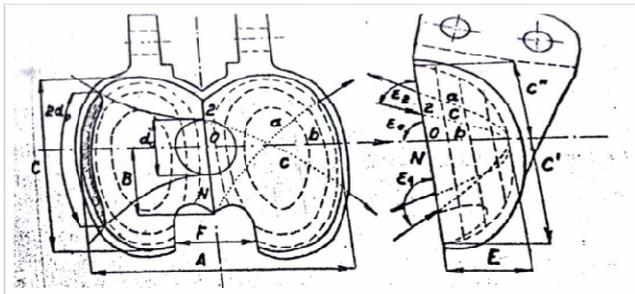

<center>Fig. 2   Main geometry that is commonly used in the Pelton turbine [13]</center>

To determine the value of A, B, C, E and F, the first bucket shape to be analyzed using velocity triangle to maintain the tangential velocity (U) remains constant even if the load changes. The condition of the optimum turbine will occur if the ratio of turbine tangential velocity to jet velocity (C_1) is 0.5 or $U/C_1 = 0.5$. A nozzle is a tool used to convert potential energy from water into kinetic energy. To define the water velocity from nozzle used Equation 1:

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

If the assumption is used in design ($U/C_1 = 0.5$), the predicted Equation 2 to determine rotational speed:

$$\omega = U/r \tag{2}$$

When the turbine rotates with a rotation speed of ω and assumed $U_2 = U_1 = U$, then turbine generated power can be predicted:

$$\sum \tau\omega = W = \dot{m}(U_1 C_{x_1} - U_2 C_{x_2} \tag{3}$$
$$\frac{W}{\dot{m}} = U_1 C_{x_1} - U_2 C_{x_2}$$

Assuming there is no friction loss on the bucket $W_1 = W_2$ so that Euler's equation on the Pelton turbine becomes:

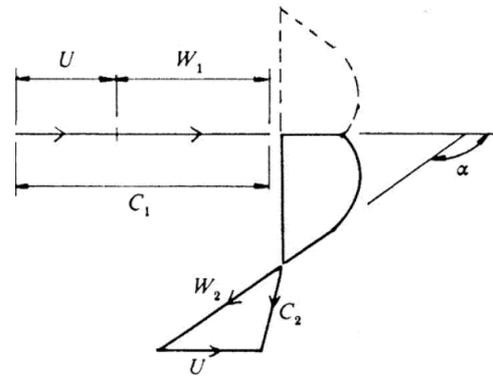$$E = \frac{U(C_1 - U)(1 - \cos\alpha)}{g} \tag{4}$$

<center>Fig. 3   The triangle velocity on Pelton turbine</center>

Hydraulic efficiency is the output power (E) divided by available power (P). The available power is a function the discharge and head of the water, then:

$$P = \rho g H Q \tag{5}$$

The nozzle diameter determines the diameter of the Pelton turbine. To find the nozzle diameter, the formula below can be used:

$$d = \sqrt{\frac{4Q}{c_1 \pi}} \tag{6}$$

The optimum ratio of the runner to nozzle diameter (D/d) is between 6-25 for this study the runner diameter ratio is between 11 to 16, and the optimum deflection angle (α_2) is between 160-165[0] [12]. The number of buckets can be calculated by using the formula below [13]:

$$z = 5.4\sqrt{\frac{E}{d}} \tag{7}$$

Theoretically, the number of buckets is 21. However, Zigonis and Aggidis (2016) reduced the number of buckets by 3 and obtained a higher efficiency by 0.4% [14]. This

also has a positive effect on the manufacturing cost of the turbine.

Type cutout that produces the best performance is made using the 3D print engine to minimize errors due to the manufacturing process because the bucket geometry is very complicated.

B. Method

Computational Fluid Dynamics (CFD) is used to explain the flow field around the cutout bucket. CFD method is used due to its ability to produce good results and insights that cannot be obtained by other methods in a short time [15]. The boundary conditions used in this work are inlet or nozzle, opening (2 phases), symmetry (only half of the bucket is simulated) and wall. The multiphase model used is free surface, and it is assumed that there is no air passing through the nozzle. Water condition is given the value 1, and for air 0. The contact between water and air is given to make sure the simulation can represent actual flow condition. The air value is 0.072 N/m, the turbulence intensity value is 5%, the pressure at the opening is assumed to be atmospheric pressure, the ambient temperature is 25^0C, gravity at Y axis is 9.81 m/s^2, and rotational speed is 30,8 rad/s clockwise. The turbulence model used is SST k-ω [16]. It is used because it can represent the actual flow condition near the wall and away from the wall. Near the wall, this turbulence model calculates the turbulent rotational speed using k-ω. For calculations away from the wall, the k-ε turbulence model is used as the primary analysis tool [17], [18]. Amod, Neopane, and Thapa (2014) analyzed a Pelton turbine runner using the CFD method. They performed simulations with two turbulent models, namely: k-ε and SST k-ω [19]. After running the simulation, the k-ε produced a different result (error). The same results were obtained in this case. Therefore, this study uses the turbulent model of RNG k-ε and SST k-ω. They explained RNG k-ε and SST k-ω is a turbulent model that can predict the actual condition of the Pelton turbine.

The grid form used in the simulation is tetrahedron as it is quite precise for complex geometries. The smaller grid is given at the wall of the cutout and inside the bucket to show the fluid pattern in more details because the level of the flow is high. After mesh independence, the number of mesh used is 1369288 elements and 250178 nodes. After the iteration, convergence is obtained at 10^{-4}.

Two experimental data were analyzed to validate the simulation results; the speed of rotation and torque. Before the data are analyzed, Chauvenet's criteria are used to filter the data to ensure all data is in the standard distribution allowed. Furthermore, ANOVA Block design is used to understand the relation of cutout type with the generated power. Visualization of flow vectors passing through ¼ and ½ high cutouts is used to view the flow patterns that occur. In addition to qualitative analysis, quantitative analysis will also be used to determine the type of cut-out recommended for this study.

III. RESULTS AND DISCUSSION

A. Result

To save time and cost of study the ratio of the runner to nozzle diameter (D/s) selected is between 11 and 16. The selection of the ratio of the runner to nozzle diameter (D/s) is based on the most considerable torque value. Thus, this study uses a ratio of a runner with a nozzle diameter of 16 with a diameter of 0.305 m. Table 1 is a summary of the mathematical analysis using Equations 1 to 5:

TABLE I

MATHEMATICAL ANALYSIS ON β, $\frac{D}{d}$, D, τ, ω AND P

β	$\frac{D}{d}$	D	τ	ω	P
20^0	11	0.209	-2.57	44.82	-115.19
	12	0.228	-2.80	41.08	-115.02
	13	0.248	-3.03	37.92	-114.90
	14	0.227	-3.27	35.21	-115.14
	15	0.286	-3.50	32.87	-115.05
	16	0.305	-3.73	30.81	-114.92
19^0	11	0.209	-2.57	44.82	-115.19
	12	0.229	-2.81	41.08	-115.43
	13	0.248	-3.04	37.92	-115.28
	14	0.227	-3.28	35.21	-115.49
	15	0.286	-3.51	32.87	-115.37
	16	0.305	-3.74	30.81	-115.23
18^0	11	0.209	-2.58	44.82	-115.64
	12	0.228	-2.82	41.08	-115.85
	13	0.248	-3.05	37.92	-115.66
	14	0.227	-3.29	35.21	-115.84
	15	0.286	-3.52	32.87	-115.70
	16	0.305	-3.75	30.81	-115.54
17^0	11	0.209	-2.59	44.82	-116.08
	12	0.229	-2.82	41.08	-115.85
	13	0.248	-3.06	37.92	-116.04
	14	0.227	-3.29	35.21	-115.84
	15	0.286	-3.53	32.87	-116.03
	16	0.305	-3.77	30.81	-116.15
16^0	11	0.209	-2.59	44.82	-116.08
	12	0.228	-2.83	41.08	-116.26
	13	0.248	-3.07	37.92	-116.41
	14	0.227	-3.30	35.21	-116.19
	15	0.286	-3.54	32.87	-116.36
	16	0.305	-3.77	30.81	-116.15
15^0	11	0.209	-2.60	44.82	-116.53
	12	0.229	-2.84	41.08	-116.67
	13	0.248	-3.07	37.92	-116.41
	14	0.227	-3.31	35.21	-116.55
	15	0.286	-3.55	32.87	-116.69
	16	0.305	-3.78	30.81	-116.46

Determination of deflection angle (α_2) is done by computation method because computation method can display flow pattern clearly that cannot be done with another method. The simulation result shown is vector velocity at 3 locations, i.e. ¼, ½ and ¾ height of bucket. From Fig. 4 shows the more significant the deflection angle, the water flowing in the bucket wall will be slower due to the shape of the bucket that resembles the letter U. On the other hand, it is advantageous for power because it increases torque. However, a high deflection angle may cause the previous bucket to decrease torque and rotation as it is inhibited by a splash of water from the after bucket. The numerical result indicates that the deflection angle has a slight repulsion of 163^0 or β is 17^0. In summary Table 2 is the dimension of the Pelton turbine bucket to be:

TABLE II
DIMENSIONAL BUCKET OF PELTON TURBINE

Description	Dimensions	Unit
z	18	-
D	0,3048	m
A	0,075	m
B	0,017	m
C	0,047	m
E	0,019	m
F	0,0275	m
d	0,019	m

The simulation result shows the torque and flow pattern. Torque is used to determine whether there is a cutout geometry relationship with the resulting torque and to validate the suitable turbulent model used for the simulation. The flow pattern is used to analyze the flow losses in each cutout type and to determine the best cutout type on the pico hydro Pelton turbine. Comparison with the experimental did validation of the simulation result. The two types of turbulent model used in the simulation are SST k-ω and RNG k-ε. **Error! Reference source not found.** is a comparative summary of experimental and simulated results:

TABLE III
COMPARATIVE TURBULENT MODEL SST K-Ω AND RNG K-Ε WITH EXPERIMENTAL RESULT

Variable comparison	Power (Watt)
SST k-ω	107.8
RNG k-ε	126.896
Experimental	107.87 ± 5.4

From TABLE III3, SST k-ω is a turbulent model considered to be suitable for Pelton turbine simulation. SST k-ω gets results closer to experimental. This is because it has a smaller error, which is 0.1%. Thus, the turbulent model used in the simulations is SST k-ω. Furthermore, the relation of cutout geometry to Fluid velocity is revealed by performing analysis using ANOVA block design. Blocking technique is used because the controlled variables are the fluid velocity and bucket type.

TABLE IV and
TABLE V shows the results.

From the analysis, the value F_0 obtained is 10.93 while the value $F_{(0.05;2;6)}$ obtained is 5.14. Thus, the relation between the value of torque and the type of cutout can be concluded. Qualitative analysis is conducted to determine the cut-out that can extract more energy. It involves analyzing the fluid flow field around the cutout. The Coanda effect and backpressure were used as criteria to determine the best cutout type. Another criterion to be considered for cutout selection is the difficulty of the manufacturing process.

TABLE IV
TORQUE IN EVERY BUCKET TYPE

Velocity (m/s)	Torque (Nm)			
	ω type	v type	w type	u type
9.81	0.416	1.76	1.36	1.75
14	1.19	4.87	4.05	5.29
17.15	1.65	7.29	6.1	8

TABLE V
SUMMARY ANALYSIS ANOVA BLOCK DESIGN

Source of variation	Sum of squares	df.	Mean square	Fo
Treatment	155.08	3	51.69	10.93
Blocks	111.14	2	55.57	
Error	28.38	6	4.73	
Total	294.60	11		

1) Analysis of Flow at Cutout at 9.81 m/s: On the ω type, it can be seen that at 1/4 height that are many disturbances due to the surface area of the cut out which seems to constrict the fluid flow and create a drawback effect. The other reason is due to the splitter tip. As the fluid hits the center of the bucket and with the sudden change in the area, it causes a shear effect between the top and bottom boundaries of fluid in the center of the cutout. The velocity vector also shows the change in length and color after it passes the cutout.

On the v type, the fluid is seen to be at a transition phase of reaching a disturbance as the velocity vector of the fluid shows a reverse direction. This is due to the inertial force of the fluid that is almost the same as the velocity of flow. On the other hand, there is also a drop in pressure as the fluid is in a transition phase. This is a sign of a pressure loss.

On the w type, the flow of the fluid after passing the cutout spreads evenly as seen from the velocity vector. The suction of fluid can be observed as there is a vector pointing to the direction of the primary fluid flow. This has a positive effect on the power but hurts the construction as it can cause damage to the bucket of the turbine.

On u type, it can be seen that there is a high disturbance of fluid as compared to the other types. A backward facing flow is also observed. This is because there is a drop in pressure due to the sudden changes in the surface area of the cut-out that is higher than the viscous force at the fluid layer. However, at the center of the cutout, it can be seen that the fluid is moving towards the next bucket at a more stable and uniform manner, thus producing a more stable torque. This has a positive effect towards the life of the generator.
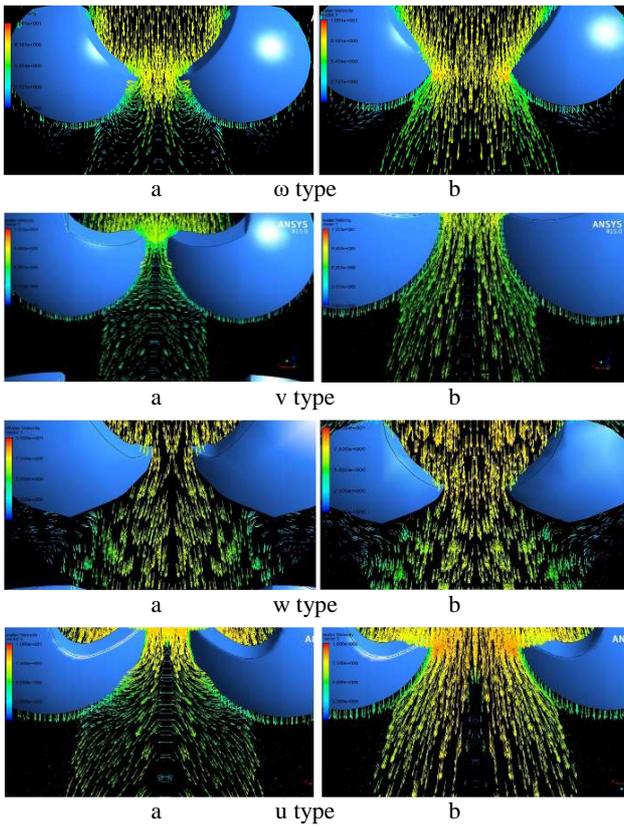
Fig. 4 Velocity vector of the fluid after passing the cut out at 9.81 m/s: a. ¼ height from the cutout base; b. ½ height from the cutout base
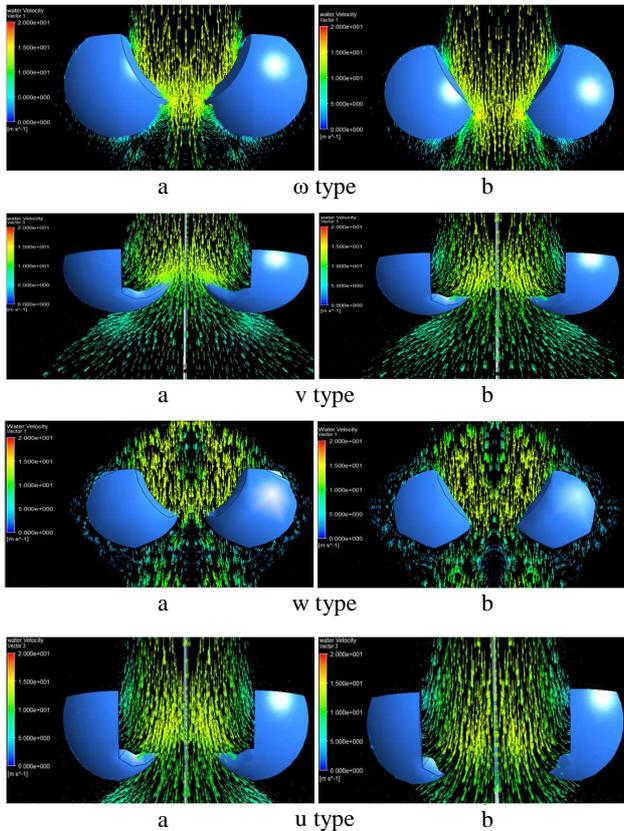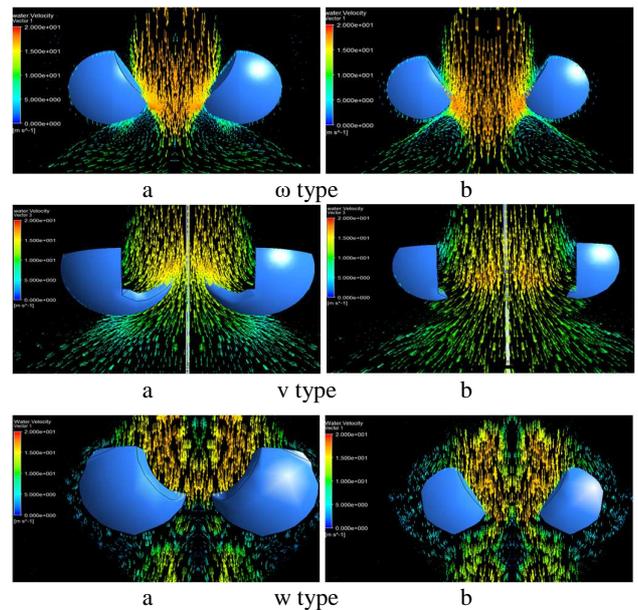

Fig. 5 Velocity vector of the fluid after passing the cut out at 14 m/s: a. ¼ height from the cut-out base; b. ½ height from the cut-out base

2) Analysis of Flow at Cutout at 14 m/s: On the ω type, there is a reversed flow, which is caused by the sudden change in the area after it passes the cutout. This indicates that the bucket movement can be halted due to the presence of the water and can have a negative impact on the torque that is produced. At ½ of the cutout height, there is also a velocity vector pointing in an unfavorable direction. It can be concluded that the flow causes the torque to be reduced at half and quarter of the cutout height.

On the v type, at ¼ of the height, it can be observed that the flow shows a spreading pattern. At half of the cutout, the same pattern can be observed. Theoretically, this indicated that there is a drop in pressure after the fluid has passed through the cutout. As the flow spreads, the pressure drops and thus the pressure of the fluid that is received by the following bucket also drops and the power absorbed is not optimum.

On the w type, at ¼ of the height, it can be observed that the fluid that passes through the center of the cut out follows the contour of the bucket which theoretically has a positive impact on power if it is analyzed using the Coanda effect. At the point where the fluid meets, circulation can be observed which might lead to cavitation. If it is not dealt with, it will cause the layer of the bucket to peel off. At the half height of the cutout, the Coanda effect can be observed even more clearly. However, if the vector is observed, then it can be seen that there is a reduction in velocity as the fluid also passes from the side of the bucket. This will cause a loss to the power as not all of the fluid's energy is being extracted by the bucket.

On u type, the fluid flow is similar to that when the water is flowing at 9.81 m/s, that is, there is no reversed flow at ¼ of the cutout. The same is observed at ½ of the height where the fluid flows to the following bucket. At this cutout type, the pressure distribution is smoother as compared to the other cut out type, and this will prolong the age of the generator.
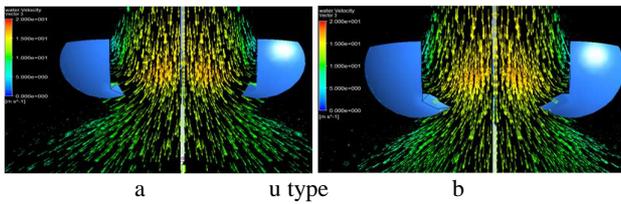
Fig. 6 Velocity vector of the fluid after passing the cut out at 17.15 m/s: a. ¼ height from the cut-out base; b. ½ height from the cut-out base

3) Analysis of Flow at Cutout at 17.15 m/s: On the ω type, the fluid flow pattern is similar at both the heights, which shows the presence of recirculation of water. The same was observed at two previous fluid velocities. As explained before, recirculation is unfavorable as it may peel off the backside of the bucket and thus reduces the power transferred to the shaft. In general, this type of bucket is not suitable for pico hydro application.

On the v type, the fluid flow pattern is also similar to the previous fluid velocities tested. However, the effect is clearer now. As previously explained, there is a spread of flow, which is caused by the sudden change in the area. This

is unfavorable as sudden changes will reduce the life of the generator and the cut out will not be able to perform its function, i.e. to provide a stable flow.

On the w type, the fluid flow pattern is also similar to the previous fluid velocities tested. At this cutout, recirculation occurred, and thus it will cause the bucket layer to be peeled off and reduce its overall lifespan. To maximize the bucket life, the contact of fluid to the wall of the bucket should be avoided. This is because a pico hydro turbine is meant to be placed in remote areas where there is a lack of preparation facilities.

On u type, the fluid flow spreads after passing half and quarter of the height of the cutout, but the differences with the v type are that there is a reduction in velocity as shown in Fig.. The reduction is not too significant, and thus the transition of fluid is better in v type. At half of the cut-out height, the flow is seen to be at the centerline of the axis and the same axis as the inlet. This sort of fluid flow pattern indicates that there is a more stable flow as compared to the other cut out and thus it is recommended for pico hydro turbine.

TABLE VI
SUMMARY OF ANALYSIS AT EVERY CUT-OUT

| Cut-Out | Qualitative Analysis | | | | | | Manufacturing Difficulty Level |
| | 9.81 m/s | | 14 m/s | | 17 m/s | | |
	¼	½	¼	½	¼	½	
ω	Recirculation of fluid (unfavorable)	Recirculation of fluid (unfavorable)	Recirculation is more dominant near the wall as compared to the back.	Recirculation occurs but not as significant at ¼ in height.	Recirculation is stronger at the wall (Increase in pressure drop)	Recirculation of fluid is dominant	Complex (Consists of curves at the cutout base)
v	Transition to turbulent flow (Spread)	Transition to turbulent flow (Spread)	Transition to turbulent flow is clearer (spread)	Transition to turbulent flow is clearer (spread)	Flow spreads and more uniform velocity vector	Spreads and the reduction of flow is not drastic	Difficult (has sharp surfaces)
w	Coanda effect (favorable) cavitation (unfavorable)	Coanda effect (favorable) and reversed flow (pressure drop)	Coanda effect (favorable) cavitation (unfavorable)	Coanda effect (favorable) cavitation (unfavorable)	Coanda effect is more dominant, but there is a reduction in kinetic energy as fluid passes from behind the bucket	Coanda effect is more dominant, but there is a reduction in kinetic energy as fluid passes from behind the bucket	Difficult (Similar to ω type)
u	Better distribution of flow (maximum energy absorption)	Better distribution of flow (maximum energy absorption)	Better distribution of flow (maximum energy absorption)	Better distribution of flow (maximum energy absorption)	Spreads and there is a slight reduction in kinetic energy	Spreads and there is a slight reduction in kinetic energy	Simple

B. Discussion

TABLE VI6, it can be seen that u type shows a better fluid flow pattern as compared to the other cut out and this is caused by the fact that in another cutout types, there is a sudden change in area and thus causes the flow to be unstable and also unfavorable. Stable flow will reduce the fluctuation of current and will not reduce the life of the generator or the object to which the current is supplied. From the geometrical perspective, u type is not difficult to

manufacture. The power obtained from the simulation results is shown in Fig. . In addition to qualitative analysis (

TABLE **VI**), the quantitative analysis also shows the same results. U type cutout produces the highest power compared to other types. For these reasons, u type is recommended for pico hydro Pelton turbine.

To get the best conditions, the minimum head recommended for implementing the Pelton turbine is 5 meters. This is because, when the head is less than 5 meters, the kinetic energy of the water is only used to tackle obstacles or friction, such as friction on the shaft, pulley and belt. When evaluated from efficiency, mechanical efficiency

of this turbine is above 80%, precisely at 83%. When compared with previous studies, this turbine has the same efficiency as the researchers conducted by Gupta et al. (2016) [16], Vesely and Varner (2001) [20] and Perrig (2007) [21].
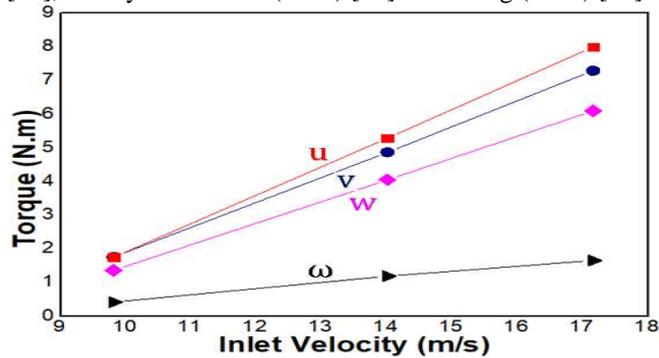

Fig. 7 Velocity vs. torque

IV. CONCLUSIONS

The cutout has a significant effect on generating torque (power). From the qualitative and quantitative analysis, the best cutout type is u type for pico hydro Pelton turbine. This is caused by the transition of torque that is received by the turbine (not discrete rotation). Furthermore, u type is the easiest to manufacture and the minimum head recommended for implementing the Pelton turbine is 5 meters.

NOMENCLATURE

P	Power	Watt
ρ	Water density	kg m^{-3}
H	Head	m
r	Radius	m
Q	Discharge	m^3 s^{-1}
C	Absolute velocity	m s^{-1}
C_x	Axial velocity	m s^{-1}
φ	Nozzle efficiency	0,95-0,98
g	Acceleration of gravity	m s^{-2}
d	Nozzle diameter	m
D	Wheel diameter	m
$\dot{m}$	Mass flow	kg s^{-1}
U	Velocity tangential of the turbine	m s^{-1}
ω	Rotational speed	RPM
τ	Torque	Nm
β	Angle of bucket	degree
α	Deflection angle	degree
W	Work	Watt
z	Number of buckets	
1	Inlet	
2	Outlet	

REFERENCES

[1] PLN, "Rencana Usaha Penyediaan Tenaga Listrik (RUPTL) 2015-2024," Jakarta, 2015.
[2] A. Himawan, "Rasio Elektrifikasi Indonesia Jelang Akhir 2015 Capai 87%," *Suara*, Suara, Jakarta, 2015.
[3] A. P. Harsarapama, "Turbin Mikrohidro Open Flume dengan Hub to Tip Ratio 0,4 Untuk Daerah Terpencil," Universitas Indonesia, Depok, 2012.
[4] Budiarso, Warjito, Dendy Adanta, "Kajian Turbin Air Piko Hydra Untuk Daerah Terpencil di Indonesia," in *Seminar Nasional Tahunan Teknik Mesin XV*, 2016.
[5] B. Ho-Yan, "Design of a low head pico hydro turbine for rural electrification in Cameroon," 2012.
[6] B. Thomas, "Pico-Hydropower Franchising in Rural Honduras," *Int. J. Serv. Learn. Eng. Humanity. Eng. Soc. Entrep.*, vol. 6, no. 1, pp. 46–63, 2011.
[7] A. A. Williams and R. Simpson, "Pico hydro–Reducing technical risks for rural electrification," *Renew. Energy*, vol. 34, no. 8, pp. 1986–1991, 2009.
[8] M. Pigaht and R. J. van der Plas, "Innovative private micro-hydro power development in Rwanda," *Energy Policy*, vol. 37, no. 11, pp. 4753–4760, 2009.
[9] S. Vicente and H. Bludzuweit, "Flexible design of a pico-hydropower system for Laos communities," *Renew. Energy*, vol. 44, pp. 406–413, 2012.
[10] W. Drinkwaard, A. Kirkels, and H. Romijn, "A learning-based approach to understanding success in rural electrification: Insights from Micro Hydro projects in Bolivia," *Energy Sustain. Dev.*, vol. 14, no. 3, pp. 232–237, 2010.
[11] S. J. Williamson, B. H. Stark, and J. D. Booker, "Low head pico hydro turbine selection using a multi-criteria analysis," *Renew. Energy*, vol. 61, pp. 43–50, 2014.
[12] Harinaldi, Budiarso, *Sistem Fluida (Prinsip Dasar dan Penerapan Mesin Fluida, Sistem hidrolik dan Sistem Pnuematik)*. Jakarta: Erlangga, 2015.
[13] M. Nechleba, "Hydraulic turbines, their design and equipement," 1957.
[14] A. Židonis and G. A. Aggidis, "Pelton turbine: Identifying the optimum number of buckets using CFD," *J. Hydrodyn. Ser. B*, vol. 28, no. 1, pp. 75–83, 2016.
[15] A. Židonis, A. Panagiotopoulos, G. A. Aggidis, J. S. Anagnostopoulos, and D. E. Papantonis, "Parametric optimisation of two Pelton turbine runner designs using CFD," *J. Hydrodyn. Ser. B*, vol. 27, no. 3, pp. 403–412, 2015.
[16] V. Gupta, V. Prasad, and R. Khare, "Numerical simulation of six jet Pelton turbine model," *Energy*, vol. 104, pp. 24–32, 2016.
[17] F. Menter, "Zonal two equation kw turbulence models for aerodynamic flows," in *23rd fluid dynamics, plasmadynamics, and lasers conference*, 1993, p. 2906.
[18] F. R. Menter, "Improved two-equation k-omega turbulence models for aerodynamic flows," 1992.
[19] A. Panthee, H. P. Neopane, and B. Thapa, "CFD Analysis of Pelton Runner," *Int. J. Sci. Res. Publ.*, vol. 4, no. 8, pp. 1–6, 2014.
[20] J. Veselý and M. Varner, "A case study of upgrading of 62.5 MW Pelton turbine," in *Proceedings of the International Conference, IAHR*, 2001.
[21] A. Perrig, "Hydrodynamics of the free surface flow in Pelton turbine buckets," 2007.