Optimization of Nozzle Number, Nozzle Diameter and Number of Bucket of Pelton Turbine using Computational Fluid Dynamics and Taguchi Methods

O Y Leman, R Wulandari, and R D Bintara
Mechanical Engineering Department, Engineering Faculty, Universitas Negeri Malang, Indonesia
E-mail: retno.wulandari.ft@um.ac.id

Abstract. Along with the depletion of fossil fuel reserves in Indonesia, water resources can be used as an alternative source of energy. Pelton turbines are one type of water turbine that can be used. However, Pelton turbines still have weaknesses in terms of determining the optimal number of buckets and nozzles. This study aims to optimize the experimental variations in the number of buckets ($N_b$), the diameter of the nozzle ($D_j$), and the number of nozzles ($N_j$) on the efficiency of the Pelton Turbine. The number of buckets was varied namely 24 and 27 pieces, nozzle diameter 5.5 mm and 7 mm, and number of nozzles using a single nozzle and double nozzle with horizontal direction. The research design began with Design of Experiment (DoE) using Taguchi method in Minitab 18.0. The next step was to calculate and then designed turbine using Autodesk Inventor 2016. The turbine design was then simulated using ANSYS Fluent 17.0 Workbench. The calculation of the largest efficiency using the number of 27 buckets double nozzle 5.5 mm producing an efficiency of 64.69%. Based on Taguchi optimization delta result, the most influential variable on the efficiency was the nozzle diameter ($M=0.1943$).

1. Introduction
The increasing population in Indonesia is directly proportional to the electrical energy needs. The main energy source of power generation is still dependent on energy resources such as petroleum, natural gas and coal. The fossil energy resources are limited in number since fossil fuel is not a renewable energy and dwindling numbers because it continues to be exploited [1].

Water is one of the abundant renewable energy sources in number, thus it could potentially be a source of electrical energy generation alternative. According to the total water potential in Indonesia, which can be exploited by 691.3 million m$^3$/year, only 175.1 million m$^3$/year, or about 25.3% that had been utilized. While it is still 516.2 million m$^3$/year, or about 74.7% of untapped [2]. One of the tools that use water as an energy source for the plant is water turbines.

Pelton turbine is one type of water turbine that right to be used, because it does not require a large flow rate, relatively high efficiency, and a simple construction suitable for use as a power plant on picohydro scale (100-5000 watts) [3]. However, on the other hand Pelton turbines still have weaknesses in terms of determining the optimum number of bucket and nozzle on the efficiency of the turbine. According to this term required further research on Pelton turbine.
Research using computational approaches with methods *Computational Fluid Dynamics* (CFD) and optimization using the Taguchi method chosen in this study because it is an appropriate method when viewed from the side of efficiency in terms of time and cost. CFD methods used to find the value of the torque and velocity of the tangential water. While optimization using the Taguchi method is used to determine the most optimal experimental variation and the influence of each variable on the efficiency of turbine [4,5].

2. Methodology of Research

This study used quasi-experimental research that begins with a Design of Experiment (DoE) on Minitab 18.0 to obtain a variation experiments on variables that have been determined. These variables include the number of buckets 24 and 27, the number of single and double nozzle, and the nozzle diameter of 5.5 mm and 7 mm. The next step is conducting computational design of Pelton turbine using Autodesk Inventor Professional 2016 with a bucket and runner dimensions are calculated by using theoretical calculations. Each turbine section is formed that can represent the condition of the actual model.

The following step is conducting CFD analysis using software FLUENT in ANSYS Workbench 17.0 in order to obtain the value of torque and tangential velocity. This value is used as a parameter equation of Pelton turbine performance. In conducting CFD analysis using ANSYS Workbench 17.0 is divided into three steps: Pre-processing, Solving (Processing), and Post Processing.

The first step is pre-processing. In this step, the geometry of Pelton turbine model that designed is imported by using CAD software (Computer Aided Design). The following step conducting meshing or divide the volume into small parts that can be analyzed in ANSYS Workbench 17.0. At this step also set the boundary conditions are applied according to the conditions in the field. The boundary conditions include general, models, materials, cell zone conditions, boundary conditions, mesh, interfaces, dynamic mesh, references values.

The second step is Solving (Processing). Solving step is the core step of CFD analysis to calculate a solution based on the boundary conditions have been applied to the pre-processing step. At this step it is determined solution methods, solution controls, solution initialization, calculation activities, run calculation, and the number of iterations used.

The third step is post-processing. Post-Processing step is the last step in conducting CFD with interpretation of simulation data. The data generated can be a number, contours, vectors, curves, histograms, etc. [5].
CFD analysis in this study is used to find the results of torque and tangential velocity values that are used to calculate the performance of Pelton turbine includes a turbine wheel, power turbines, and turbine efficiency. The value of tangential velocity (v) is used in equation (1) to calculate the rotation of turbine wheel (n).

\[ n = \frac{v \times 30}{\pi D} \]  

(1)

While the torque value (T) is used in equation (2) to calculate the Turbine Power (Po).

\[ Po = T \times 2\pi \times \frac{n}{60} \]  

(2)

The result of the calculation of turbines power (power output) is used in the calculation of turbine efficiency. After obtaining all the efficiency values of each variation on experiment, the optimization is conducted by using the Taguchi method in each of experimental variation on the efficiencies generated.

DoE is an experimental design that contains of several experimental variables that can examine the changes because of the efficiency of Pelton turbine. By using Taguchi optimization can shorten experiment variation.

**Table 1.** Design of Experiment (DoE)

| Designs | 2 level | 3 level | 4 level |
|---------|---------|---------|---------|
| L4      | 2-3     |         |         |
| L8      | 2-7     |         |         |
| L9      |         | 2-4     |         |
| L12     | 2-11    |         |         |
| L16     | 2-15    |         |         |
| L16     |         | 2-5     |         |
| L25     |         |         |         |
| L27     | 2-13    |         |         |
| L32     | 2-31    |         |         |

In Taguchi’s design on Table 1, this study optimized using Minitab 18.0 produced four variations of the experiment are composed of three factors design and two level designs. Three factors include the number of bucket design, the number of nozzles and nozzle diameter, whereas the two-level design is 24 and 27 (the number of buckets), 1 and 2 (the number of nozzles), 5.5 mm and 7 mm (diameter nozzle). The experimental design based optimizations presented in Table 2.

**Table 2.** Variation of experiment

| Variables | Efficiency (%) |
|-----------|----------------|
| Bucket Number | Total Nozzle | Nozzle diameter (mm) |
| 1          | 24           | 1 | 7     |
| 2          | 2            | 2 | 5.5   |
| 3          | 27           | 1 | 5.5   |
| 4          |              | 2 | 7     |
To validate and compare the results of the research design has been optimized using the Taguchi method, the study also made calculations on the eight variations of the experiment. The calculations include the performance of a turbine with full factorial design data retrieval as shown in Table 3.

| Table 3. Full factorial design of data retrieval |
|---|---|---|---|---|---|---|
| Variables | \( N_b \) | \( N_j \) | \( D_j \) | \( T \) | \( V_t \) | \( \text{Rpm} \) | \( P_i \) | \( P_o \) | \( \mu \) |
| 1 | 24 | 1 | 5.5 |
| 2 | 7 |
| 3 | 2 | 5.5 |
| 4 | 7 |
| 5 | 27 | 1 | 5.5 |
| 6 | 7 |
| 7 | 2 | 5.5 |
| 8 | 7 |

3. Results and Discussion

Torque is a measure of rotational force that causes the turbine runner rotates around the axis point. The value of the torque is calculated using the calculator function in FLUENT software. When opening the solution menus, calculator function option can be found on the menu. Torque calculation results shown in Figure 2 shows the results of torque calculation by calculator function and shows the wall solid section where the torque is calculated, which is on the body turbine that is blue.

**Figure 2. Torque on Bucket Number Variation of 24 with Single Nozzle of 5.5 mm**

Variations experiment with bucket number of 24 with single nozzle of 5.5 mm generate torque values of 0.846598 Nm. The torque value is calculated on a wall solid that is all part of the Pelton turbine blue with global axis point is in the center of the design of the runner with the direction of the Z axis (blue axis) as the axis of rotation torque calculation.

The tangential velocity is the velocity of water coming out of the nozzle and mashing the inside of the bucket, causing the Pelton turbine spinning divided cos (90°-θ). The flow velocity is obtained by using the CFD method by using contour on result to bring its flow. Meanwhile, in order to determine the value of the tangential velocity is known to use a plane on the ground inside the bucket of water.
flow from the nozzle is divided cos angle in the bucket (Figure 3). Pounded bucket angle is 45° nozzle flow turbine with a number of nozzles 24 and 42° in the turbine nozzle number 27.

![Figure 3. Tangential angle on Bucket 24](image)

Tangential velocity (v) is calculated using trigonometry equation of \( \cos \theta = \frac{v_{\text{linear}}}{v} \), then the value of \( v \) can be calculated using Equation (3).

\[
\begin{align*}
  v &= \frac{v_{\text{linear}}}{\cos \theta} \\
\end{align*}
\]

Furthermore, the value of the tangential velocity is used as a variable to calculate the magnitude of the Pelton turbine rotational velocity expressed in rotations per minute (rpm). Turbine power (Po) is the power generated by the turbine and the applicability used to turn a generator. Calculation of efficiency at each variation of the experiment is calculated using Equation (4).

\[
P = T \times 2\pi \times \frac{n}{60}
\]

To facilitate the identification of the calculation results power Pelton turbine, then presented a graph of the eight trials against power turbine in Figure 4.

![Figure 4. Graph of Turbine Power Calculation Results](image)
Based on the graph in Figure 4 it can be seen that the largest turbine power values obtained in the experiment-7 with the number of buckets 27, double nozzle with diameter of 5.5 mm which results in a value of 151.367 watts of power turbines. The smallest turbine power value obtained in experiment 2 with the number of bucket 24, single nozzle with diameter of 7 mm turbine that generates power value of 25.41 watts. Referring to Equation (2), a large power turbine power output equation is affected by the value of the torque and rotation of the turbine. Great torque and a turbine wheel that will quickly produce output power (power turbine) that is greater to turn a generator.

Pelton turbine efficiency ($\eta$) is the ratio between the power generated by the turbine ($P_o$) with the incoming water power ($P_i$) and expressed in units of percent (%). Water power is calculated using Equation (5).

$$P_i = \rho \cdot g \cdot C_n \cdot H \cdot Q \cdot N_j$$  \hspace{1cm} (5)

While the calculation of the efficiency is calculated using Equation (6).

$$\eta = \frac{P_o}{P_i} \times 100\%$$  \hspace{1cm} (6)

To facilitate the identification of the calculation results efficiency Pelton turbine, then presented a graph of the eighth trial against efficiency turbine in Figure 5.

![Figure 5. Graph of Turbine Efficiency Calculation Results](image)

Based on the graph in Figure 5 can be seen that the largest turbine efficiency values obtained in the experiment-7 with the number of buckets 27, double nozzle with diameter of 5.5 mm which produces turbine efficiency value of 64.69%. The smallest turbine efficiency value obtained in experiment 2 with the number of bucket 24, single nozzle with diameter of 7 mm which produces turbine efficiency value of 21.72%. In a study [6] the efficiency of 64.69% at a reaction turbine is a high efficiency when the value obtained in experimental research. However, this study is a research using computational approach that many ignore factors outside interference or losses which are prevalent in the generator, the nozzle penstock and transmission system that caused the fall of the value of efficiency in experimental research.

Optimization testing using the Taguchi method is used to determine the factors most giving effect to the efficiency as well as determine the most optimal experimental variation. Optimization begins with the Design of Experiment (DoE) that produce a response in the form of Means.
Response main effect plot for means is average analysis of each variable of the study. Value Response Means test variation which has been optimized using the Taguchi method at each level presented in Table 4, while the value Response Means full factorial experiment variations presented in Table 5.

Table 4. Response Table for Means (Taguchi)

| Level | Bucket Number | Total Nozzle | Diameter Nozzle |
|-------|---------------|--------------|-----------------|
| 1     | .4833         | .4312        | .6073           |
| 2     | .5370         | .5891        | .4130           |
| Delta | .0537         | .1578        | .1943           |
| Rank  | 3             | 2            | 1               |

Table 5. Response Table for Means (Full Factorial)

| Level | Bucket number | Total Nozzle | Diameter Nozzle |
|-------|---------------|--------------|-----------------|
| 1     | .5813         | .5534        | .7565           |
| 2     | .6205         | .6484        | .4453           |
| Delta | .0393         | .0949        | .3113           |
| Rank  | 3             | 2            | 1               |

Table 4 and Table 5 shows the average ratio for each variation of the research that the number of buckets, the number of nozzles and nozzle diameter on the efficiency of the Pelton turbine. The results produced by the response means taking the average at every level variation resulting in an average difference. The magnitude of the effect of three parameters described in the Delta.

Table 4 shows the response sequence Means (M) is the highest to the lowest, namely Diameter Nozzle (M = 3.612), Total Nozzle (M = 3.022), and the amount Bucket (M = 1.530). Based on the results Means response to any variation of the research note that the parameters of the nozzle diameter has the highest influence on the efficiency of the Pelton turbine for generating value Delta is the greatest of the number of nozzles, and the number of buckets. Election results level setting of optimal factors in Table 4, namely Total Bucket level 2 (27 pieces) with a value of -5.405 Means response, Total Nozzle level 2 (double nozzle) by Means response value of -4.659, and the diameter of the nozzle level 1 (5.5 mm) with a value of -4.364 Means response.

In Table 5 the order of highest to lowest Means response showed the same order as Table 4 but with a different value Delta. The sequence is Diameter Nozzle (M=4.785), Total Nozzle (M=1.859), and the amount Bucket (M=0.714). Election results level setting of optimal factors in Table 5 also shows the selection of the same level as Table 4 with values different response. Selection of these levels are Total Bucket level 2 (27 pieces) with a value of -4.507 Means, Total Nozzle level 2 (double nozzle) by Means response value of -3.934, and Level 1 Nozzle diameter (5.5 mm) with a value of -2.471 Means response.

Based on the results of the response means in Tables 4 and 5, the design of the experiment variations using optimization Taguchi or full factorial showed the same results in the order of the variables most affect the efficiency of the Pelton turbine, the diameter of the nozzle in the first place, the number of nozzles in the second, and the number of bucket in third. Taguchi or full factorial optimization also showed the same results in the selection of the most optimal level, ie the number of bucket level 2 (27 pieces), the number of nozzles level 2 (double nozzle), and level 1 nozzle diameter (5.5 mm).
ANOVA (Analysis of Variance) is one of the statistical methods used to investigate the relationship between the response variable/dependent with one or several independent variables. In this study, ANOVA was used only to determine the influence of the variables on the efficiency of the Pelton turbine. Table 6 shows a large percentage of research variables influence on the efficiency of the variations of the experiment based on the Taguchi method, while Table 6 shows a large percentage of variable influence on the efficiency study on the variation of Full Factorial experiments.
Table 6. ANOVA on Experiment Taguchi

| Source         | DF | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
|----------------|----|--------|--------------|--------|--------|---------|---------|
| Bucket number  | 1  | 0.002889 | 4.41%        | 0.002889 | 0.002889 | *       | *       |
| Total nozzle   | 1  | 0.024914 | 38.00%       | 0.024914 | 0.024914 | *       | *       |
| Nozzle diameter| 1  | 0.037762 | 57.59%       | 0.037762 | 0.037762 | *       | *       |
| Error          | 0  | *       | *            | *       | *       |         |         |
| Total          | 3  | 0.065564 | 100.00%      |         |         |         |         |

Table 6 shows the percentage contribution of the study variables (factors) on the efficiency in Orthogonal Array (OA) L4 or four variations of the experiment based Optimization of Taguchi. In ANOVA with OA L4 shows that the percentage of contribution is the largest diameter nozzle that has contributed to the response percentage of 57.59%, followed by Total nozzle that produces the second largest percentage of contribution is equal to 38%, and Total Bucket produce the lowest percentage of contribution that is equal to 4.41%.

Table 7. ANOVA of Full Factorial Experiment

| Source          | DF | Seq SS  | Contribution | Adj SS  | Adj MS | F-Value | P-Value |
|-----------------|----|---------|--------------|---------|--------|---------|---------|
| Bucket Number   | 1  | 0.003082 | 1.20%        | 0.003082 | 0.003082 | 0.29    | 0.620   |
| Total Nozzle    | 1  | 0.018023 | 7.00%        | 0.018023 | 0.018023 | 1.69    | 0.264   |
| Nozzle Diameter | 1  | 0.193792 | 75.23%       | 0.193792 | 0.193792 | 18.16   | 0.013   |
| Error           | 4  | 0.042695 | 16.57%       | 0.042695 | 0.010674 |         |         |
| Total           | 7  | 0.257592 | 100.00%      |         |         |         |         |

Table 7 shows the percentage of contribution to the efficiency of research variables on Orthogonal Array (OA) L8 or 8 variations of the experiment. In Full Factorial ANOVA with OA showed that the largest percentage of contribution resulting diameter nozzle that has contributed to the response percentage of 75.23%, followed by Total nozzle that produces the second largest percentage of contribution that is equal to 7%, and Total Bucket produce the lowest percentage of contribution that is equal to 1.2%.

4. Conclusion
The efficiency value is generated at full factorial experiment variations to 7 using a double nozzle with a nozzle diameter of 5.5 mm, and the number of bucket 27 pieces which produce an efficiency of 64.69%. Taguchi methods of optimization results based on the responses of Means (M) shows the most optimal experimental variation is the variation of the number of bucket 27 (M=0.5370), a double nozzle (M=0.5891) with a diameter of 5.5 mm (M=0.6073). Based on the Delta, the variables that most influence on the efficiency of the largest to the smallest diameter of the nozzle (M=0.1943), the number of nozzles (M=0.1578), and the number of buckets (M=0.0537). In further research can be done using other optimization methods such as RSM, etc. using research variable else to validate these results.
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