Design and Velocity Distribution of Runner Blade of Kaplan Turbine Using CFD (Computer Fluid Dynamic) for Small Hydroelectric Power Plant

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Abstract. Procedures for designing runner of Kaplan water turbine based on the specific conditions in the water potential of the area to be placed, and assessed on the terms of the theoretical analysis and engineering. The main objective of this study was to determine the main characteristics of runners, namely suction head, water flow, and the hydraulic forces that occur when the turbine operates. Modern software for engineering such as computational fluid dynamics (CFD) is used to predict the flow of fluid passing through the runner and Computer Aided Engineering (CAE) to verify the design with Finite Element Analisys (FEA). Kaplan turbine runner is designed to place the suction head low and as an option for power generation in Galih Pakuan isolated from Ciwidey area and has not been electricity. The available head and flow rate for turbine are 8 m and 0.3 m³/sec in this site. The output power is 20kW estimated and turbine speed is 900 rpm. In designing blade, blade element theories are the main theories of blade parameter calculation. This paper selecting airfoil shape of the blade from Gottingen (GOE) series and modelling the exact airfoil geometry by using Airfoil.com software.

Keyword: CAE, CFD, FEA, GOE, Kaplan Turbine, Runner.

1. Introduction
Geographically, Galih Pakuan village’s isolated from the Ciwidey, because it is located in the valley Patuha. The problems faced by the citizens are not interconnected electricity directly from PLN (Perusahaan Listrik Negara), so the state of the village a bit behind compared to other village in the Sugihmukti. In the face of such problems, the villagers exploit the potential of the river for the manufacture waterwheel as shown in Figure 1. Total waterwheel already installed a total of 35 turbines with a power output of each mill 100-150 watts, enough power to turn on the television and one light for each of the family, while the other 15 of families do not have a water mill and still request with neighbors. The potential of the initial survey conducted according to the data obtained, namely the existence of two streams that are parallel to discharge 0.3 m³/s and has a height difference (head) of 8 m between the position of the river that flows above and river below. Such conditions may
produce the hydraulic power of 23,544 watts and can be converted into electricity is 20,000 watts, the power reduction due to the efficiency of the turbine.

Based on the head, and water discharge at this point, the power plant microhydro power can be created with specific Kaplan turbine to obtain high efficiency. This study explains the procedure for designing the runner on the water turbine Kaplan is based on local conditions (head H and debit Q) of the flow of the river in the village that have not been electricity, for the application of micro (50kW-100kW) use the Software modern engineering such as Computational Fluid Dynamics (CFD) is used to predict the flow of fluid passing through the runner and Computer Aided Engineering (CAE) to verify the design with FEA (Finite Element Analysis). When the design process, the shape of the runner can be based on the typical flow optimization, and most importantly the runner can be produced.

2. Material and Methods

The RBKP (Runner Blade of Kaplan Turbine) in the most important part of a reaction turbine in the power generator. The runner, which is responsible of the conversion of hydraulic energy to mechanical energy, is the most vulnerable component since it is exposed to the load due the water pressure. The runner has three to six blade of airfoil shape; the number of blade depends of the specific speed. The runner blade are movable and can be change their position. The blade are assembly with bolt and nut on hub of RBKP. The flow enters the runner through guide vanes which have an angle fixed and runner is fully immersed in water, and must be strong enough to withstand the operating pressure.

The blade has very complex geometry that depends on the rated flow (Q) and net head (H) of the site in which the hydroelectric power plant is going to operate. The blade are complex to manufacture due to their irregular shape, and the design is based on airfoil profiles, due to the blades ability to generate a big lift force and a relatively low drag force[1].

Based on empirically studies of Kaplan turbine schemes, correlation are established between the geometry of the runner (the runner exterior diameter De, or runner diameter, the runner interior diameter Di, or hub diameter), the echanical power produce (P), the rotational speed (N), the specific speed (Ns), the net head (H) and the rated flow (Q). Table 1 presents the aforementioned correlations (equation1-5), which can found in the literature. With these correlation it is possible to determine the external diameter and internal diameter of the runner [1].

| Table 1 Fundamental dimensions of RBKP. |
|----------------------------------------|
| | \( P = \eta \rho g Q H \) | (1) |
| | \( N_s = \frac{2.716}{H^{0.5}} \) | (2) |
| | | |
| | \( D_e = 84.5 \cdot (0.79 + 1.602 \cdot N_s) \cdot \sqrt{H} \cdot \frac{1}{60 \cdot N} \) | (3) |
\[ D_1 = (0.25 \frac{0.0951}{N_s}) \cdot D_e \]  

\[ c_m = \frac{4Q}{(D_e^2 - D_i^2) \cdot \pi} \]  

Where: P-generated mechanical power (watts), Q- Debit provided on the water flow (m³/s), N- Rotational of runner (rpm), Ns value specific rotation of the turbine, g Acceleration due to gravity (m²/s), H- Head / high water fall (m), \( \eta_h \)- hydraulic efficiency, \( c_m \)-Speed axial turbine inlet (m/s), \( D_e \)- Exterior diameter of runner / rotor (m), \( D_i \)- interior diameter or the diameter of the hub (m).

The design of the blade not only depends on the stress analysis, but also in other several factors play a significant role. The leading edge is thicker than trailing edge for a streamlined flow. Furthermore, the blade should be as thin as possible to reduce cavitation effects. The blade thicker near the runner interior diameter becoming thinner towards the tip. The leading edge is also an important factor in defining the shape of the profile and the distortion of the blade.

The velocity triangle are shown in table 2. Where “u” is the tangential velocity, “c” is the absolute velocity and “w” is the relative velocity. When a cylindrical cut is set a the runner and the cut is developed into a drawing plane, a grating like that shown table 2 occurs. In this figure, “x” represent the grating partition and “L” denote the chord. And approximate solution of the problem of the behaviour of the flow through the blades can be obtained considering a constant plane of motion the grating[2].

**Table 2** the velocity triangle, which occur on the blade

\[ u = \frac{2 \pi n r}{60} \]  

\[ c_{u1} = \frac{g \eta_h H}{u} \]  

\[ w_\infty = \sqrt{c_m^2 + \left(\frac{u - c_{u1}}{2}\right)^2} \]  

\[ \tan \beta_\infty = \frac{c_m}{u - c_{u1}} \]  

\[ x = \frac{\pi D_i}{z} \]  

\[ L = \frac{x}{(x/l)} \]  

\[ \xi_u = \frac{2 \cdot g \eta_h H \cdot c_m}{w_\infty^2 \cdot u \cdot \sin(\beta_\infty - \epsilon)} \]  

\[ \xi_t = \frac{2 \cdot g \eta_h H \cdot c_m \cdot t}{w_\infty^2 \cdot u \cdot \sin(\beta_\infty - \epsilon) L} \]  

\[ \tan \epsilon = 0.012 + 0.06 \frac{y_{\text{max}}}{L} \]  

\[ \delta = \left( \frac{\xi_u - 4.8 \frac{y_{\text{max}}}{L}}{0.092} \right) \]
\[ \beta = \beta_m - \delta \]  
(15)

\[ F_L = \xi_a \frac{\rho w_\infty^2}{2} Lb \]  
(16)

\[ F_D = \xi_w \frac{\rho w_\infty^2}{2} Lb \]  
(17)

\[ F_t = (F_L \sin(\beta - \lambda) - F_a \cos(\beta - \lambda)) \cdot z \]  
(18)

\[ F_a = (F_L \sin(\beta - \lambda) + F_D \cos(\beta - \lambda)) \cdot z \]  
(19)

\[ T = F_t \times r \]  
(20)

where: \( r = \frac{(D_{i+2} + D_{i+3})}{2} \)  
(21)

Where: \( u \)- blade peripheral velocity (m/s), \( r \)- The radius of the cross section of the blade (m), \( c_{u1} \)- velocity entrance tangential direction (m/s), \( w_\infty \)- velocity entrance relatively average (m/s), \( \beta_\infty \)- average entry angle (degrees), \( x \)- distance for between two adjacent blade (pitch) (mm), \( z \)- Number of blades, \( L \)- airfoil cord length (mm), \( \xi_a \)- coefficient of lift, \( \varepsilon \)- the angle formed between the force lift (A) with a resultant force on the turbine blades (degrees), \( \delta \)- angle of attack (angle of attack) (degrees), \( \beta \)- entry angle (degrees), \( L \)- chord length (mm), \( F_L \)- lift force (N), \( F_D \)- drag (drag force) (N), \( F_t \)- Tangential force (N), \( F_A \)- Axial force (N), P-mechanical power turbine \( N. \ m. \ s^{-1} \) or watt

The table also shows the equations used for the hydraulic design of the runner. These equations can be obtained with theoretical and empirical methods of analysis of flow. The calculation of the blade system was for blade with a degree of reaction \( \varepsilon \) between 0.5-1[2][5].

To define the distortion of the blade, velocity triangle of five different cylindrical sections of the blade, located at a proportional distance, are determined (figure 2). The angle \( \beta_i \) of each radius gives conclusion to the distortion of the blade, therefore, between the external and internal diameter an arithmetical ratio can be established obtain the diameters[3][4].

\[ D_0, D_{i+1}, D_{i+2}, D_{i+3}, \text{ and } D_e \] or the radius \( r_0, r_{i+1}, r_{i+2}, r_{i+3}, \text{ and } r_e \) respectively.

From the design of the profile a type Gottingen-364 was chosen. The selection was made following recommendation from several author such as Pfleiderer, for applications in turbine and axial pump. The characteristics of the blade were obtained from the institute of Aerodynamic of Gottingen, Germany. Table 3 shows the characteristics of the profile at different sections, expressed as a percentage of length \( L \). \( y_0 \) and \( y_u \) represent of ordinates of the top and bottom of the profile corresponding to the absisssa \( x \)[6].

| x   | 0   | 1.25 | 2.5 | 5   | 7.5 | 10  | 15  | 20  | 30  | 40  | 50  | 60  | 70  | 80  | 90  | 95  | 100 |
|-----|-----|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| y_0 | 0.85| 4.05 | 5.45| 7.3 | 8.6 | 9.65| 11  | 11.85| 12.5 | 12.1 | 11.1 | 9.5  | 7.55| 5.35| 2.9 | 1.55| 0.1 |
| y_u | 0.85| 0    | 0.05| 0.35| 0.55| 0.65| 1.05| 1.3 | 1.75| 1.85| 1.8  | 1.55 | 1.25| 0.9 | 0.45| 0.2 | 0.1 |

The correlation between table 1, table 2 and the profile characteristic of the blade enable a preliminary design of the RBKP. For the designed it is recommended to use an axial velocity \( c_u < 7 \text{m/s} \) and a ratio \( t/l \) between 1 and \( L \), in order to select the best combination of the external and internal diameters for the runner (from 0.3 to 0.5 \( D_e \) ) [2].
The calculation process on the blade design and blade direction of the turbine include the calculation of the parameters of the design and calculation of the coordinates turbine blade profile. While calculating the coordinates of turbine blade profile is useful to determine the profile cross-sectional shape pieces of turbine blades on each blade pieces that have been determined, and the modeling of turbine blades in three dimensions[3].

First find the initial data, then choose the parameters that need to be like efficiency, the number of blades, and $\epsilon$. Using the formula and the selected parameters can be obtained by the value of the flow rate, specific speed. Can then be computed value of $L$ and $Y\text{maks} / L$. Previous need to count the value of $L$ and $Y\text{maks} / L$ of the equation there is to be examined whether the same or not. If it is the same followed by the selection of blade profiles to be modeled along the manufacture of construction. Once construction is made, the model simulated the strength of the blade then its software Autodesk Inventor Pro 2014, with the base of the finite element method or the Finite Element Analysis (FEA) which will be able to see the results later.

In the design of the movable blade on turbo engines, there are a lot of airfoil profiles can be used. In general, the election is based on the value of the coefficient of lift and drag. For this reason the design is always expected that the selected profile has a high lift coefficient and a low drag coefficient in order to generate greater power. Here is a cross-sectional illustration of some of the airfoil profile. Selection of the airfoil profile on the design of turbine blade motion is G'o364 profile, and a calculated done using airfoiltool.com. The calculator on the website we live enter parameters such as thickness and length of cord airfoil $y\text{maks}$.

Later, CFD can be used in the verification of the hydraulic design of the runner, to give a graphic description of the water flow inside of the propeller turbine and to obtain the velocity and pressure distribution. The boundary condition should be consistent with the design. This is useful information in the design of the turbine because it helps reduce construction mistakes, or it allows to the geometry of the runner to obtain the design power. In the CFD software is possible to estimate important design parameters such as hydraulic power and torque on the blades of the runner.

In conclusion, the development of the RBKP in this paper has followed five steps: planning, design, evaluation (CFD, CAE), and prototyping.

Result

The RBKP was design for a head 6m and a flow 0.3 m$^3$/s. a moderate working hydraulic efficiency of 80% was assumed and a fixed operating speed of 900rpm. It was expected that power generated was equal to 13.44kW. the specific speed, the runner diameter, the hub diameter and the characteristic of the blade profile for different sections can be calculated with some relations of tables 1 and 2. The ratio of the hub diameter to the runner diameter is taken to be 0.35. the runner was design with 4 blade and guide vanes were design using correlations found in the technical literature. Table 4 shows the main geometric characteristics of blades.
Table 4 main geometric characteristic of blades

| Z    | 4 blades |
|------|---------|
| De   | 0.322277092 m | Q 300 l/s |
| Di   | 0.1112796982 m | H 6 m |
| Vw2Rw| 0.097 m^2/s |
| Vw1Rw| 0.540 Initial guess |
| Eff  | 0.75 |
| Speed| 900 rpm 94.2 rad/s |

| Section | tip | mid | hub |
|---------|-----|-----|-----|
| R       | 0.161138546 | 0.13495353 | 0.1087685 |
| x       | 0.253 | 0.212 | 0.171 |
| Eff     | 0.71 | 0.76 | 0.76 |
| Va      | 4.19 | 4.19 | 4.19 |
| Vw1     | 3.35 | 4.00 | 4.96 |
| u       | 15.19 | 12.72 | 10.25 |
| Vw2     | 0.60 | 0.49 | 0.61 |
| W1      | 12.56 | 9.67 | 6.75 |
| W2      | 15.17 | 12.93 | 10.52 |
| Beta1   | 19.50 | 25.68 | 38.41 |
| Beta2   | 16.03 | 18.91 | 23.48 |
| Betainf | 17.77 | 22.30 | 30.95 |

| Winf   | 13.74 | 11.05 | 8.15 |
| L (chord) | 0.177 | 0.162 | 0.146 |
| (x/L)approx | 1.43 | 1.31 | 1.17 |
| Kb      | 0.572 | 0.832 | 1.249 |
| CL      | 0.572 | 0.925 | 1.470 |
| alpha   | 0.5 | 1.5 | 2 |
| Blade thkn's (mm) | 1 | 1 | 1 |
| thickness (%) | 0.56 | 0.62 | 0.68 |
| camber (%) | 2 | 2.2 | 3 |
| beta calculated | 17.3 | 20.8 | 28.9 |
| camber (mm) | 3.54 | 3.56 | 4.39 |

in figure 3 the assemble of the Kaplan turbine can be seen, the main component are, lower section and RBKP placed inside, upper section is bearing assembly, 12 kw alternator mounting assembly, draft tube assembly, belt B-114 Inch, and belt shield. The figure can seen bellow.

Using CFD software, the flow through the RBKP was analyzed and the runner design verified. These analyses were performed by means of the program Solidwork Flow Simulation that use finite volume theory, which show in a graphic manner the phenomena that takes place inside the turbines. The geometrical model of the flow domain was built according to the provide spesifications in the three-dimensional model of figure 4, the entire fluid passageway between the inlet from inlet tube for the turbine is considered. The boundary conditions that were introduced at the inlet of te turbine includes the net water head (H) or water fall and flow rate (Q) at the outlet of the turbine, the outlet pressure was defined equal to the atmospheric pressure. Furthermore, the rotational speed of the ruuner wall and the shaft were also defined in the numerical model.
To obtain the data/calculations are appropriate and in accordance with the conditions of the river will be verified by using the CFD software Solidwork. If the verification is not in accordance with the design phase of the repetition of the design is done again, to obtain the final design.

The results obtained as the torque runner as shown in the table below.

| Table 5 | Results obtained from CFD simulation in the form of torque |
|---------|----------------------------------------------------------|
| Goal Name | Unit | Value | Av Value | Min Value | Max Value |
| GG Torque (X) | [N*m] | 219.75 | 219.9 | 219.7 | 220.0 |
| Iterations: | 73 | | | | |

With the torque generated by 220N.m the maximum state and turbine rotation 900rpm the mechanical power generated at 20.680 watts or about 22.7kW, it can be concluded that the runner is designed according to the specifications of the conditions of the potential energy is in the Galih Pakuan village’s. To convince or feel safe design obtained then do the design verification by using FEA (Finite Element Analysis) with the following results:

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![Fig 4](image)

**Fig 4 Analysis of the runner stresses material with FEA using Inventor software**
With thought being given to that criterion safe is the safety factor (safety factor) more than one \( S_f > 1 \), then the left image above shows that \( S_f \) is happening \( S_f > 15 \) then design a runner in the safe category, with a voltage that occurs at 1.917 MPa indicated by the degradation of yellow color and green on the right image above.

Using CNC (Computer Numerical Control) with three axil milling machine, the design runner has been manufactured and can seen below in figure 5, and this may be the pattern for the casting for the purposes of making Kaplan turbines more and applied to the condition of head and discharge the same.

**Fig 5** the manufacturing process of each component runner with CNC

**Conclusion**

Defending on the head \( (H) \) and the discharge \( (Q) \) of a particular site, a runner has been design in order to get the highest efficiency. For the premiliary hydraulic design of the runner, correlation between the geometry if the runner and these parameters \( (H,Q) \) found in the literature have been used. The premilinary geometry of the runner has been cecked with modern engineering tools such as Computational Fulid Dynamic and Computer Aided Engineering.

It has been pointed out how CFD in a graphic manner shows the phenomena which takes place inside Kaplan turbin. Based on the data obtained from CFD model, a finite element analysis has been performed to identify stresses acting on the runner. It has been found that maximum Von Misses stresses in less than the yield strength of material mild steel, therefore, the stress analysis shows that the blades are able to withstand the occurring force inside of Kaplan turbine.

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