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CFD design and analysis in investigating the effect of turbine blade outlet angle variations on Micro-hydro turbine performance

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Abstract

South Sumatra has natural landscapes in the form of rivers, hills, lakes, and varied regional contour, storing the potential for the utilization of quite large water resources, however, many rural areas in this province still have difficulty getting access to electricity and are highly dependent on water sources. Micro Hydro Power Plants (PLTMH) are an efficient alternative solution, especially with the use of impulse turbine technology. This study aims to design and analyze a Pelton turbine using Computational Fluid Dynamics (CFD) simulation in order to determine the effect of change in the turbine blade output angle on the performance of the micro hydro turbine. The reasearch precess was conducted in three main phases starting from the preparation stage, design stage, and implementation stage where the results showed a flow velocity of 0.14 m/s and a discharge of 0.0054 m^3/s, with a maximum pressure of 103313.23 Pa and a minimum of 101877.77 Pa. The concave blade design proved to be optimal, and the highest torque on the Z axis of 0.01150 Nm was achieved in 0.011 seconds, indicating efficient and stable system performance.

Keywords: Micro Hydro Power Plant; Turbine; Cfd; Blade; Efficiency

1. Introduction

As the population increases, the need for electricity in rural areas is increasing, However, limited government funds to expand the electricity network are still an obstacle [1]. Energy is one of the vital needs for humans life [2] and energy plays an important role in the development of a country if its availability and development go hand in hand and support national development [3]–[5]. Energy is undeniably a key factor in the economic and social development of a nation today, because almost all activities carried out depend on electrical energy, while fossil energy as an energy source is increasingly depleting to meet the electricity needs of the Indonesian people [6]. South Sumatra, which has a variety of natural landscapes in the form of rivers, hills, lakes, and differences in contour, has the potential for utilizing quite large water resources, however, this region still has limited access to electricity, especially in rural areas that are highly dependent on water resources [7]–[11]. Micro Hydro Power Plants (PLTMH) are one of the alternative sources of electrical energy for the community, where by using this PLTMH, the community can utilize the existing river flow as a power plant [12], [13].

Pelton turbine is one of the widely used energy generating devices [14]. This turbine works by converting the potential energy of water into mechanical energy [15]–[17]. Therefore, simulation and analysis are needed to produce a Pelton turbine that has high efficiency. There are already several programs that are able to analyze water flow in a series of turbines so that we can improve turbine performance by making modifications based on the results of the analysis. One

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of these programs is Ansys which has a special program for analyzing fluids or commonly called CFD (Computational Fluide Dynamics).

Turbine design greatly influences its performance, as evidenced by Computational Fluid Dynamics (CFD) simulations. Previous Study by Achmad Husen (2021) shows that the shape of the blades in the design of the Pelton turbine hydroelectric power plant is made with variations of 1 half ball, 2 half cylinders, and 3 square plates with the results of the study variant 3 producing 4.04 watts of power and 0.105 Nm of torque the highest compared to other variants. This innovative and precise design of the potential of microhydro technology as an alternative energy source that is expected to be efficient, practical, and supports energy security in areas without access to electricity [18].

Based on the present situation and the prospect of water energy and from several studies that have been conducted, this is the basis for making CFD designs and analyses in investigating the effect of variations in the turbine blade output angle on the performance of microhydro turbines [11]. Good and appropriate innovative power plant designs in the use of impulse turbine technology can create renewable energy efficiency and are also expected to create sustainable and reliable energy solutions to support the provision of electricity in remote areas and in emergency situations [19].

2. Methods

Lubuklinggau is a city-level administrative region in the westernmost part of South Sumatra Province, formed through the division of Musi Rawas Regency. Geographically, Lubuklinggau City is located between 30 4' 10'' – 30 22' 30'' South Latitude and between 1020 40'' – 1030 0' 0'' East Longitude and is located at an altitude of 129 meters above sea level. Kelingi River is one of the rivers located in Lubuklinggau City, South Sumatra Province, Indonesia. Kelingi River not only has an important role in terms of ecology and history, but also provides significant benefits for the activities of the surrounding community. For local residents, this river is the main source of water for daily needs, such as for bathing, washing, and agriculture.

The designed flow system shows a flow velocity of 0.14 m/s, reflecting stable flow conditions. The flow discharge resulting from the measurement reached 0.0054 m^3/s. With this speed, the flow discharge indicates that the system is more suitable on a small scale, such as a microhydro energy utilization system. The total head of 2.7 meters provides an illustration of the potential energy available from the difference in water height. This head is significant enough to be applied to a small-scale turbine system, namely the Pelton turbine, which is designed to utilize low to medium heads. Overall, the combination of speed, discharge, and head parameters shows the potential for utilizing water energy on a small to medium scale, both for the needs of microhydro power plants.

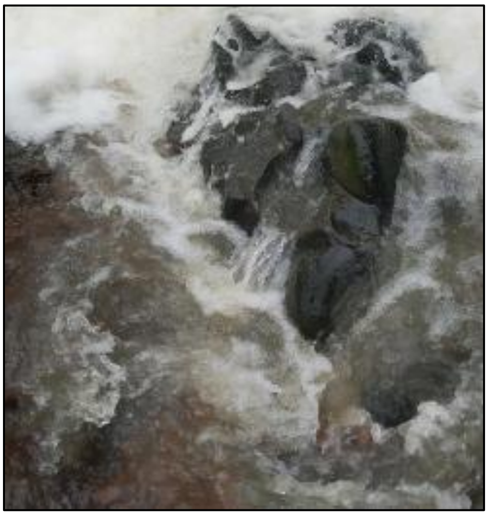

Figure 1 Kelingi River Flow

The research was conducted in three main phases. First, the preparation stage which includes an initial survey and literature study. Second, the design stage, where the initial design of the PLTMH tool is carried out by developing the working principles of the system. Third, the implementation stage, namely analyzing the design that has been prepared in the previous stage, which is carried out through simulation using SolidWorks software with a Pelton turbine model.

3. Results and discussion

3.1. Turbine Design Planning

This stage includes the calculation of technical parameters as the basis for designing the Pelton turbine. Each parameter calculated is based on initial data and specifications relevant to the needs. These results aim to ensure that the designed turbine is able to operate efficiently and optimally according to the conditions of the available water resources.

Absolute velocity of the jet (C_1):

$$C_1 = Kc\ x \sqrt{2\ x\ g\ x\ Hn}$$
$$C_1 = 0.96\ x \sqrt{2\ x\ 9.81\ x\ 2.7}$$
$$C_1 = 6.987\ m/s$$

Optimal jet diameter (d):

$$d = \sqrt{(4\ x\ Q)/(\pi\ X\ C1)}$$
$$d = \sqrt{(4\ x\ 0.0054)\ /(3.14\ x\ 6.987)}$$
$$d = 0.0313$$
$$d = 31.3\ mm$$

Optimal peripheral speed (U_1):

$$U_1 = Ku\ x \sqrt{2\ x\ g\ x\ Hn}$$
$$U_1 = 0.45\ x \sqrt{2\ x\ 9.81\ x\ 2.7}$$
$$U_1 = 3.275\ m/s$$

Stitch circle diameter (Dlt):

$$Dlt = \frac{(60\ x\ U_1\ x\ i\ )}{(\pi\ x\ nG\ )}$$
$$Dlt = \frac{(60\ x\ 3.275\ x\ 1\ )}{(3.14\ x\ 500)}$$
$$Dlt = 0.125\ m$$
$$Dlt = 125\ mm$$

Number of bowls (z):

$$z = 5.4\ x \sqrt{\frac{Dlt}{d}}$$
$$z = 5.4\ x \sqrt{\frac{125}{31.3}}$$
$$z = 10.79 \sim 11\ buah$$

Bowl width (b):

$$b = 2.5\ x\ d$$
$$b = 2.5\ x\ 31.3$$
$$b = 78.25\ mm$$

Bowl height (h):

$$h = 2.1\ x\ d$$
$$h = 2.1\ x\ 31.3$$
$$h = 65.73\ mm$$

Bowl opening width (a):

$$a = 1.2\ x\ d$$
$$a = 1.2\ x\ 31.3$$
$$a = 37.5\ mm$$

Bowl depth (t):

$$t = 0.9\ x\ d$$
$$t = 0.9\ x\ 31.3$$
$$t = 28.17\ mm$$

Mold clearance (k):

$$k = 0.1\ x\ Dlt$$
$$k = 0.1\ x\ 125$$
$$k = 12.5\ mm$$

Runner outer diameter (D_0):

$$D_0 = Dlt + 1.2\ x\ h$$
$$D_0 = 125 + 1.2\ x\ 65.73$$
$$D_0 = 203.876\ mm$$

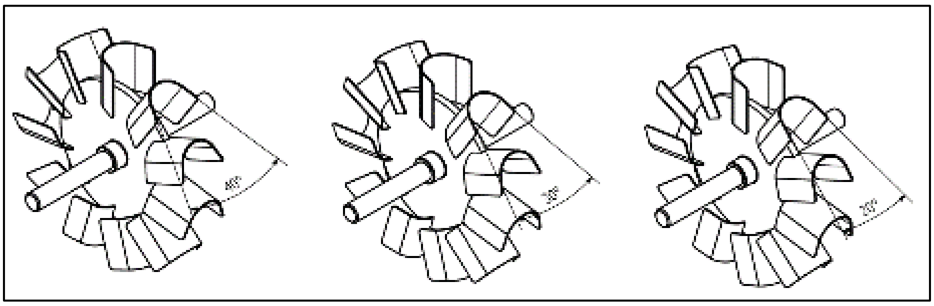

Figure 2 Blade opening angle 40°,30°,20°

3.2. Turbine CFD Simulation Using Solid Work

CFD simulation results, with flow rate as the main parameter are pressure and flow trajectories. This analysis is important to understand the flow pattern and pressure distribution in water turbines that affect the efficiency and performance of the turbine. The pressure scale indicate the highest pressure value is 103,313.23 Pa (red), occurring right at the point where the fluid first hits the turbine blade. This location mark of the transfer of fluid kinetic energy into mechanical energy used to rotate the turbine. After the fluid interacts with the blade, the pressure decreases gradually, reaching the lowest pressure value of 101,877.77 Pa (blue) which point out the release of fluid energy and the decreasing fluid velocity.

Table 1 Pressure simulation results at blade angles of 40°, 30°, 20°

Corner	Maximum Pressure	Minimum Pressure
40°	103015.79 Pa	101752.53 Pa
30°	103169.89 Pa	101674.11 Pa
20°	103313.23 Pa	101877.77 Pa

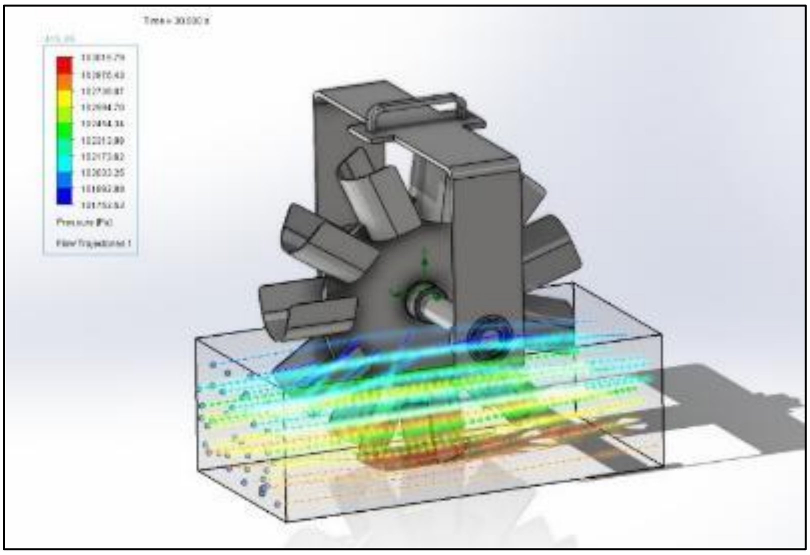

Figure 3 Pressure simulation at 40° blade angle

The fluid flow trajectory illustrated by the colored line shows a focused flow pattern towards the turbine blade. The high flow velocity when the fluid hits the blade corresponds to a large pressure gradient. The spreading flow indicates a decrease in kinetic energy due to the transfer of momentum from the fluid to the blade. The concave blade design appears to be effective in capturing fluid energy efficiently, as the highest pressure distribution is mostly focused on the concave side of the blade. The simulation results offer a detail visualization of how the fluid flow interacts with the turbine components. The following analysis will further evaluate the performance of the turbine. The following are the simulation results for designing a Pelton turbine.

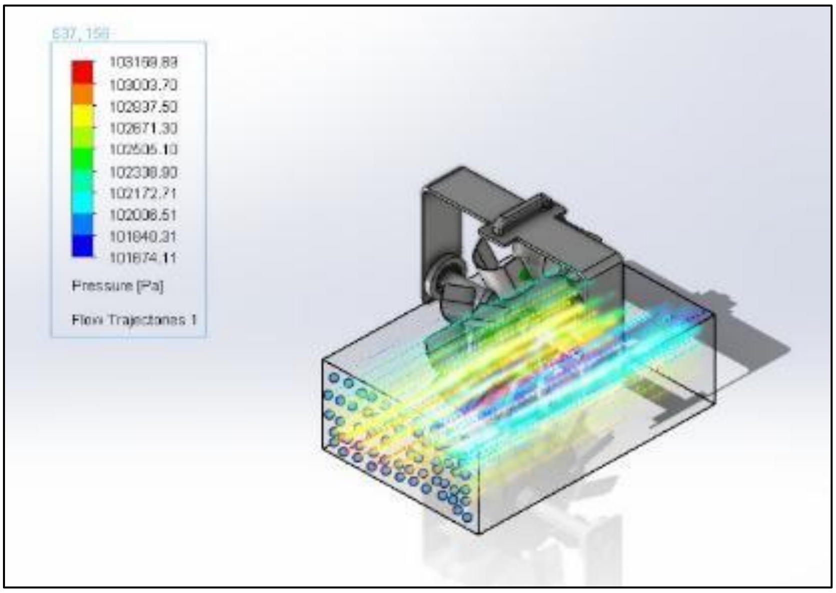

Figure 4 Pressure simulation at 30° blade angle

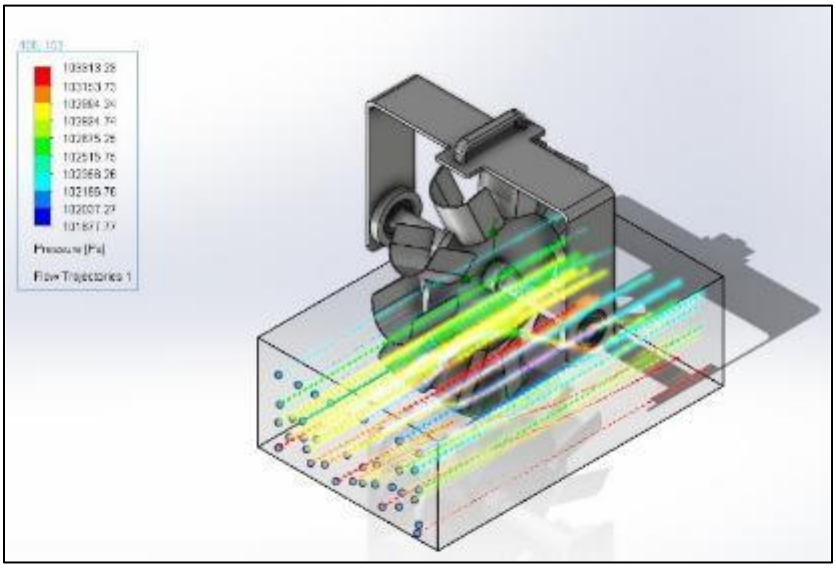

Figure 5 Pressure simulation at 20° blade angle

3.3. Turbine CFD Simulation Analysis Using Solid Work

In this section presents a detailed evaluation of the CFD simulation results of the turbine using SolidWorks as the simulation software is carried out. The simulation data provides insights into the physical parameters of torque on the X, Y, and Z axes. The torque analysis shows that the torque on the Z axis is consistently higher than the X and Y axes, with an average value of 0.01150 Nm, while the X and Y axes each have an average value of 0.00036 Nm and 0.01021 Nm. This shows that the rotational force on the Z axis dominates the system performance. The fluctuation of the torque values on the three axes is relatively small, with a maximum delta change in the range of 0.0001–0.0006 Nm. All parameters reach their maximum values at a very early time, which is around 0.011 seconds, indicating that the system quickly reaches dynamic stability.

Table 2 Simulation results of 40° blade angle torque analysis

Goal Name	GG Torque (X) 3	GG Torque (Y) 4	GG Torque (Z) 5
Unit	[Nm]	[Nm]	[Nm]
Value	0.00059066	0.00072924	0.00769327
Average Value	0.00055258	0.00068008	0.00771931
Minimum Value	0.00043263	0.00039028	0.00757221
Maximum Value	0.00065143	0.00095136	0.00816029
Progress [%]	100	100	100
Use In Convergence	Yes	Yes	Yes
Delta	0.000210310	0.00009980	0.000588080
Criteria	0	0	0
Maximum in Calculation	0.00719169	0.01841127	0.54277851
Maximum Time [s]	0.0113578	0.0113578	0.0113578

Table 3 Simulation results of 30° blade angle torque analysis

Goal Name	GG Torque (X) 3	GG Torque (Y) 4	GG Torque (Z) 5
Unit	[Nm]	[Nm]	[Nm]
Value	0.000404596	0.010108094	0.01156188
Average Value	0.000368402	0.010215017	0.011508518
Minimum Value	0.000585736	0.010305162	0.011428535
Maximum Value	0.000303168	0.010062142	0.011978156
Progress [%]	100	100	100
Use In Convergence	Yes	Yes	Yes
Delta	0.000164354	0.000049006	0.000549621
Criteria	0	0	0
Maximum in Calculation	0.000894966	0.00854917	0.525466471
Maximum Time [s]	0.027835875	0.036085404	0.011808297

Table 4 Simulation results of 20° blade angle torque analysis

Goal Name	GG Torque (X) 3	GG Torque (Y) 4	GG Torque (Z) 5
Unit	[Nm]	[Nm]	[Nm]
Value	2.50556603	0.07378109	0.00480698
Average Value	2.505514435	0.07372043	0.00505291
Minimum Value	2.50511582	0.07427634	0.00578972
Maximum Value	2.505758296	0.07281772	0.00437003
Progress [%]	100	100	100

Use In Convergence	Yes	Yes	Yes
Delta	0.000642476	0.001458611	0.000822846
Criteria	0.004721282	0.015721303	0.001038459
Maximum in Calculation	0.000384867	0.000181153	0.559053904
Maximum Time [s]	0.037595822	0.01036259	0.01036259

4. Conclusion

Through Computational Fluid Dynamics (CFD) simulations, this research successfully captures the characteristics of fluid flow and pressure distribution in a Pelton turbine. The highest pressure point of 103313.23 Pa occurs when the fluid first hits the turbine blade, indicating the main location where the transfer of kinetic energy into mechanical energy occurs. Conversely, the lowest pressure is recorded at 101877.77 Pa after the fluid energy is transferred to the blade, indicating energy release and flow deceleration. The flow path shows that the fluid flow pattern is effectively directed to the blade with a significant pressure gradient, strengthening the momentum transfer process. The concave blade design is proven to be optimal because it is able to capture high pressure efficiently on its concave side. Torque analysis from the simulation results shows that the Z axis dominates the rotation with the highest average torque value, which is 0.01150 Nm. Torque fluctuations on the three axes are relatively small and the system shows fast dynamic stability, achieved at a time of around 0.011 seconds. Overall, these findings demonstrate that the examined Pelton turbine design delivers efficient performance and reaches operational stability quickly, highlighting its suitability for application in small-scale hydropower generation systems.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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