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Analysis of the effect of high falling water on the performance of hydroelectric power plants using whirpool type turbines

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Abstract: A hydroelectric power plant (PLTA) uses the flow of water as a source of energy. Evaluating the output of hydropower facilities, including the optimal height of the waterfall, turbine torque, electrical power, generator power, and generated efficiency, was the aim of the study. This study intends to investigate the power, torque, and efficiency that may be produced by a hydroelectric power plant with a whirlpool-type turbine, as well as how the height of falling water influences the operation of the plant. The experiment in this study measures three different waterfall heights with five different blade configurations. The study on the hydropower prototype involved three trials that collected data on torque, power, efficiency, waterfall height, and water discharge. The PLTA Prototype's best potential head in Test 3 was determined to be 0.01143, with a height of 0.67 meters, no sluice, and a diameter of 0.0625 meters. The lowest water outflow was discovered at a head of 0.55 meters with a water debit of 0.01036. The third attempt, which featured a sluice opening with a diameter of 0.0625 meters and a height of 0.67 meters (head), used the most water power in the experiment. The testing yielded the following results: 75.13 watts of water power, 5.16 watts of generator power, 0.233 N.m. of torque, 2.63 watts of turbine power with a generator load 3.73 watts without one, and 6.87% efficiency. Data gathered from the hydropower prototype's operation can be used to construct testing instruments for use in laboratories.

Keywords: Hydropower; water debit; whirlpool turbine

1. INTRODUCTION

Without electricity, modern civilization would not be able to function daily or meet the many demands of the commercial and industrial sectors. The primary cause of the difficulty in meeting these demands for electricity is the significant reliance of society on non-renewable fuels, especially petroleum. This reliance raises issues with sustainability as well as the economy and ecology. In response to these problems, a wide range of alternative energy sources have been developed. Hydropower, particularly micro hydro systems, geothermal heat extraction, wind energy absorbed by turbines, and solar energy produced by solar panels are some of these more sustainable and ecologically friendly possibilities [1]. Each of these energy sources contributes to a more varied and resilient energy mix and offers unique benefits. For example, by converting sunlight into power, solar panels offer a plentiful and clean energy source. Geothermal energy comes from the heat that exists inside the earth and provides a consistent and reliable source of power. Wind turbines employ the kinetic energy of the wind to create electricity, but micro hydro devices harness the energy of flowing water even in tiny streams to generate power. Making the switch to these renewable energy sources is essential for reducing reliance on fossil fuels and for preventing climate change. Because of this, further study and advancement in these areas are necessary for a sustainable and energy-secure future.

There are notable disparities in Indonesia's availability of electricity, particularly in remote and rural areas where many communities lack access to it. The primary source of energy for these sometimes remote and underdeveloped areas is diesel power plants, also known as diesel engine power plant or PMLTD. This dependence results in serious financial and logistical challenges, which are exacerbated by the constantly rising costs of fossil fuels, also known as fuel oil or BBM. The rising cost of fossil fuels not only strains the financial resources of these regions but also raises concerns about environmental sustainability. As a result, producing power through the use of renewable energy technology has become more and more common. Renewable energy, which includes sources including solar, wind, hydro, and biomass, provides a more affordable and ecologically beneficial solution for many power-related problems. Indonesia may be able to reduce its reliance on diesel generators and the detrimental impact that burning fossil fuels has on the environment and the economy by integrating renewable energy sources into the nation's electrical infrastructure. Furthermore, by providing more constant and predictable power sources, the adoption of renewable energy technologies has the potential to enhance socioeconomic progress and the standard of living in remote areas. This shift to greener energy sources is crucial to Indonesia's quest for energy equity and sustainability and is consistent with global environmental goals [2].

The microhydro power plant (PLTMH) system is a notable illustration of small-scale renewable energy generation, especially in the area of hydropower. Although PLTMH isn't as productive as larger establishments like hydropower plants (PLTA) or steam power plants (PLTU), it is nevertheless incredibly helpful in remote or isolated locations that aren't connected to the conventional electrical grid. Its ability to provide a locally regulated, sustainable, and low-impact power source accounts for its significance. There is growing recognition of this technology's feasibility and environmental friendliness as a way to close the energy gap for marginalized communities and move toward the more general goal of achieving energy sustainability [3].

The hydropower plant (PLTA) is a cutting-edge power plant distinguished by its utilization of water's kinetic energy, which is typically found at higher altitudes. The potential energy that flowing water possesses is used as the initial stage in this process. When waterfall from a height, it loses potential energy and transforms into mechanical energy [4]. This conversion is a crucial step in the generating process because it employs mechanical energy to deliberately rotate a turbine's blades or vanes [5]. The turbine's spin is the main mechanism that converts mechanical energy into electrical energy. Conventional hydropower plants are specifically made to regulate and direct water flow, which usually originates from rivers or other natural sources, in the direction of the turbine. This regulation is necessary to ensure the effective and efficient generation of power and to maintain a continuous and controlled flow. Furthermore, reservoirs and dams are commonly included in the designs of these plants. These features are crucial for water management since they allow for the storage and controlled release of water, which increases the plant's ability to generate power in response to demand. Hydropower plants are a renewable energy source and a means of balancing the grid during times of varying demand because they can store and release water on demand [6].

The purpose of hydropower plants is to harness the inherent energy potential of bodies of water. In particular, their goal is to make use of the differences in water level and volumetric flow rate seen in water channels such as rivers, irrigation canals, and waterfalls. Their operation is based on the conversion of the kinetic energy of flowing water into mechanical energy [7]. The water's flow causes the turbine shaft to rotate, which enables this. This method of creation transfers the mechanical energy to a generator, where it is transformed into electrical energy [4]. The head, or vertical distance, from which water drops, together with the water's flow rate, are two crucial factors that define a hydropower plant's capacity to generate useful power. The amount of potential energy that can be captured and transformed is determined by these parameters. Therefore, in addition to being a way to convert the potential energy associated with water elevation and flow into mechanical and electrical energy, hydropower facilities are an example of a sustainable energy production technology. Their efficient synchronization with global initiatives for renewable energy sources offers a stable and environmentally benign alternative to fossil fuel-based power generation [8].

To use hydroelectric energy for electricity generation, water turbines are necessary. They are categorized based on specific criteria, like the head, or height at which water falls, and the water's flow capacity. They are available in a range of varieties. Based on how they operate, these turbines can be roughly classified as impulse turbines or reaction turbines. Impulse turbines are designed to convert all of the water's energy—potential, pressure, and velocity—into kinetic energy, which drives the turbine [9]. Notable examples of turbines operating on this impulse idea are the Pelton, turbo, and cross flow turbines. These turbines work particularly effectively in high-head situations where water velocity can be maximized. Conversely, all of the energy in water, including its kinetic and pressure components, is converted into rotational energy by reaction turbines. In this setup, the turbine runner is fully submerged in water and enclosed in a turbine housing. This type of turbine is used in low to medium head situations in most applications. Two typical reaction-based turbines that stand out for their efficiency and adaptability in responding to various water flow conditions are the Francis and Kaplan turbines [10].

The Whirlpool turbine design is a unique technique that makes use of the mechanics of water vortices. This design channels water in a manner similar to the whirling motion found in sink drains, creating a vortex.

The Whirlpool turbine's operating principle, which effectively drives the turbine, captures this vortex movement [11], [12]. Unlike traditional vertical turbines, which need large fall heights, the Whirlpool turbine performs effectively with a lower height differential. These turbines are well known for their economical electricity production. The structure of the basin is robust and long-lasting, with a lifespan of up to a century. It is often made of concrete. according to turbulent, a company that specializes in this technology, these turbines are not only environmentally friendly but also carefully designed to take aquatic surroundings into consideration [13], [14]. These turbines are useful in part because they are not too difficult to maintain. Because it is easier to offer a steady supply of energy due to the turbine's rotation, this technology is a feasible alternative in the field of sustainable power generation [15], [16].

A fluid is characterized by its transitory nature and capacity to change shape. A fluid is a material that moves when force is applied. Fluids take on a multitude of shapes as they move through solid objects, adapting to their shapes. Important aspects of fluid flow include shear stresses, total pressure, dynamic pressure, and fluid velocity [17], [18]. The three primary types of fluid flow are turbulent, transitional, and laminar. Laminar flow is the term used to describe the uniform, homogeneous fluid movement that happens when particles travel parallel to streamlines. This type of flow is characterized by a steady state, where the velocity and flow rate remain constant throughout time, as is commonly observed in controlled water flows. Transitional flow is a state in which fluid particles go from an ordered to a disordered state [19], [20]. In environments with relatively large flows, this shift departs from laminar simplicity and results in intricate and complex movement patterns. Transitional flow is characterized by higher fluid velocities, bigger flow scales, a variety of flow patterns, anomalies in fluid channels, and typically lower viscosity. These features indicate a transition from laminar to turbulent flow characteristics, which are less uniform and more dynamic [21], [22].

The vertical difference between the upper water surface (TPA) and the lower water surface (TPB), often known as the "head," is used to compute hydraulic energy for hydroelectric power facilities [23]. This feature must be understood in order to calculate the potential waterpower available for energy conversion. Figure 1, explains the concept and provides a visual representation of how head affects hydraulic energy estimations in the context of hydroelectric power generation [24].

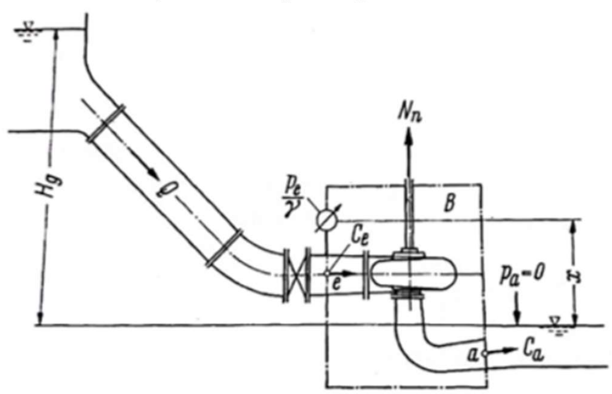

Figure 1. Waterfall height (head).

This study aims to ascertain the relationship between water head height and turbine power output. Finding the optimal head height at which turbines operate at their best is its aim. This study also aims to comprehend the effects of rising head height on torque and the subsequent effects on energy output. The ultimate aim of the study is to completely understand the relationship between head height and generator performance in order to enhance hydroelectric power plant design and operation.

2. METHOD

This study was conducted at the Mechanical Engineering Laboratory, Department of Mechanical Engineering, Universitas Medan Area. The equipment used were hydropower plant (HPP) prototype, water pump, and Whirlpool Turbine Blades. Built to prototype scale, the hydropower plant (HPP) uses the energy of flowing water as its energy source. A form of energy conversion known as hydropower plants uses a channel to convey water at a given height and discharge rate. The generator and turbine are rotated by the canal, which directs a particular water discharge at a decreasing velocity. The format of this HPP is displayed in Figure 2. Turbine blades are the components of the turbine that convert the action of the water jets into rotational motion. In this investigation, five-bladed turbine blades were employed, as seen in Figure 3.

A number of research procedures were completed, including setting up the tools and supplies for the study, filling the water container, turning on the SU 50 water pump to move water from the lower reservoir to the upper reservoir tube via pipes, and utilizing 12 mm bolts on the waterway support to adjust the water head height in three different increments of 0.55 m, 0.60 m, and 0.67 m. The upper reservoir tube will then receive water until it reaches a volume of 110.70 L. The water gate, which has a diameter of 0.0635 meters, will thereafter be opened. The next step is to measure the turbine rotation speed using a tachometer that is 20 cm from the generator, a tachometer that is not 20 cm from the generator, a multitester that is connected to the generator to measure electric voltage, and a multitester that is connected to the generator to measure electric current.

Figure 2. Hydroelectric power plant prototype

Figure 3. Whirlpool turbine blades.

Additionally, the discharge in three experimental trials with water head heights of 0.55, 0.60, and 0.67 meters was calculated. The water power produced by the prototype Hydropower Plant (HPP) was also calculated, as was the generator power produced by the HPP. Torque was calculated using the prony brake method, the turbine power produced by the HPP was calculated, and the Whirlpool turbine was used to determine the efficiency of the HPP. The experiment on the prototype HPP is the last stage of this study series.

3. RESULTS AND DISCUSSION

Table 1 displays the findings of tests conducted on five turbine blades, assessing three different waterfall height fluctuations. It is evident that at a waterfall height of 0.67 meters, the ideal head, which was determined through three trials, increases. The maximum hydraulic power output attained is 75.13 watts at a water flow rate of 0.01143 m3/s. Generator power output is 5.16 watts, torque is 0.233 N.m., turbine power without generator load is 3.73 watts, turbine power with generator load is 2.63 watts, and efficiency is 6.87%. Water flow rate, volume, and waterfall height (head) are all strongly influenced by electrical power. The water flow to operate the turbine is faster at higher waterfall heights (head), which increases the amount of electricity produced. On the other hand, if the height of the waterfall is smaller, the water flow that rotates the turbine slows down and produces less electricity.

The impact of head on energy production can be expressed as follows: a higher head height is associated with more potential energy that can be transformed by the turbine into mechanical energy and then by the generator into electrical energy. An increase in head from 0.55 m to 0.67 m causes an acceleration of the turbine rotation speed due to the link between head and turbine rotation. This shows that the greater energy from the water dropping from a higher height causes the turbine to rotate more quickly. Turbine rotation, current, and voltage are directly correlated; as the turbine rotates faster, more current and voltage are produced at the same time. This implies that when the turbine spins faster, the generator's electrical output increases, demonstrating better energy conversion efficiency. Since the amount of water used in each test is the same, it can be concluded that the head—rather than the different amounts of water—is the only factor affecting the turbine's performance comparison. Although increased head leads to increased water discharge, head elevation does not directly correlate with this increase. This may indicate that there is a threshold at which the turbine can no longer handle higher water flows. Elevating the head in hydroelectric power plants successfully increases the electrical output, as seen by the nearly perfect or very high correlation found between head, turbine rotation, current, voltage, and the resulting power output. The strong association suggests that these factors are intimately related to one another during the hydroelectric power facility's energy producing process.

Table 1. Measurement of electrical voltage at variations in the height of the waterfall

Testing	Head	Volume	Water Discharge	Turbine Rotation	Current	Voltage
	(m)	(m^3)	(m^3/s)	(rpm)	(A)	(V)
1	0,55	0,11077	0,01036	94,3	0.48	5.41
2	0,60	0,11077	0,01083	103,7	0.6	6.4
3	0,67	0,11077	0,01143	107,7	0.73	7.07

Table 2 shows that an increase in head corresponds to an increase in turbine power and efficiency. The vertical drop of water is referred to as the "head," and it is a crucial factor in determining the potential power of the water that the turbine can convert into electrical energy. Interestingly, there was a noticeable increase in hydraulic power from 55.90 Watts to 75.13 Watts when the head increased from 0.55 m to 0.67 m. This suggests that there is more potential energy available for the turbine to convert. In addition, generator power increased in tandem with the head elevation, showing that the generator can produce more electrical energy from the mechanical energy that the turbine provides. The generator power increase from 2.60 Watts at a 0.55 m head to 5.16 Watts at a 0.67 m head is proof of this. In addition, with the rising head, the turbine torque—a measure of the rotational force produced by the turbine—also rose, rising from 0.168 N.m. to 0.233 N.m. This increase indicates that the turbine can handle more work. Testing further demonstrated an increase in turbine power both with and without the generator. Turbine power increased from 2.35 to 3.73 watts in the absence of the generator and from 1.66 to 2.63 watts in the presence of the generator. These additions suggest that the turbine performs better at higher heads. Finally, the turbine's efficiency soared from 4.65% to 6.87% as the head increased. This efficiency, which is the ratio of the power output to the power input, indicates that the turbine is getting increasingly better at transforming potential water energy into mechanical energy and then electrical energy.

Table 2. Measurement of turbine power and efficiency

Testing	**Head**	**Water Discharge**	**Waterpower**	**Generator Power**	**Torque**	**Turbine Power (Watt)**		**Efficiency**
	(m)	**(m^3/s)**	**(Watt)**	**(Watt)**	**(N.m)**	**Without Generator**	**With Generator**	**(%)**
1	0,55	0,01036	55,90	2.60	0,168	2.35	1.66	4.65
2	0,60	0,01083	63,75	3.84	0,231	3.38	2.50	6.02
3	0,67	0,01143	75,13	5.16	0,233	3.73	2.63	6.87

Figure 4 A graph depicting the results of measuring hydraulic power as a function of head is shown in Figure 4. The relationship between the water height (head) and the power produced by a Whirpool water turbine is seen in this graph. A correlation between an increase in head and a matching rise in generated power

is revealed by the graphical analysis. In particular, the power output is roughly 55.90 Watts at a head of 0.55 meters. The power output increases to approximately 63.75 Watts when the head is raised to 0.60 meters. Elevating the object by 0.67 meters results in a notable boost in power output, reaching roughly 75.13 Watts. This link makes sense scientifically since the height of the head and the velocity of water flow directly affect the power generated by a hydroelectric turbine. The formula $P = \rho ghQ$ can be used to determine the power (P) produced by a hydroelectric turbine. In this formula, ρ stands for water density, g for gravitational acceleration, h for head, and Q for water flow rate. As a result, a higher head increases the water's potential gravitational energy that the turbine can harness to create mechanical energy, increasing power. According to the underlying physical principles, this graph supports the idea that increasing a hydroelectric power station's head height can increase its power production.

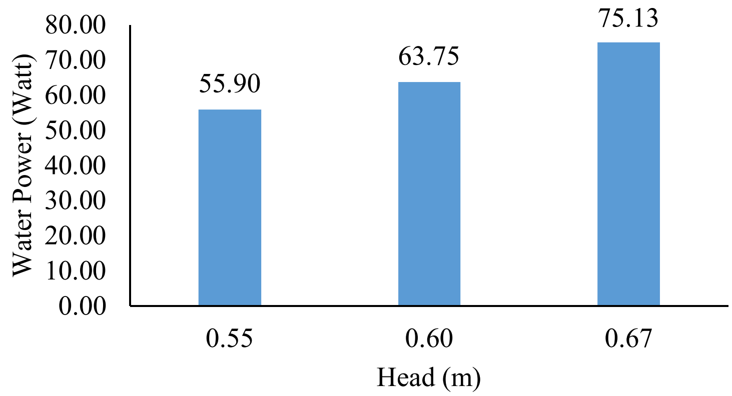

Figure 4. Results of waterpower measurements with head variations

The graph showing a generator's power output measurements in relation to head variation is shown in Figure 5. Research has shown that the power produced by a hydropower plant (HPP) that uses a Whirlpool engine rises in direct relation to the increase in head values. The generator's power output is specifically recorded at 2.60 Watts at a Head of 0.55 meters, rising to 3.84 Watts at a Head of 0.60 meters and 5.16 Watts at a Head of 0.67 meters. Scientific explanation for this increase in generator power can be found in the idea that potential energy in water at a given height (Head) can be transformed into mechanical energy by means of a turbine, and then into electrical energy by means of a generator. More potential energy is available at higher heads, which causes the water to flow through the turbine more forcefully and produces more electrical power.

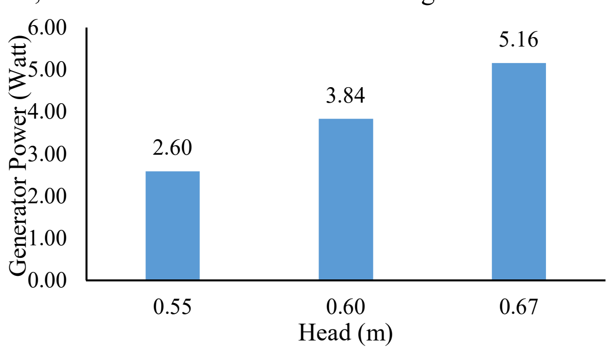

Figure 5. Graph of generator power measurement results based on Head variations

According to the hydroelectric power equation $P = \rho ghQ$, where g is the acceleration due to gravity, h is the head, Q is the water flow rate, and P is power, the relationship between Head and the resulting power output is typically linear within a specific optimally operated range. According to this graph, the system is probably running at peak efficiency and hasn't yet achieved saturation, which is the point at which adding Head results in noticeably higher power production.

A graph showing the power measurements of a turbine in a hydroelectric power plant powered by a Whirpool engine both with and without a generator is shown in Figure 6. The hydroelectric plant with a Whirpool engine's power output is depicted on the graph under three different water head levels: 0.55 meters, 0.60 meters, and 0.67 meters, both while the turbine is running "with a generator" and "without a generator." It can be shown that the turbine without a generator continuously produces more power than the turbine with a generator at every water head level. Science can explain this occurrence by pointing to the energy losses that occur when the turbine and generator are coupled. The generator transforms the mechanical energy of the turbine into electrical energy, although this process is not totally efficient because of energy losses from electromagnetic resistance, friction, and other sources. For example, the turbine produces 2.35 Watts of power output without a generator at a water head level of 0.55 meters, but 1.66 Watts of power output with the generator. This disparity demonstrates how the energy used to generate electricity and the losses sustained during energy conversion lower the turbine's overall power output. The difference in power production between the two scenarios tends to climb as water head levels do, indicating that stronger flows or higher head levels are when the relative losses brought on by the generator become more noticeable.

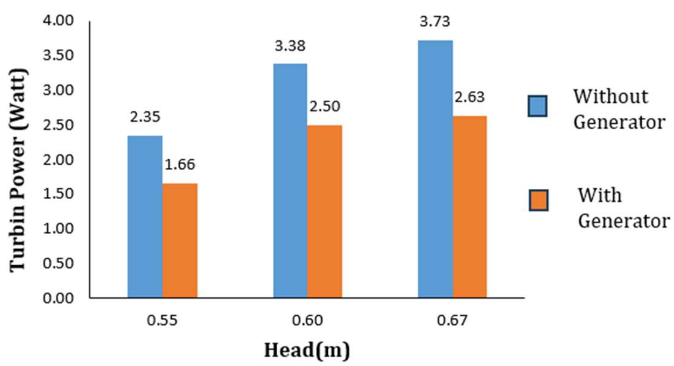

Figure 6. Graph of turbine power measurement results with and without generator based on Head variations.

A thorough graph illustrating the variance in torque measurements in a water turbine system as a function of head height is shown in Figure 7. The graph unequivocally shows that there is a discernible increase in the turbine's torque production as the head, or the vertical distance of water fall, rises from 0.55 meters to 0.67 meters. To illustrate, the torque value is measured at 0.168 Nm at a head of 0.55 meters. As the head is increased to 0.60 meters, the torque value increases to 0.231 Nm, and at 0.67 meters, it reaches its maximum of 0.233 Nm. Given that it emphasizes the fundamentals of hydraulic energy conversion in water turbines, this trend has scientific significance. Water with accumulated potential energy at a given head or height goes through the turbine and becomes kinetic energy as it descends. Consequently, a larger head translates into more potential energy, which is then translated into a greater amount of kinetic energy, resulting in increased torque on the turbine's rotor. This torque is an important measure of the mechanical energy that the turbine produces and then converts to electrical power. The graph also shows that there are situations in which an increase in torque is not immediately correlated with an increase in head. Numerous factors, including as turbine efficiency, energy losses from turbulence or friction, and particular features of the water flow, might be blamed for this fluctuation. It implies that the actual relationship between head and torque is more complicated and may be impacted by the particulars of the turbine's design as well as its operating environment.

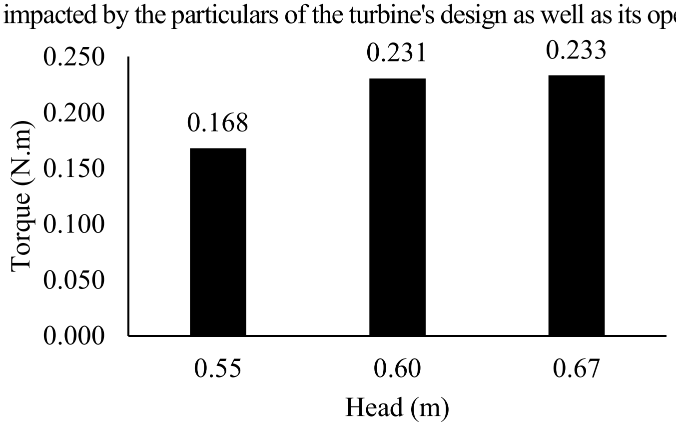

Figure 7. Graph of torque measurement results based on Head variations

3 CONCLUSION

Important insights have been gained from the study of how head affects hydroelectric power plant performance with Whirlpool-type turbines. It was found that the hydraulic head is essential to the turbine's power production. Hydraulic power increased from 55.90 Watts to 75.13 Watts in tandem with a head increase from 0.55 meters to 0.67 meters. This suggests that at higher head levels, a greater potential energy is accessible for the turbine to convert. The head rise was precisely proportional to the turbine's increased rotational speed and the generator's increased power output, which increased from 2.60 Watts to 5.16 Watts. This result shows that the turbine performs better at higher heads, as seen by the 6.87% efficiency increase from 4.65%. In addition, the torque of the turbine—a measurement of the rotating force generated—rose from 0.168 N.m. to 0.233 N.m. This indicates that the turbine's ability to do work has increased. These findings support the basic physical theories underlying the generation of hydroelectric power by showing that increasing head in hydroelectric power plants efficiently increases the electrical power output. This conclusion is essential for the advancement and improvement of turbine designs in order to generate hydroelectric power more efficiently.

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