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Effects of Hydraulic Pressure and Number of Nozzles on the Power Output and Efficiency of a Laboratory-Scale Pelton Turbine

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A R T I C L E I N F O

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A B S T R A C T

This study investigates the effects of water pressure and the number of nozzles on the rotational speed, input power, output power, and efficiency of a laboratory-scale Pelton turbine for micro-hydropower applications. Experimental tests were conducted under controlled laboratory conditions by varying the water pressure (2, 2.5, and 3 kg/cm²), the number of nozzles (one and two), and the applied load (5–25 W). Turbine rotational speed, input power, and output power were measured to evaluate performance, while efficiency was calculated as the ratio of output power to input power, expressed as a percentage. The results showed that turbine efficiency was influenced by the combined effects of water pressure, nozzle configuration, rotational speed, and applied load. The highest efficiency of 8.2% was obtained using one nozzle at a water pressure of 3 kg/cm² and a load of 25 W, with a rotational speed of 290 rpm, an input power of 112.52 W, and an output power of 9.21 W. The findings also indicated that increased input power did not necessarily result in higher efficiency, as efficiency depended on the proportion of input power converted into useful output power. These results demonstrate the importance of optimizing operating parameters to improve the performance of laboratory-scale Pelton turbines for micro-hydropower applications

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INTRODUCTION

Growing electricity demand, declining fossil fuel reserves, and environmental concerns have driven the development of renewable energy, with hydropower offering reliable generation, long service life, and low emissions. Micro-hydropower (MHP) provides a cost-effective electricity solution for remote areas by utilizing small water resources. Pelton turbines are widely used in MHP systems, particularly under high-head and low-flow conditions. A Pelton turbine operates based on the impulse principle, where the kinetic energy of a high-speed water jet is converted into rotational mechanical energy through direct interaction with bucket-shaped blades mounted on the runner. Energy conversion efficiency depends on water pressure, jet velocity, rotational speed, nozzle configuration, and electrical load. In laboratory-scale Pelton turbines, these factors influence flow stability and energy transfer. Therefore, investigating water pressure and nozzle variations is essential to optimize turbine performance and support practical learning in micro-hydropower systems.

Recent Scopus-indexed studies (2022–2026) have advanced Pelton turbine optimization through improvements in nozzle geometry, blade design, operating pressure, and flow conditions. Semlitsch (2024) highlighted that inflow disturbances and jet instability can increase turbulence-related hydraulic losses, reducing jet quality and turbine efficiency. Deng et al. (2023) further explained that deviations in nozzle jet alignment may negatively affect turbine rotational stability and energy conversion efficiency. In addition, Xiao et al. (2024) investigated the interaction between bucket number and Pelton turbine performance, concluding that the compatibility between hydraulic input and runner geometry strongly influences turbine power output. Zhang et al. (2025) also analyzed the effect of injector needle tip geometry on jet flow characteristics and found that nozzle design substantially affects water jet velocity distribution and mechanical performance. On the application side, Delgado-Currín et al. (2025) demonstrated that electrical loading conditions and operating pressure significantly influence hydraulic efficiency and generator performance in micro-hydropower systems. Furthermore, Setyawan et al. (2024) investigated the utilization of multiple nozzles and reported that increasing nozzle number can improve mechanical input power under certain operating conditions. However, previous investigations have primarily focused on industrial-scale or medium-capacity hydropower systems, while comparative experimental studies specifically evaluating the performance differences between single-nozzle and double-nozzle configurations in laboratory-scale Pelton turbine systems remain relatively limited. This limitation indicates the need for further experimental studies capable of clarifying the relationship between pressure variation, nozzle number, turbine rotational characteristics, and electrical efficiency under controlled laboratory conditions.

The novelty of this study lies in the experimental comparison of single- and double-nozzle Pelton turbines under consistent laboratory conditions, with variations in water pressure and electrical load. Unlike studies primarily focused on turbine geometry or large-scale hydropower, this research examines how pressure variation and nozzle configuration affect hydraulic flow distribution

and energy conversion performance in a compact, recirculating micro-hydropower system.

This study investigates Pelton turbine performance at water pressures of 2, 2.5, and 3 kg/cm² under electrical loads ranging from 5 to 25 W, focusing on rotational speed, output power, and efficiency. The experimental results showed that the single-nozzle configuration achieved higher rotational speed and efficiency than the double-nozzle configuration. Despite its greater water discharge, the double-nozzle system did not consistently improve power output or energy conversion efficiency, suggesting potential hydraulic losses and uneven jet distribution. These findings highlight the importance of nozzle configuration and operating conditions in optimizing laboratory-scale micro-hydropower systems and provide practical insights into impulse turbine performance under varying hydraulic conditions. This study examines the effects of water pressure and nozzle configuration on the performance of a laboratory-scale micro-hydropower system. Experiments were conducted at pressures of 2, 2.5, and 3 kg/cm² under varying electrical loads to assess turbine rotational speed, output power, and efficiency. The performance of single- and double-nozzle configurations was also compared to identify the more effective arrangement for laboratory-scale applications. This study also evaluates the effects of electrical loading on turbine performance by measuring voltage, current, rotational speed, and hydraulic power. It further identifies the operating conditions that yield the highest efficiency and output power in the experimental micro-hydropower system. Using a controlled recirculating water system, the findings are expected to support the optimization of laboratory-scale Pelton turbines for renewable energy education and small-scale hydropower applications, while informing future research on hydraulic performance, nozzle configuration, and energy conversion efficiency.

THEORETICAL REVIEW

This study employed an experimental approach to evaluate the performance of a laboratory-scale Pelton turbine micro-hydropower (MHP) system under varying water pressures and nozzle configurations. The experimental apparatus comprised a recirculating water system, centrifugal pump, piping network, control valve, pressure gauge, Pelton turbine, and electrical loading unit, all mounted on a rigid steel frame to minimize vibration and maintain stability. Water was continuously circulated from a reservoir using a pump, with operating pressures set at 2, 2.5, and 3 kg/cm². A control valve regulated the water flow, while a pressure gauge monitored system pressure throughout testing. These controlled conditions enabled systematic assessment of turbine rotational speed, electrical power output, and overall efficiency. The recirculation configuration enabled continuous testing while reducing water consumption and maintaining stable laboratory operating conditions.

The pressurized water flowing through the pipeline was directed toward the nozzle assembly, where the hydraulic pressure energy was converted into high-velocity kinetic energy in the form of water jets. These jets were then projected onto the Pelton turbine buckets to generate rotational motion. Two

nozzle configurations were evaluated in this study, namely a single-nozzle system and a double-nozzle system, in order to analyze the effect of jet distribution on turbine performance. The Pelton turbine employed in the experiment was an impulse-type turbine equipped with bucket-shaped blades specifically designed to efficiently capture the momentum of the water jet.

The turbine bucket geometry is shown in Figure 1. The water jet strikes the bucket splitter, changing the water momentum and generating torque to rotate the turbine runner. The turbine shaft is directly connected to a 220 V AC generator rated at 5.1 A, which converts mechanical energy into electrical power. Electrical loading was provided by five 5 W incandescent lamps, giving a maximum load of 25 W. The lamps served as electrical loads for evaluating generator performance. Before testing, the Pelton turbine system was designed, fabricated, assembled, and calibrated to ensure stable operation and reliable measurements, as shown in Figure 2. The experiments were performed systematically by varying water pressure and electrical load for both nozzle configurations. The pump was activated, and the control valve was adjusted to achieve the target pressures of 2, 2.5, and 3 kg/cm². Electrical loads were then increased incrementally from 5 W to 25 W under each test condition.

During each test, turbine rotational speed, output voltage, electric current, and water flow rate were measured. Rotational speed was recorded in rpm, while voltage and current were measured at the generator terminals under each load condition. The collected data were used to calculate hydraulic input power, electrical output power, and system efficiency. Hydraulic input power was determined from the water density, gravitational acceleration, flow rate, and hydraulic head corresponding to each pressure setting. Electrical output power was calculated as the product of generator voltage and current. Turbine efficiency was then determined by expressing the ratio of electrical output power to hydraulic input power as a percentage. The calculated results were compared to identify the optimal operating conditions and the most effective nozzle configuration for laboratory-scale Pelton turbine applications.

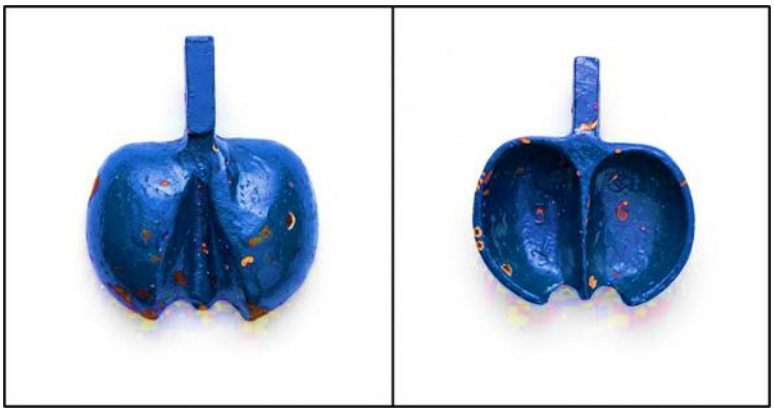


Figure 1. Pelton turbine blade shape

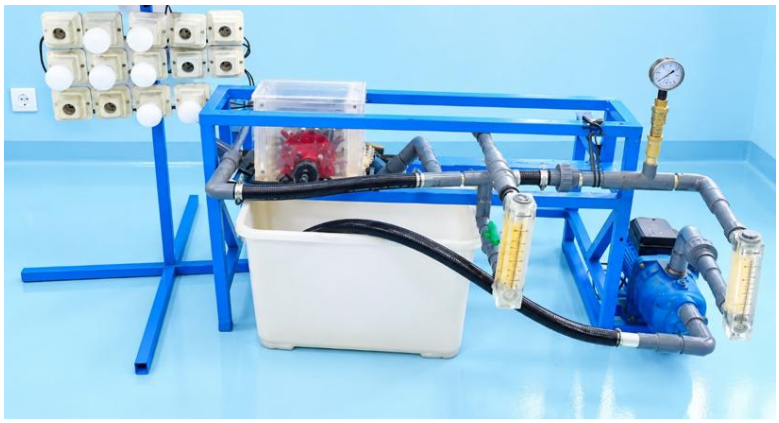


Figure 2. Laboratory-scale Pelton turbine

METHODOLOGY

This study employed an experimental method to analyze the effects of water pressure and the number of nozzles on the output power and efficiency of a laboratory-scale Pelton turbine in a micro-hydropower (MHP) generation system. The experimental apparatus consisted of a water recirculation system, centrifugal pump, piping network, control valve, pressure gauge, Pelton turbine, generator, and electrical loads comprising five incandescent lamps rated at 5 W each. The experimental variables included water pressures of 2, 2.5, and 3 kg/cm², single- and double-nozzle configurations, and electrical loads ranging from 5 to 25 W. Under each test condition, turbine rotational speed, voltage, electric current, and water flow rate were measured to evaluate system performance. Hydraulic input power was calculated based on water flow parameters and hydraulic head, while electrical output power was determined by multiplying voltage by current. Turbine efficiency was subsequently calculated as the percentage ratio of electrical output power to hydraulic input power. The measured and calculated data were analyzed comparatively to evaluate the effects of variations in water pressure, nozzle configuration, and electrical load, and to identify the operating conditions that produced the highest output power and efficiency.

RESEARCH RESULTS AND DISCUSSION

The laboratory experiments conducted on a micro-hydropower system equipped with a single-nozzle Pelton turbine produced the results presented in Table 1. Tests were performed at water pressures of 2, 2.5, and 3 kg/cm² under different load conditions. The results indicate that increasing water pressure generally increased turbine rotational speed, with the highest rotational speeds recorded at 3 kg/cm² across the tested load conditions. In contrast, increasing the electrical load from 5 to 25 W reduced both rotational speed and output voltage, while the current increased with the applied load. These findings demonstrate that water pressure plays an important role in determining turbine rotational performance, whereas the electrical load influences the generator's output characteristics. The interaction between these operating parameters consequently

affects the overall performance of the laboratory-scale micro-hydropower system.

Table 1. Test results data for 1 nozzle with pressure variations

Water Pressure (kg/cm²)	Load (Watts)	Flow rate 1 (l/min)	Flow rate 2 (l/min)	Current (A)	Voltage (V)	Turbin rotation (rpm)
	5	58	32	0.35	13.5	340
	10	58	32	0.42	12.3	325
2	15	58	32	0.5	11.2	310
	20	58	31	0.57	10.1	295
	25	58	31	0.64	9.2	280
	5	50	24	0.4	13.5	385
	10	50	24	0.47	12.6	365
2.5	15	50	23	0.54	11.5	340
	20	49	22	0.62	10.4	315
	25	49	21	0.69	9.5	295
	5	38	14	0.48	14.5	395
	10	38	14	0.58	13.4	365
3	15	40	12	0.7	12.2	340
	20	43	12	0.82	11	315
	25	43	12	0.94	9.8	290

Meanwhile, the test results using 2 nozzles at varying water pressures are shown in Table 2. The results of the two-nozzle test showed that increasing pressure was not always directly proportional to the increase in system performance. At all pressure variations, the turbine rotation speed (rpm) tended to decrease with increasing load, while the current increased and the voltage decreased due to the increase in output power and internal generator losses. A pressure of 2 kg/cm² showed the most optimal performance, in terms of higher initial rotation, operational stability against loading, and a relatively larger total discharge compared to pressures of 2.5 and 3 kg/cm². This indicates that in the two-nozzle system configuration tested, there is an optimum operating pressure that is able to produce the most effective turbine and generator performance, so that increasing the pressure above that value does not provide a significant increase in performance. By obtaining the test result data, the turbine input power can be calculated, namely $Pin=\rho \times g \times H$, where Pin is the input power (Watt), ρ is the fluid density (kg/m3), g is gravity (m/s2), and H is the height (m) obtained from the specified water pressure variations. In addition to the input power, the turbine output power is also obtained, namely $Pout=V \times I$, where V is the voltage (volt), and I is the current (Ampere) produced. By obtaining the input power and output power of the turbine, the turbine efficiency can be calculated, namely η= (Input power)/ (Output power) (%).

Table 2. Test results data for 2 nozzles with pressure variations

Water Pressure (kg/cm2)	Load (Watts)	Flow rate 1 (l/min)	Flow rate 2 (l/min)	Current (A)	Voltage (V)	Turbin rotation (rpm)
2	5	56	32	0.3	12.8	300
	10	56	32	0.36	11.9	285
	15	56	32	0.42	10.8	270
	20	56	31	0.49	9.8	255
	25	57	31	0.56	8.9	240
2.5	5	48	24	0.34	13	310
	10	48	24	0.4	12.1	295
	15	48	23	0.46	11.1	280
	20	47	23	0.52	10.1	265
	25	47	23	0.59	9.2	245
3	5	40	15	0.45	13.5	320
	10	40	15	0.54	12.5	300
	15	43	15	0.64	11.4	280
	20	43	14	0.74	10.3	260
	25	45	14	0.85	9.3	240

Using the equations presented above, the input power, output power, and turbine efficiency were calculated, with the results summarized in Table 3. The experimental data from the laboratory-scale Pelton turbine micro-hydropower system with one nozzle were analyzed at water pressures of 2, 2.5, and 3 kg/cm². The results indicate that increasing water pressure generally increased the available hydraulic energy; however, the corresponding changes in rotational speed, output power, and efficiency were not consistently proportional. At a pressure of 2 kg/cm², the output power ranged from 4.73 to 5.89 W, with an efficiency of 5.7%–7.4%. At 2.5 kg/cm², the output power varied from 5.40 to 6.56 W, while the efficiency ranged from 5.2% to 6.6%. The highest efficiency of 8.2% was achieved at a pressure of 3 kg/cm², with a rotational speed of 290 rpm, an output power of 9.21 W, and an input power of 112.52 W. In principle, higher water pressure can increase the velocity and kinetic energy of the water jet striking the turbine buckets, potentially improving power generation. Nevertheless, the overall efficiency is also affected by the applied load and energy losses within the system, meaning that an increase in water pressure or input power does not necessarily result in a proportional increase in output power or efficiency.

For the two-nozzle configuration, experiments were conducted at water pressures of 2, 2.5, and 3 kg/cm² to evaluate the effects of pressure on turbine performance. The results showed that increasing water pressure generally improved power generation, although rotational speed tended to decrease as the applied lamp load increased. At a pressure of 2 kg/cm², the output power ranged from 8.9 to 12.8 W, with an efficiency of 4.9%–6.6%. At 2.5 kg/cm², the output power ranged from 9.2 to 13 W, while the efficiency varied between 4.5% and 5.8%. The best performance was recorded at a pressure of 3 kg/cm², with an output power of 9.3 W and a maximum efficiency of 7.0%. In general, employing two nozzles can increase the water flow directed toward the turbine buckets,

potentially enhancing power generation. However, the lower efficiency compared with the single-nozzle configuration suggests that the additional flow did not translate proportionally into useful output power. This behavior may be associated with hydraulic losses, jet interaction, or nonuniform water distribution across the turbine buckets.

Table 3. Calculation results for 1 and 2 nozzles with pressure variations in the laboratory-scale Pelton turbine micro-hydro power plant

Number of nozzles (pcs)	Water pressure (kg/cm2)	Load (Watts)	Turbin rotation (rpm)	Input power (watts)	Output power (watts)	Efficiency (%)
1	2	5	340	83.35	4.73	5.7%
		10	325	83.35	5.17	6.2%
		15	310	81.68	5.60	6.9%
		20	295	81.68	5.76	7.0%
		25	280	80.02	5.89	7.4%
1	2.5	5	385	104.19	5.40	5.2%
		10	365	104.19	5.92	5.7%
		15	340	102.10	6.21	6.1%
		20	315	100.02	6.45	6.4%
		25	295	100.02	6.56	6.6%
1	3	5	395	117.52	6.96	5.9%
		10	365	117.52	7.77	6.6%
		15	340	115.02	8.54	7.4%
		20	315	115.02	9.02	7.8%
		25	290	112.52	9.21	8.2%
2	2	5	300	78.35	3.84	4.9%
		10	285	78.35	4.28	5.5%
		15	270	76.68	4.54	5.9%
		20	255	76.68	4.80	6.3%
		25	240	75.02	4.98	6.6%
2	2.5	5	310	97.94	4.42	4.5%
		10	295	95.85	4.84	5.0%
		15	280	95.85	5.11	5.3%
		20	265	93.77	5.25	5.6%
		25	245	93.77	5.43	5.8%
2	3	5	320	120.02	6.08	5.1%
		10	300	117.52	6.75	5.7%
		15	280	117.52	7.30	6.2%
		20	260	115.02	7.62	6.6%
		25	240	112.52	7.91	7.0%

From the calculation results above, we can see a comparison graph between the power generated and the lamp load installed at various pressures for 1 and 2 nozzles, shown in Figure 3. The graph in the figure 3 shows the relationship between the output power generated with variations in electrical load from 5 to 25 watts at three different water pressure conditions, namely (a) 2 kg/cm², (b) 2.5 kg/cm², and (c) 3 kg/cm², with a comparison of the use of 1 nozzle and 2 nozzles. In general, in all three graphs, it can be seen that an increase in the load is followed by an increase in the output power generated. In addition, the

use of 1 nozzle produces higher power than 2 nozzles at all load and pressure variations. At a pressure of 2 kg/cm² (a), the power increases gradually as the load increases, with the highest value at a load of 25 watts. At a pressure of 2.5 kg/cm² (b), the trend of increasing power also appears more stable than at the previous pressure. Meanwhile, at a pressure of 3 kg/cm² (c), the power generated is the largest among the three conditions, indicating that the higher the water pressure, the higher the output power generate.

Meanwhile, a comparison graph between the efficiency against the load of lamps installed at various pressures for 1 and 2 nozzles is shown in Figure 3. The graph in Figure 4 shows the relationship between system efficiency and load variations from 5 to 25 W at three pressure conditions, namely 2 kg/cm², 2.5 kg/cm², and 3 kg/cm², with a comparison of the use of 1 nozzle and 2 nozzles. At a pressure of 2 kg/cm² (Figure a), efficiency tends to increase with increasing load, where the 1 nozzle configuration produces a higher efficiency with a maximum value of about 7.9% at a load of 25 W, while 2 nozzles reach about 7.5%. At a pressure of 2.5 kg/cm² (Figure b), the trend of increasing efficiency also appears stable, with the highest efficiency of about 7.0% at 1 nozzle and about 6.6% at 2 nozzles at a load of 25 W. Meanwhile, at a pressure of 3 kg/cm² (Figure c), efficiency increases more significantly, especially when using 1 nozzle, which reaches about 9.8% at a load of 25 W, while 2 nozzles only reach about 7.1%. In general, increasing load and pressure causes system efficiency to increase, because under higher load conditions, energy conversion takes place more optimally and losses are relatively smaller in relation to the power produced.

The comparison graph between the performance or power generated against the pressure at various lamp loads installed for 1 and 2 nozzles is shown in Figure 4. Figure 4 shows the relationship between turbine output power and water pressure variations in laboratory-scale Pelton turbine micro hydropower testing using 1 nozzle and 2 nozzles and load variations of 5–25 watts. The test results show that the higher the water pressure applied (2, 2.5, up to 3 kg/cm²), the turbine output power also increases at each load variation. At a pressure of 2 kg/cm², the power generated is still relatively low, then increases at 2.5 kg/cm², and reaches its highest value at a pressure of 3 kg/cm². Furthermore, the graph also shows that increasing the load from 5 to 25 watts tends to be followed by an increase in turbine output power at each pressure level. This test shows that the 1-nozzle configuration produces greater power than the 2-nozzles configuration at the same pressure, with maximum power occurring at 3 kg/cm². This indicates that water pressure significantly affects the performance of the Pelton turbine in generating electrical power in a laboratory-scale microhydro power plant system.

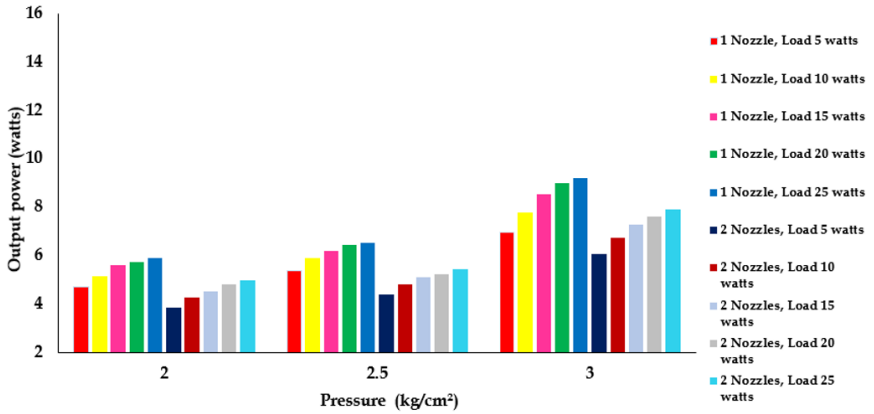


Figure 3. Graph of power generated vs pressure variation

Figure 4 shows the relationship between turbine efficiency and variations in water pressure in laboratory-scale Pelton turbine microhydro power plants (MHP) tests using one nozzle and two nozzles, with loads ranging from 5 to 25 watts. In general, increasing the pressure from 2 kg/cm² to 2.5 kg/cm² and 3 kg/cm² tends to increase turbine efficiency across almost all load variations. At 2 kg/cm², the resulting efficiency remains relatively low, then increases at 2.5 kg/cm², and reaches its highest value at 3 kg/cm². This indicates that higher water pressure increases the kinetic energy of the water jet hitting the turbine blades, thus making the energy conversion process more effective. Furthermore, the graph also shows that increasing the load from 5 to 25 watts is generally accompanied by an increase in turbine efficiency at each pressure level. This test shows that the single-nozzle configuration produces higher efficiency than the two-nozzle configuration at the same pressure. The highest efficiency value occurred at a pressure of 3 kg/cm² with a load of 25 watts, especially when using one nozzle, while using two nozzles resulted in slightly lower efficiency. This indicates that under laboratory-scale test conditions, the distribution of water flow through one nozzle is more effective in rotating the turbine blades than using two nozzles.

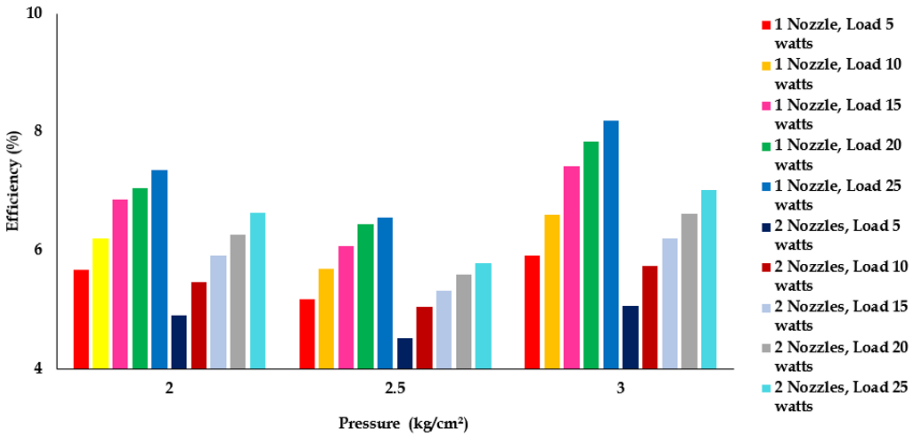


Figure 4. Graph turbine efficiency vs pressure variations

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of testing and performance analysis of a laboratory-scale Pelton turbine microhydro power plant (MHP) with pressure variations of 2, 2.5, and 3 kg/cm², and the use of one nozzle and two nozzles, it can be concluded:

1. The results indicate that turbine rotational speed generally increased with turbine efficiency, although the relationship was not consistently linear. For one nozzle, the highest efficiency of 8.2% was achieved at 290 rpm under a water pressure of 3 kg/cm², demonstrating the influence of operating conditions on turbine performance.
2. Turbine efficiency was influenced by the interaction between rotational speed, water pressure, and the number of nozzles. Although higher rotational speeds were generally associated with higher efficiency in several operating conditions, this trend was not consistent across all tests. Therefore, turbine efficiency depended on the combination of operating parameters rather than rotational speed alone.
3. The relationship between input power, output power, and turbine efficiency indicates that higher output power generally resulted in higher efficiency when compared under similar operating conditions. The highest efficiency of 8.2% was achieved at an output power of 9.21 W and an input power of 112.52 W, using one nozzle at a water pressure of 3 kg/cm² and a load of 25 W.
4. Turbine efficiency depended on the ratio of output power to input power, as efficiency was calculated by dividing output power by input power and multiplying by 100%. The results show that a higher input power did not always produce higher efficiency, because the increase in output power was not always proportional to the increase in input power. Therefore, turbine performance was determined by how effectively the supplied hydraulic power was converted into mechanical output power.

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