**JURNAL TEKNIK MESIN DAN MEKATRONIKA**
*Journal of Mechanical Engineering and Mechatronics*
*ISSN: 2527-6212, Vol. 11 No. 1, pp. 15- 23*


# Effect of Blade Roughness on Laboratory Scale Pelton Turbine Efficiency

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**Abstract.**
Pelton turbines are widely used in high-head and low-flow hydropower systems because the kinetic energy of a water jet can be converted directly into runner torque. However, deterioration of the bucket surface can disturb the water sheet, increase local friction, and reduce momentum transfer. This study experimentally investigated the effect of controlled bucket surface roughness on the shaft power and efficiency of a laboratory scale Pelton turbine. Four roughness levels were prepared by polishing, graded sanding, light sand blasting, and heavy sand blasting, producing average Ra values of 0.8, 1.6, 3.2, and 6.3 micrometers, respectively. The tests were conducted on a single nozzle closed loop Pelton turbine rig at an effective head of 10.0 m and discharge of 5.45 L/s. Discharge, head, rotational speed, torque, and roughness were measured using calibrated instruments, and the uncertainty of efficiency was estimated using propagation of measurement errors. The results show that increasing roughness consistently reduced performance. The maximum shaft power decreased from 419.7 W at Ra = 0.8 micrometers to 314.9 W at Ra = 6.3 micrometers, while efficiency decreased from 78.5% to 58.9%. The combined relative uncertainty of efficiency was estimated at approximately 2.2%. The findings confirm that bucket surface finishing and roughness control are important for maintaining Pelton turbine performance in laboratory-scale and small hydropower applications.

**Keywords:** Pelton turbine; surface roughness; bucket; efficiency; experimentation; shaft power.

## Introduction

Hydropower remains an important renewable energy technology because it can convert water energy into mechanical and electrical power with relatively stable operation. Among various hydraulic turbines, the Pelton turbine is widely used for high head and low flow conditions, where the water jet transfers kinetic energy directly to the runner buckets. This characteristic makes Pelton turbines suitable not only for large hydropower schemes but also for micro hydro and laboratory scale energy conversion studies [1]. The efficiency of energy conversion is strongly influenced by the quality of interaction between the water jet and the bucket surface. The jet must strike the bucket at an appropriate position and then split smoothly along the bucket profile to generate torque. Any disturbance in this interaction can reduce the useful momentum transfer and increase hydraulic losses [2]. Laboratory scale Pelton turbines are commonly used to study turbine performance because they allow controlled variation of operating and design parameters. Parameters such as head, discharge, nozzle diameter, jet velocity, bucket geometry, number of buckets, and electrical load can be adjusted and measured more easily in laboratory conditions. Therefore, laboratory scale testing is useful for understanding the basic performance behavior of Pelton turbines before application in real micro hydro systems [3,4].

Previous studies have shown that Pelton turbine performance is affected by operating conditions such as pressure head, flow rate, and nozzle jet diameter. Changes in nozzle diameter and discharge can alter jet velocity, input power, torque, and overall turbine efficiency. This indicates that even small hydraulic changes in the inlet system may significantly influence the output performance of a Pelton turbine [5]. Besides operating parameters, the physical condition of the bucket surface is also an important factor in

Pelton turbine performance. In ideal conditions, the bucket surface should guide the water sheet smoothly with minimum friction and separation. However, in real operation or repeated laboratory use, the bucket surface may become rough due to wear, sediment impact, manufacturing imperfections, corrosion, or intentional surface treatment [6]. Blade roughness refers to irregularities on the surface of the turbine bucket that can disturb the flow of water over the blade. In Pelton turbines, this roughness can affect the development of the water sheet after the jet strikes the splitter and moves along the bucket. A rougher surface may increase frictional resistance, disturb the water path, and reduce the amount of kinetic energy converted into useful shaft power [7].

The effect of blade roughness is important because Pelton turbine flow involves free surface, multiphase, and highly unsteady behavior. The water jet interacts with air and bucket surfaces within a short contact time, making the flow sensitive to geometric and surface conditions. As a result, surface irregularities on the bucket may create additional losses that are not fully captured when only nozzle, head, or discharge parameters are considered [8]. Sediment erosion studies on Pelton turbines provide strong evidence that surface degradation can influence bucket condition and turbine performance. Sediment particles carried by water may hit the bucket surface repeatedly, producing erosion marks, surface roughness, and material loss. These changes can modify the bucket profile and disturb the intended water flow path [9]. In laboratory scale turbines, roughness may appear in different forms compared with field turbines. Laboratory runners are often made from metal, plastic, resin, or fabricated components, and the surface quality may vary depending on manufacturing method and finishing process. Therefore, laboratory-scale turbines provide a practical platform to isolate and test roughness levels under controlled hydraulic conditions [10].

Study of blade roughness is also relevant because many laboratory-scale experiments focus mainly on nozzle diameter, number of nozzles, head, discharge, and bucket number. Although these variables are important, the condition of the bucket surface is often treated as constant or ideal. This creates a research gap, especially for understanding how different roughness levels affect the efficiency of a small Pelton turbine [11]. Computational and experimental studies have improved the understanding of Pelton turbine flow behavior. Numerical investigations using CFD have been used to analyze jet flow, torque, bucket geometry, erosion, and performance prediction. However, experimental validation at laboratory scale is still needed because actual surface conditions, friction, leakage, vibration, and mechanical losses may differ from ideal numerical assumptions [12].

Nozzle jet quality plays a key role in determining how much energy is transferred to the Pelton bucket. A well formed jet can strike the bucket splitter accurately and produce stable torque. If the jet deviates from the bucket pitch circle or becomes disturbed before impact, the turbine may experience unstable operation and reduced efficiency [13]. Blade roughness can interact with jet quality after impact. Even if the nozzle produces a good jet, a rough bucket surface can disturb the water sheet as it spreads along the bucket. This disturbance may cause higher friction, uneven flow distribution, and reduced exit velocity control, which ultimately lowers the mechanical power produced by the runner [14]. The hydraulic efficiency of a Pelton turbine depends on the ability of the bucket to change the direction of the incoming jet while minimizing energy losses. Smooth bucket surfaces are expected to support more uniform water movement, while rough surfaces can increase local turbulence and resistance. Therefore, blade roughness should be considered as a measurable variable in turbine efficiency studies [15,16]

In addition to hydraulic losses, roughness may also influence mechanical behavior indirectly. If roughness causes uneven water flow on the bucket surface, the resulting torque may become less stable. In small laboratory scale turbines, where output power is relatively low, these losses may become more visible in efficiency calculations the number and geometry of buckets have been reported to influence Pelton turbine efficiency because they affect water sheet flow, torque distribution, and leakage behavior. This shows that the bucket region is a critical location for energy transfer. Since roughness is located on the same energy transfer surface, it is reasonable to examine whether blade roughness can also change the efficiency trend of a laboratory scale Pelton turbine Recent optimization studies have emphasized the importance of Pelton bucket geometry in improving hydraulic efficiency. Parameters such as exit angle, tilt angle, bucket length, bucket width, bucket depth, and pitch diameter can influence turbine performance. However, a geometrically optimized bucket may still experience performance decline if its surface becomes rough during operation [17].

The relationship between roughness and efficiency is also important for maintenance and design decisions. If roughness significantly reduces efficiency, then surface finishing, polishing, coating, or material selection may become necessary even for small scale turbines. On the other hand, if roughness has only a minor effect under certain operating conditions, maintenance priority may be placed on nozzle alignment, head stability, or discharge control In micro hydro applications, low-cost fabrication is often preferred to reduce investment costs. However, low cost manufacturing may produce bucket surfaces with higher roughness than precision-manufactured components. Studying the effect of blade roughness at laboratory scale can provide useful information for balancing manufacturing cost and turbine efficiency [18,19]

The use of laboratory scale testing also allows roughness levels to be prepared systematically. For example, the bucket surface can be tested under smooth, medium rough, and high roughness conditions. The turbine efficiency can then be compared based on measured flow rate, head, rotational speed, torque, and output power [20,21]. Efficiency analysis in a Pelton turbine generally requires the comparison between hydraulic input power and mechanical or electrical output power. Hydraulic input power is influenced by water density, gravitational acceleration, flow rate, and head, while output power depends on torque, rotational speed, or generator output. When blade roughness changes the interaction between jet and bucket, the output power may decrease even if the input power remains constant [22,23]

Based on previous research, Pelton turbine performance is a result of combined effects from nozzle condition, jet direction, bucket geometry, flow behavior, erosion, and operating conditions. However, direct experimental studies on blade roughness in laboratory scale Pelton turbines are still limited. This limitation supports the need for a focused investigation on how controlled blade roughness affects turbine efficiency. Therefore, the present study entitled “Effect of Blade Roughness on Laboratory Scale Pelton Turbine Efficiency” is designed to examine the influence of bucket surface roughness on turbine performance. The study focuses on comparing efficiency under different blade roughness conditions using a laboratory scale Pelton turbine test rig. The results are expected to clarify whether rougher blade surfaces reduce turbine efficiency and how strong the effect is under controlled testing conditions.

The findings of this study are expected to contribute to the development of small scale Pelton turbines, especially in relation to surface finishing, maintenance, and performance testing. This research may also provide practical insight for educational laboratories, micro-hydro prototypes, and low cost turbine fabrication. By focusing on blade roughness, the study complements existing research on nozzle design, bucket geometry, sediment erosion, and Pelton turbine efficiency.

## Research Method

The experiment was conducted using a laboratory-scale Pelton turbine operated in a closed-loop water circulation system. The test rig consisted of a water reservoir, centrifugal pump, discharge control valve, flowmeter, pressure gauge, single nozzle, turbine casing, Pelton runner, tachometer, and Prony brake dynamometer. Water from the reservoir was pumped through the pipeline, controlled by the valve, measured by the flowmeter, and discharged through the nozzle as a free jet toward the Pelton buckets. After striking the runner, the water returned to the reservoir.

The pressure gauge was installed upstream of the nozzle to determine the effective head available for jet formation. The flowmeter was placed in the inlet pipe to measure discharge. Shaft speed was measured using a digital optical tachometer, while torque was obtained from the braking force and moment arm of the Prony brake. The nozzle position, runner alignment, and bucket geometry were kept constant for all roughness conditions so that any change in performance could be attributed primarily to surface roughness.

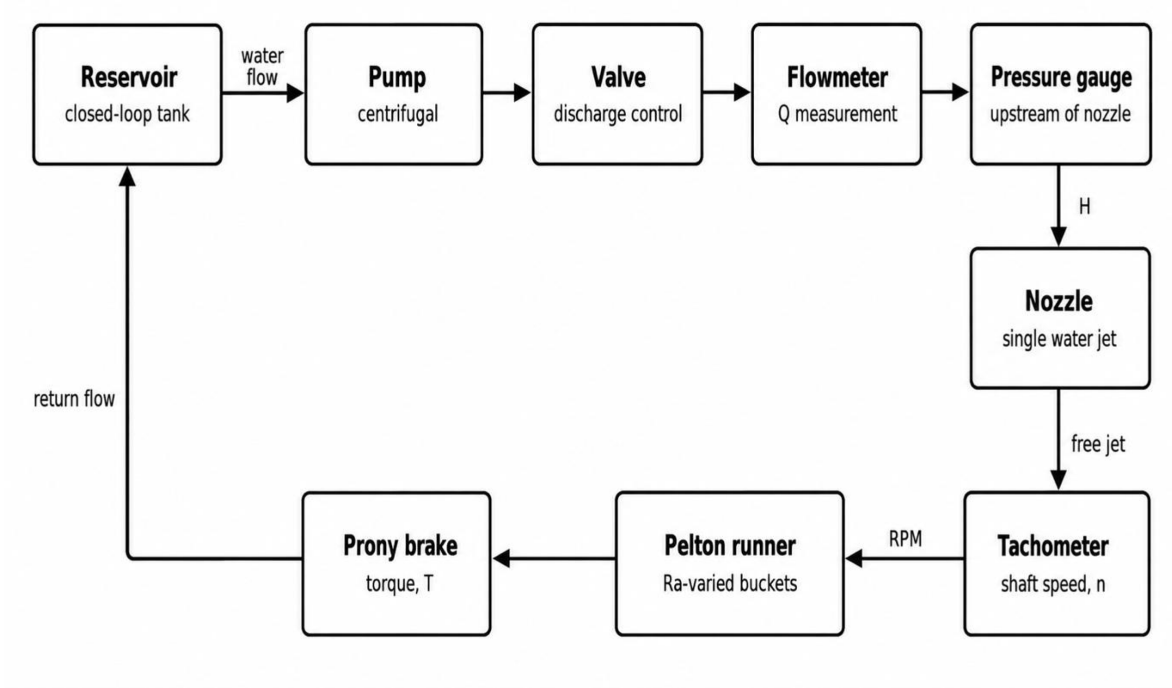


**Fig. 1** Schematic of the laboratory scale Pelton turbine experimental setup.

**Surface roughness preparation and measurement**

Surface roughness was varied by applying different treatments to the main flow trajectory area of the bucket, namely the surface directly contacted by the water jet. The bucket geometry was maintained for all tests; only the surface texture was changed. Roughness was produced using polishing, graded sanding, light sand blasting, and heavy sand blasting. The arithmetic mean roughness, Ra, was measured using a surface roughness tester before performance testing. For each condition, measurements were taken at five points on the bucket flow path and averaged to represent the surface condition.

**Table 1.** Surface treatment and measured roughness levels.

| Surface condition | Surface treatment | Average Ra (micrometers) | Classification |
|---|---|---|---|
| Smooth | Polishing | 0.8 +/- 0.1 | Fine |
| Medium roughness | Graded sanding | 1.6 +/- 0.1 | Medium |
| Rough | Light sand blasting | 3.2 +/- 0.2 | Coarse |
| Very rough | Heavy sand blasting | 6.3 +/- 0.3 | Very coarse |

**Operating conditions**

All tests were conducted under the same hydraulic and mechanical settings for each roughness variation. The effective head and discharge were maintained at the selected operating point, and the same loading sequence was applied to each bucket condition. The reported shaft power and efficiency values represent the maximum average operating point obtained from three repeated measurements for each roughness level.

**Table 2.** Operating conditions of the Pelton turbine experiment.

| Parameter | Value used in the experiment | Unit/description |
|---|---|---|
| Turbine type | Single-nozzle laboratory-scale Pelton turbine | - |
| Nozzle diameter | 22 | mm |
| Effective head, H | 10.0 | m |
| Discharge, Q | 5.45 L/s (0.00545 m3/s) | L/s or m3/s |

| | | |
|---|---|---|
| Hydraulic input power, Ph | 534.6 | W |
| Runner diameter | 300 | mm |
| Number of buckets | 16 | - |
| Moment arm length | 0.15 | m |
| Jet orientation | Tangential to the runner pitch circle | - |
| Stabilization time before reading | 60 | s |
| Water temperature | 27 +/- 1 | degrees C |
| Number of repetitions | 3 | times for each measurement point |

**Instrumentation, calibration, and reliability control**

Before data collection, all instruments were checked and calibrated to reduce systematic error. The flowmeter was verified using the volumetric method by collecting a known volume of water over a measured time interval. The pressure gauge was checked at zero pressure and compared with a reference manometer. The tachometer was verified using repeated constant-speed readings, while the Prony brake force measurement was checked using known calibration weights. The surface roughness tester was calibrated using a standard roughness specimen. Each data point was measured three times, and the average value was used for analysis.

**Table 3.** Instrument calibration and verification procedure.

| Measured quantity | Instrument | Accuracy/resolution | Calibration or verification procedure |
|---|---|---|---|
| Discharge, Q | Flowmeter and volumetric check | +/- 0.10 L/s or +/- 1.5% of reading | Verified by collecting a known water volume over a measured time interval. |
| Effective head, H | Pressure gauge/manometer | +/- 0.01 bar (about +/- 0.10 m head) | Zero checked and compared with a reference manometer or calibrated gauge. |
| Shaft speed, n | Digital optical tachometer | +/- 1 rpm | Verified using repeated constant-speed readings. |
| Torque, T | Prony brake and load balance | +/- 0.01 N.m | Checked using known calibration weights and moment arm length. |
| Surface roughness, Ra | Surface roughness tester/profilometer | 0.01 micrometers | Calibrated using a standard roughness specimen. |
| Water temperature | Thermometer | +/- 0.5 degrees C | Checked against a reference thermometer. |

**Experimental procedure**

The experimental procedure was performed in the same sequence for every roughness condition. First, the bucket surface was prepared and its Ra value was measured. Second, the runner was installed while maintaining the same nozzle position and alignment. Third, the pump was operated and the control valve was adjusted until the target discharge and effective head were reached. Fourth, the system was allowed to stabilize for 60 s before data recording. Fifth, the external load was varied using the Prony brake to obtain several operating points. For each point, discharge, effective head, shaft speed, braking force, moment arm, and water temperature were recorded. The measurement was repeated three times, and the test was repeated when a large deviation occurred between repeated readings.

### Data reduction and uncertainty analysis

Hydraulic input power, shaft power, and turbine efficiency were calculated from the measured variables. Shaft power was calculated from torque and shaft speed as follows:

$$Pt = (2*pi*n*T) / 60 \quad (1)$$

where Pt is shaft power (W), n is shaft speed (rpm), and T is torque (N.m). Hydraulic input power was calculated as:

$$Ph = rho*g*Q*H \quad (2)$$

where Ph is hydraulic power (W), rho is water density (kg/m3), g is gravitational acceleration (m/s2), Q is discharge (m3/s), and H is effective head (m). Turbine efficiency was calculated as:

$$eta = (Pt / Ph) \times 100\% \quad (3)$$

Based on the instrument accuracies in Table 3, the combined relative uncertainty of turbine efficiency was estimated at approximately +/- 2.2%. The uncertainty bars in the performance figures represent this measurement uncertainty, while repeatability was controlled by triplicate measurements.

## Results and Discussion

### Prepared roughness levels

The surface treatments produced clearly separated roughness levels. The polished bucket had the lowest Ra value, followed by the graded-sanded bucket, while light and heavy sand blasting produced higher roughness values. This confirms that the treatment method was effective in creating controlled roughness variations on the main jet contact area of the bucket.

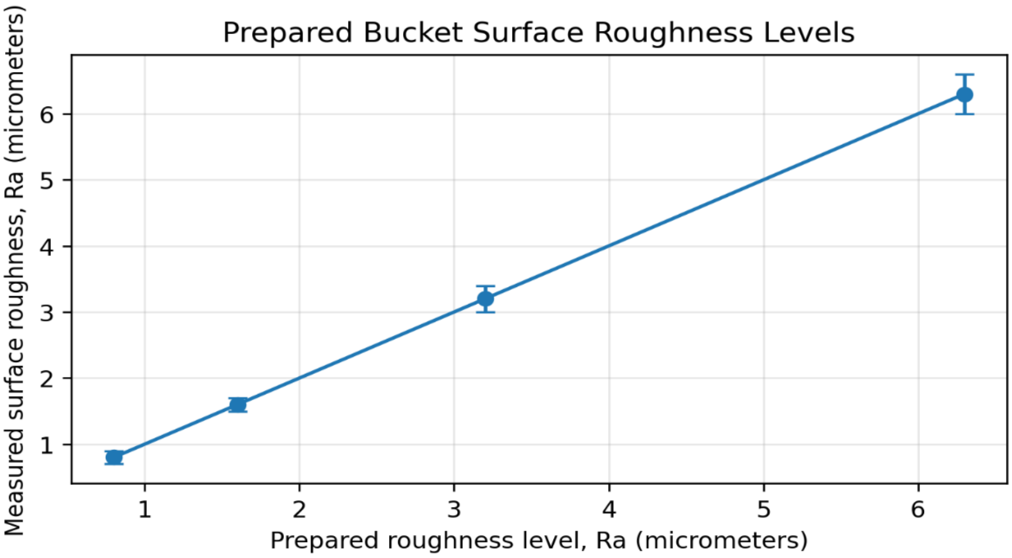


**Fig. 2** Prepared bucket surface roughness levels for each treatment.

### Effect of roughness on shaft power

The effect of bucket surface roughness on turbine performance was evaluated by comparing the maximum shaft power obtained under the same head, discharge, nozzle position, bucket geometry, and load sequence. Figure 3 shows that shaft power decreased consistently as the Ra value increased. The smooth bucket produced 419.7 W, while the very rough bucket produced 314.9 W. This represents a power reduction of approximately 25.0% relative to the smooth condition.

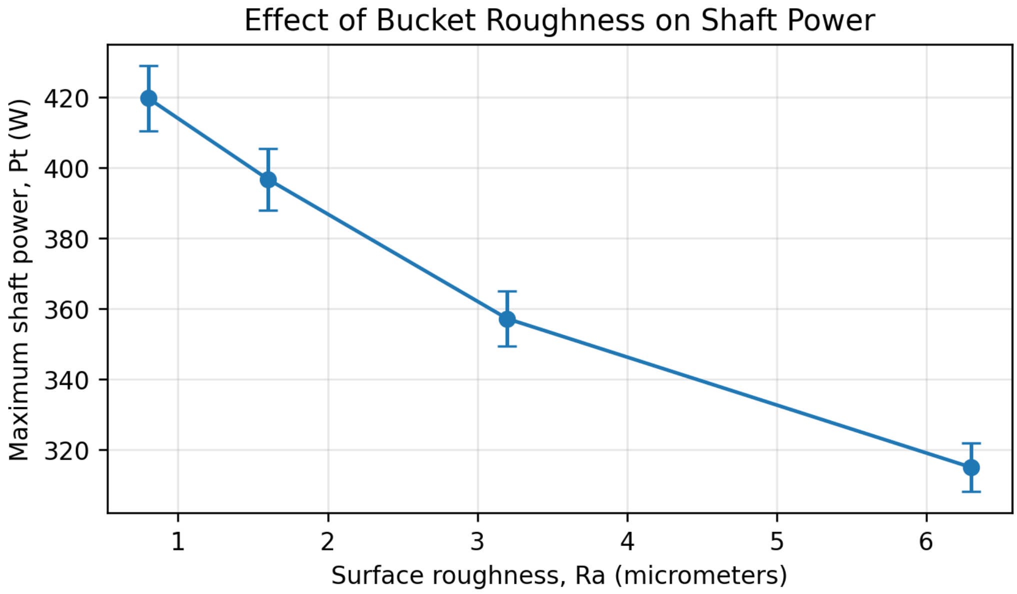


**Fig. 3** Relationship between bucket surface roughness and maximum shaft power.

The decrease in shaft power can be explained by the reduction in effective jet momentum transfer. A rougher bucket surface increases near-wall disturbance and causes part of the jet kinetic energy to be dissipated as friction and local turbulence. Roughness may also increase water sheet dispersion after the jet strikes the splitter, causing less uniform flow deflection along the bucket profile. As a result, a smaller portion of the hydraulic input power is converted into useful mechanical power at the shaft.

**Effect of roughness on turbine efficiency**

Turbine efficiency was calculated as the ratio between shaft power and hydraulic input power. Because the hydraulic input power was maintained at approximately 534.6 W for all roughness levels, the decrease in efficiency directly reflects the reduction in shaft power. Figure 4 shows that the highest efficiency was obtained at Ra = 0.8 micrometers, while the lowest efficiency occurred at Ra = 6.3 micrometers.

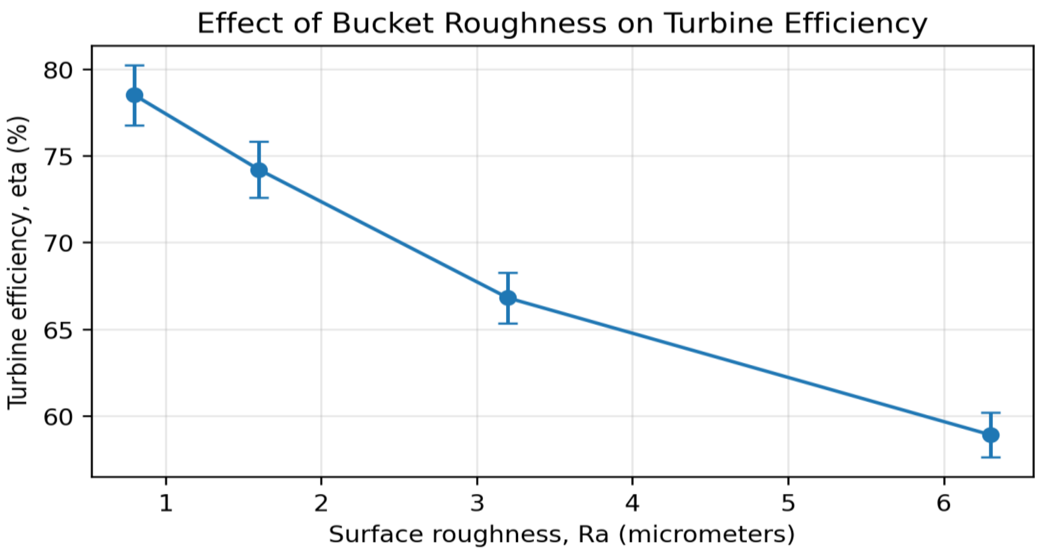


**Fig. 4** Relationship between bucket surface roughness and turbine efficiency.

The efficiency decreased from 78.5% for the smooth bucket to 74.2%, 66.8%, and 58.9% for Ra values of 1.6, 3.2, and 6.3 micrometers, respectively. The decrease was relatively small between the smooth and medium-roughness surfaces, but it became more pronounced at roughness values above 3.2 micrometers. This indicates that a low-to-medium roughness range may still be tolerable, whereas coarse surfaces cause larger hydraulic losses and a sharper decline in performance.

**Performance mechanism and practical implication**

The trend observed in this experiment is consistent with the expected flow mechanism in Pelton buckets. A smooth bucket surface supports more stable water sheet development and more effective deflection of the incoming jet. In contrast, rough surfaces increase frictional resistance and create micro-scale disturbances that disrupt the water path. In small turbines, these disturbances become important because the available hydraulic power is limited and mechanical output is sensitive to additional losses.

From a practical perspective, the results show that bucket surface quality should not be neglected in laboratory-scale and micro-hydro Pelton turbines. Low-cost fabrication can be useful for reducing investment cost, but excessive roughness may reduce efficiency. Therefore, polishing, controlled finishing, protective coating, or periodic maintenance should be considered when high performance is required. For educational laboratories, documenting roughness and calibration conditions also improves the reproducibility of Pelton turbine experiments.

## Conclusions

Increasing bucket surface roughness consistently decreased shaft power and turbine efficiency under comparable operating conditions; at a constant effective head of 10.0 m and a discharge of 5.45 L/s, the maximum shaft power declined from 419.7 W at Ra = 0.8 μm to 314.9 W at Ra = 6.3 μm, while turbine efficiency dropped from 78.5% to 58.9% with an estimated combined relative uncertainty of approximately ±2.2%; this performance reduction is primarily attributed to the decreased effectiveness of jet momentum transfer due to increased friction, localized turbulence, and water sheet dispersion on rough bucket surfaces; therefore, proper bucket surface finishing, roughness control, and regular maintenance are essential to preserve the performance of both laboratory scale and small scale Pelton turbines.

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