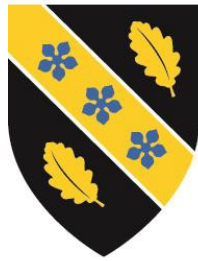


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Fluid Flow Pelton Wheel

ACEA6005 – Structural and Fluid Analysis

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1.0 Executive Summary

This report analysed the behaviour and characteristics of fluid dynamics through the application of a Pelton Wheel. The results of a lab experiment used to collect data for the Pelton Wheel will be critically studied and detailed to find common trends and fluid dynamic laws in practise. The laws of fluid dynamics and fluid flow will be considered throughout the report, providing a thorough analysis of fluid properties and Pelton Wheel mechanisms.

The first section of the report identifies the early findings of the Pelton Wheel, along with the improvement and development that it has had over time. This will act as the first step in understanding how the developments of rotational energy and hydroelectric applications have progressed over time, and how they affect present day energy transition.

The second part of the report focuses on the results obtained from practical examination of the Pelton Wheel from the lab. This data will be critically appraised to identify data trends and correlation in properties such as speed (rev/min), torque (Nm), and energy efficiency. This section aims to provide evidence for several fluid dynamic laws being present in the application.

Finally, the report will critically analyse the design and application of the Pelton Wheel, playing particular attention to the practical and theoretical limitations of the wheel. This is aimed to demonstrate the between physical limitations of the wheel in its design and use.

2.0 Introduction

The use of the Pelton Wheel has relied upon key development and advancements throughout time, in areas of materials selection and design of the system. The Pelton Wheel is an impulse turbine, converting energy from a free jet into kinetic energy with the runner. The change in momentum caused by the angle of the runner is the main characteristic of the Pelton wheel and theoretically proves energy transition in the application of the Pelton wheel.

Through several theoretical models, Pelton Wheel performance can be calculated and simulated. Use of fluid dynamic laws, conservation of energy, and momentum theory can all support understanding of the Pelton Wheel application.

The experiment and testing can then be used to show discrepancies in module theory and highlight the physical losses that occur in practise. Overtime, this has created improvements and developments in the way that Pelton wheel simulations and predictions can be identified.

3.0 Pelton Wheels History and Development

The use of basic principles of Pelton Wheels dates back to centuries ago, where romans would use Water mills as a way of harnessing kinetic energy from water movement. The bucket design was inefficient, lacked power density, and required large structures in order to harness enough of the energy. In order to improve and further develop the design, further development of shape and principle was required.

Lester Allan Pelton developed critical theory in fluid dynamics and behaviour, concluding that the Pelton Wheel he developed have the fluid hit the edge of the bucket as appose to the centre, transferring more energy. Along with this, the change of direction of the fluid against the edge increased force due to change in momentum, further improving the power density and effectiveness of the design. This development inspired and created the impulse turbine.(Zhang, 2016).

The larger angle of the jet to the bucket aimed to produce the highest force against the bucket, whilst ensuring that the projected fluid not interfere with the next bucket. Momentum theory dictates that the following equation is improved by increase the momentum due to small difference between initial velocity and final velocity.

$$f = \dot{m}(V_{in} - V_{out})$$

Current applications for the Pelton Wheel surround its use in hydroelectricity, a form of energy generation from water. Whilst several examples and methods are used for this, the most common is the use of hydroelectric power stations. The Dinorwig Power Station in the north of Wales uses a type of design similar to a Pelton wheel called a Francis Turbine. The basic principle of this type of energy generation uses a falling reservoir of water that hits the wheel at high momentum due to gravity. This creates a large amount of energy and power in a short space of time to cope with high energy demands that are suddenly required. This is especially useful in mountainous environments where suspended water with potential energy can be harnessed for use. (Zhang, 2016).

Further developments have taken place in the testing and use of Pelton wheels. Computational Fluid Dynamics (CFD) is now adopted across the industry, allowing for simulated results to be considered along with fluid dynamic theory. The spatial and transient detail provided from CFD can be used to maximise fluid flow around the bucket. (*Naik, 2025*).

Further optimisation of the design of the Pelton wheel can be seen with added jets, material upgrades and coatings, and high-level material monitoring and testing. The primary aim of the developments in the design and manufacture of the Pelton Wheel is increased efficiency, by increasing the transition of energy to kinetic energy on the bucket.

4.0 Materials

The unique loading conditions applied to the Pelton wheel runner is a demanding feature that the material of the runner must be suitable to work effectively. The high velocity water impacts differ to that of a reaction turbine, where pressure acts continuously over the blades. With each jet strike providing a cyclic impulsive load, the material selection must consider the mechanical properties on high strength, high fatigue resistance, tough and hard, and corrosion resistance. The blade is required to maintain dimensional stability consistently over time, which must be considered in the material selection. (*E.J. Hearn, 1997*).

Stainless steel is most commonly used across nearly all modern Pelton wheels. Key characteristics of the material allow for a balance between strength, manufacturability, and corrosion resistance. In comparison to materials such as aluminium and cast iron, the mechanical properties combine to create a sufficient product able to perform in the desired environment of high speed, high impact, and wet applications. (*Kutz, 2002*).

Titanium alloy would be considered the highest performance material for this application; its mechanical properties outperform stainless steels and further metals.

Despite its high-performance metrics for this application, the cost of both the material and the manufacturing and machining makes it too expensive for widespread adoption in Pelton wheels. On this occasion, the properties that are on offer in stainless steel are good enough to avoid significant extra cost.

More specifically in hydroelectric power stations, Duplex Stainless Steel (SS) provides a higher yield strength, Ultimate Fatigue Strength, and hardness to prevent stress corrosion cracking. The relatively high expense for this material is deemed appropriate for such application and provides longer term savings in replacement and maintenance costs. Continuous usage of the Pelton wheel is common, where creep and fatigue are considered high risk. The impact resistance and lack of crack propagation ensure those issues are less likely.

5.0 Manufacturing

The manufacturing of the wheel and buckets is often dependant on the size of the wheel used, along with the budget assigned. Techniques such as Casting, Forging, and Computer Numerical Control (CNC) machining have all been used in the manufacturing of Pelton Wheels, with most preferring to follow the CNC route.

Whilst casting allows for complex geometrical shapes and it being economical, the limitations far outweigh the advantages. Casting the wheel and buckets would make it susceptible to porosity, shrinkage, along with requiring non-destructive testing. Similar limitations are apparent with forging, difficult bucket shape and the added amount of machining make it impractical for the application. (*Amar et al., 2021*).

Considering the limitations of the two other processes, the use of multi-axis machining is the most effective process to use for three-dimensional machining. The accuracy that the CNC machine will work to also provides a low surface roughness. This is crucial to minimise bucket friction and less of energy. This proves that the machined surface finish effects turbine efficiency and performance, as appose to being merely a cosmetic advantage. (*Kutz, 2002*).

To maximise Pelton wheel efficiency, quality control is rigorous post manufacture and pre installation. Common discrepancies in surface finish, dimension tolerancing, and material integrity must be identified and tested. Hardness testing, ultrasonic inspection, and surface roughness checking. (*Amar et al., 2021*).

Only by following the quality assurance steps does the process create accurate and effective runners for continuous and cyclical loads. Testing these features at post manufacturing stage provides confidence in its overall effectiveness and energy efficiency.

6.0 Experimental Procedure

Dynamics laws dictate several of the characteristics of the Pelton Wheel, with several theoretical equations and research used to prove fluid behaviour.

Bernoulli's principle considers the impact of speed of fluid on fluid pressure and kinetic energy. In this experiment, where the water is pumped from a reservoir, and pressured at the nozzle to create a jet stream to hit the bucket, the equation shows the kinetic energy loss and gain at each side of the nozzle.

$$\frac{p_1}{\rho g} + \frac{v_1^2}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{v_2^2}{2g} + z_2 + h_L$$

Bernoulli's principle does not, however, consider practical limitations and external factors. It is assumed that the fluid is incompressible, steady flow, and streamline flow. Whilst nozzle losses due to friction, turbulence from fluid, along with idealised fluid behaviour are not considered. This makes the principle an ideal theory rather than accurate per the experiment. (*Bansal, 2005*).

The purpose of the experiment is to understand the relationship between water pressure, flow rate, and the force that can be generated by this. Fixed variables include the weight and size of the wheel and buckets, the fluid used (in this case, water), and the measuring and recording methods.

The force placed on the wheel as a force meter is used to create the most amount of energy via torque / power. This is achieved by adjusting the tension on the wheel in incremental amounts at each N.

The jet pressure is set at 0.4 bar and set to a consistent flow directed at the bucket. Once the force meter 1 is set, the jet is turned on, and the speed is read on a tachometer to record the revolutions per minute. Once a reading is taken, the next force meter is added. This is repeated from 1.0 N to 20.0 N.

7.0 Experimental Results

Figure 1 - Experimental Data Results.

Force meter 1	Force Meter 2	Speed	Braking Force	Torque on Shaft	Power on Shaft	Hydraulic Power	Efficiency
(N)	(N)	(rev/min)	(N)	(Nm)	(W)	(W)	(%)
1.0	0.50	1185.00	0.50	0.013	1.55	23.87	6.50%
2.0	0.75	1140	1.25	0.031	3.73	23.87	15.63%
3.0	1.00	1100	2	0.050	5.76	23.87	24.13%
4.0	1.25	1020	2.75	0.069	7.34	23.87	30.77%
5.0	1.50	975	3.5	0.088	8.93	23.87	37.43%
6.0	2.00	935	4	0.100	9.79	23.87	41.02%
7.0	2.25	885	4.75	0.119	11.01	23.87	46.11%
8.0	2.75	830	5.25	0.131	11.41	23.87	47.80%
9.0	3.00	775	6	0.150	12.17	23.87	51.01%
10.0	3.50	725	6.5	0.163	12.34	23.87	51.69%
11.0	4.00	685	7	0.175	12.55	23.87	52.60%
12.0	4.50	640	7.5	0.188	12.57	23.87	52.65%
13.0	5.00	600	8	0.200	12.57	23.87	52.65%
14.0	5.25	530	8.75	0.219	12.14	23.87	50.87%
15.0	5.50	465	9.5	0.238	11.56	23.87	48.46%
16.0	6.00	400	10	0.250	10.47	23.87	43.88%
17.0	6.25	310	10.75	0.269	8.72	23.87	36.56%
18.0	6.50	235	11.5	0.288	7.08	23.87	29.64%
19.0	7.00	150	12	0.300	4.71	23.87	19.74%
20.0	7.75	0	12.25	0.306	0.00	23.87	0.00%

The data results above were taken from the experiment. The Force Meter 1 was the control Variable used, with the speed being recorded for each of the Force meter and used to then calculate the other data in the table.

The trends and correlation between several properties are clearly identified in the data. The relationship between the Force Meter and the Speed are inverse, with the speed constantly decreasing as the force meter increases.

The breaking force and torque on shaft increased throughout the experiment when the force meter was increased, which was expected when considering added force being added on the shaft and spindle.

The power on shaft varies in its format to the other readings, where the highest value is shown at 12.0N and 13.0N. This represents the relationship between power and speed, as shown in the graph below.

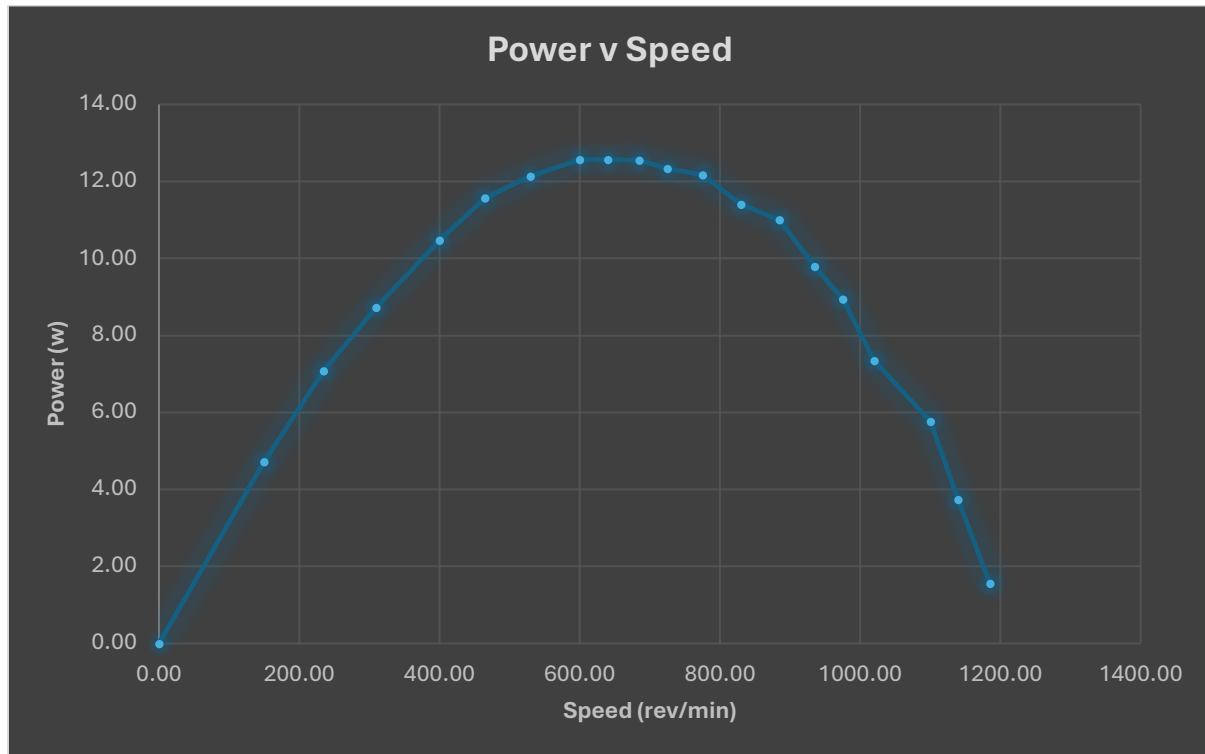


Figure 2 - Power v Speed Comparison from Experiment Results.

The power reaches its most effective output at 12.0N and 13.0N, where the speed is 640 rpm and 600 rpm respectively. This demonstrates the optimum trade-off between force being placed in the wheel, allowing for enough speed to generate the most power.

$$P_{out} = M \times 2 \times \pi \times \frac{n}{60}$$

$$P_{out} = 0.188 \times 2 \times \pi \times \frac{640}{60}$$

$$P_{out} = 12.57 \text{ W}$$

The torque calculated in the results was derived from the following formula:

$$M = F \times \frac{d}{2}$$

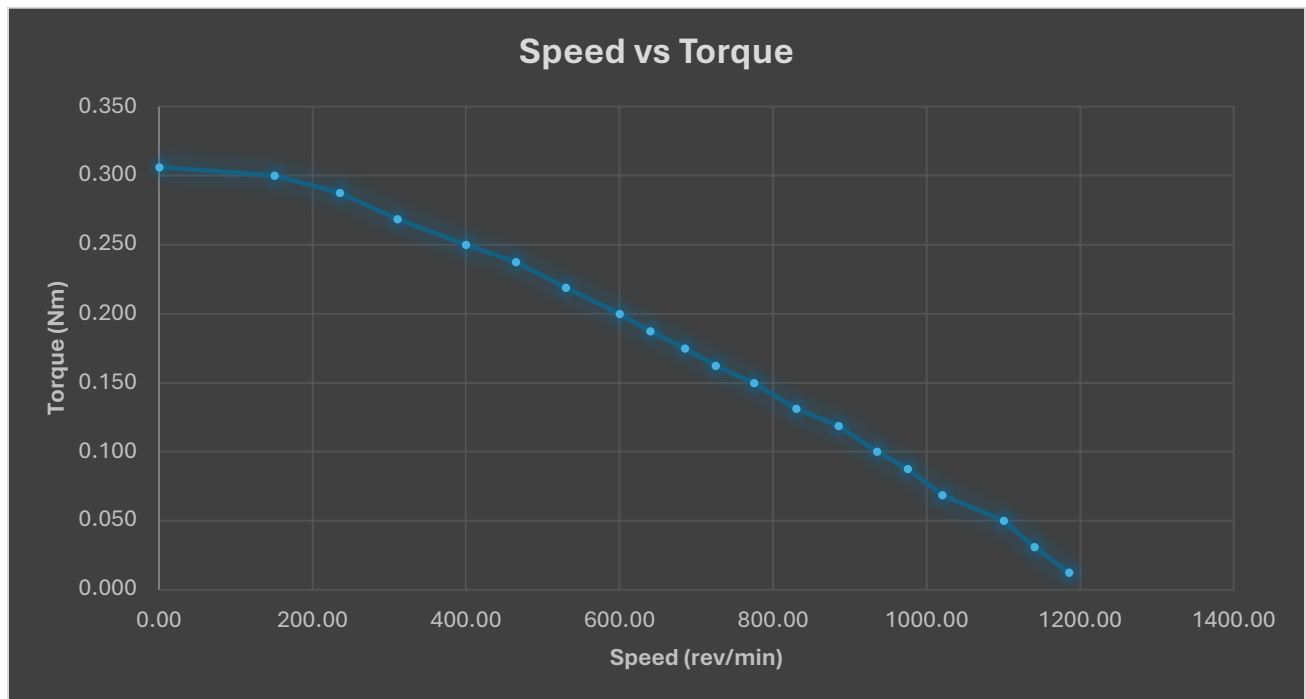


Figure 3 - Speed v Torque Comparison from Experiment Results.

8.0 Theories of Results

Jet impact of the stream is referred to as the following:

$$V_j$$

The jet impact creates further streams from the initial impact on the bucket. The curved shape of the bucket creates the change of direction away from the bucket. Newton's second law comes into practise in this instant, where changing the fluid momentum creates an opposite and equal reaction force to propel the bucket away from the jet.

Boundary Layer

$$\tau = \mu \frac{du}{dy}$$

$$V_{wall} = 0$$

Boundary layer is created by a thin low-pressure zone along the surface of bucket. This acts as a contributor to energy losses in heat and friction, as the viscous effects of the fluid create a negative pressure. The splitter and inner bucket contours create this, as the bucket's curved inner makes the bucket susceptible to this. This occurs when the velocity of the fluid is 0, where viscous shear creates energy dissipation. (*Rahman, 1997*).

Friction loss can be limited in its application. Smoother surface finish and optimised shape design of the bucket can act as catalysts to improving overall boundary layer energy losses.

Reynolds Number

$$Re = \frac{\rho VL}{\mu}$$

The Reynolds number in the application of the Pelton wheel is extremely high, at between 10^5 and 10^6 . This is due to the inertial forces that far outweigh the forces of that of viscous forces in the high-speed jet on the runner surface. The effect of friction is minimal and the flow is highly turbulent.

Flow Separation

$$\frac{dp}{ds} > 0$$

Flow separation occurs at the bucket splitter, where the main jet stream is split into two even streams. The effect of flow separation is an increase in momentum change, as this supports more surface contact and change of direction from the mainstream. This is also key for avoiding high amount of water interrupting the next bucket. By having the two streams, water can be dissipated from the buckets more effectively, thus making the system for efficient. (*Zoppé et al., 2006*).

Material selection of manufacturing standard also has an effect on flow separation. Surface finish will dictate the runner ability to dissipate the fluid most effectively; therefore high standards of manufacturing are required.

9.0 Critical Analysis

The experiment provided expected data trends for the speed, torque, and power of the Pelton Wheel. The data showed the significance of repeatability and experiment control, ensuring that the correlation between results was accurate.

The Pelton Wheel data shows the clear trade-off between the rotational velocity of the wheel and the torque generated. The speed of the wheel spinning generates more energy as it increases, however, this reaches a peak prior to the highest rpm.

The relationship between power and speed can be best shown in the equation for power, whereby ;

$$P = T\omega$$

Power relies on Torque and Rotational speed, whereby either one being low or at zero, then $P=0$. This provides the theoretical reason and principle for the optimum Power be somewhere between runaway speed and stall.

Theoretically, the peak of the energy performance of the wheel should be at 10.5N. The practical results taken, however, show the highest energy produced was at 12N and 13N.

This can be expected from principles of energy loss in this application, as described in Boundary layer and Flow separation losses. This is also down to angle of bucket deflection. Whilst 180 degrees deflection angle is theoretically aimed for, this would have been inconsistent throughout the experiment when considering the shape of the bucket and the surface it is hitting. (*Versteeg and Weeratunge Malalasekera, 2007*). Whilst the experiment observes efficiency deficit consistent with Boundary Layer and flow separation losses, along with further energy loss mechanisms, the experiment does not measure the bucket surface flow rate, therefore, their impact cannot be quantified in the values provided in the tested data.

The practical results from the lab differ in rate of change between measurements, with no perfect curve for results across all of the tests. Experimental error will have played a role throughout the results, creating uncertainty in accurate results. The equipment

used such as the tachometer, torque device, nozzle, and Pelton Wheel spindle will all be subject to losses in accuracy and potential energy. Vibration and friction will have reduced energy transition to kinetic energy, as with noise. Whilst human factor can be counted a contributing factor, far more external factors will affect readings. This can be represented with the equation:

$$\frac{\Delta P}{P} = \sqrt{\left(\frac{\Delta T}{T}\right)^2 + \left(\frac{\Delta N}{N}\right)^2}$$

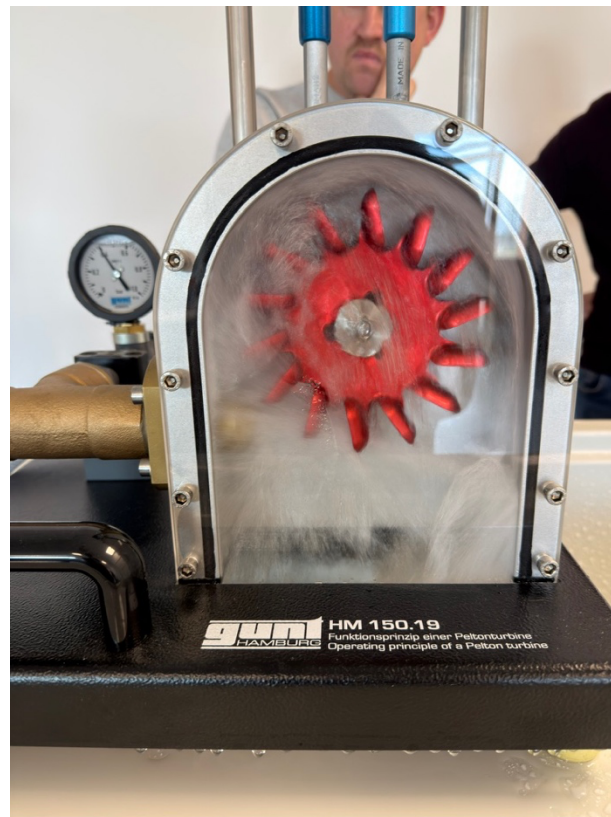


Figure 4 - Pelton Wheel set up at UWTSD.

Whilst the application of a small Pelton Wheel as shown in the image above for the experiment is fairly small, the standards and procedures must be consistent with IEC and BS. There are several IEC standards and correspond and relate to that of the Pelton Wheel.

IEC 63461 refers specifically to Pelton hydraulic turbines, in both their application and testing. This includes measuring, operating and maintaining the equipment and wheel properly to ensure repeatability and safety with their use. (*Bsigroup.com*, 2025).

This is crucial to providing a legitimate set of results that can be followed and repeated in other establishments that follow the same standards of experiment.

Several other BSI and IEC standards are relevant to Pelton Wheels, however, are less specific than IEC 63461.

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