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Modification, Simulation and Demonstration of Laboratory Scale Pelton Turbine for Waterfall Hydropower Plant

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Abstract: To demonstrate the concepts of using waterfall hydropower to generate energy, a Mini-Laboratory Pelton Turbine (MLPT) was designed *and simulated. The principle of energy conversion from potential energy of water at high elevation to kinetic energy at lower elevation through gravity fall was used. To achieve relative continuity of supply as in waterfall, a centrifugal pump was used to deliver water into a set of three reservoirs positioned at different heights. Water from the reservoirs through pipes of different diameters was used to drive the pelton Wheel turbine. A pipe matrix that allows combination of water from two or three sources at different heights and different pipe diameters was designed to demonstrate principle of conservation of flow at a junction. In the laboratory scale design, a power of 750 W was targeted. The required flow rates from different heights of reservoirs to deliver the power were used to establish nozzle diameters, rotor size, rotational speeds and power coupling ratios. A simulation of the model was conducted with different heights, pipe diameters and flow combinations using pipe matrix, were conducted using Matlab Simulink environment. The results showed that the velocity of flow under gravity increases with height of water and the force and torque associated with the flow rate increase with flow area and height of water. The sum of flows from matrix pipes was always found to be conserved with a variance of 0.27. For water heights of 7, 9 and 11 m, the nozzle diameter was found to be 19.0, 25.4, and 38.1 mm and the corresponding jet velocities were 11.2, 12.5, and 13.8 m/s. The flow rates for the scenarios were 0.0026, 0.0046 and 0.0103 m^3/s. The optimum wheel diameter was 313 mm with a power coupling of 5.6:1. Compared to other models [27, 35] from the direct use of jets from pumps, the results have similar characteristics and geometric profiles. The average velocity is lower but, flow rate is higher due to the influence of larger cross sectional area. Thus, it is possible to produce the same power output using lower pressure heads when flow rate is optimized using nozzle diameter to compensate loss in velocity. Such systems can be used to harness most of the low head waterfall in Nigeria. However, the possibility of harnessing waterfalls to generate electricity for low energy demand such as recreation centers and farm settlements is faced with problem of hard-to-reach water source due to topographic complexities.*

Keywords: *Artificial Waterfall, Design and Simulation, Pelton Wheel Turbine, Pipe Network Matrix, Matlab Simulink.*

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1. INTRODUCTION

1.1 Background

Electricity as a source of energy is the most significant manmade input to the survival of humanity [1-2]. Its availability is essential for the social, economic, and psychological needs of man in both rural and urban settings [3-4]. The demand for Electricity grows with the global population and even increases faster than installed capacity. In Nigeria, the available capacity is about 4 GW as against peak demand of 8.25 GW out of an installed capacity of 13.5 GW. There is abundant hydro energy resource for electricity which is estimated to be 15 GW and 73% of it is immediately exploitable. Currently, the constituent of hydropower in Nigeria's energy supply is about 1.28 GW representing 32% of the national grids and 11.6% of the exploitable hydro sources. Small exploitable hydropower sources have a potential of 734 MW but less than 5% is currently being exploited as small hydropower (SHP) [5]. Average energy demand in rural settings can be accomplished without the extension of the national grid supply. Hydro sources such as waterfalls can be harnessed to provide for the small-scale energy demand in rural areas [6]. The activities of the Rural Electrification Agency (REA) are hampered by the enormous amount of money required to take electricity to such remote and hard-to-reach places which is estimated to be between N311 billion to N519 billion for 75% access by 2020 and a further N484 billion to N807 billion for 100% rural access by 2040, REA [7]. It is more feasible and cheaper to generate electricity within the vicinity of rural settings than to sink a humongous amount of money into transmission facilities. Furthermore, studies in terms of exploitable electrical power generation capacities and the required technology models are not sufficiently available to preinform policymakers of the feasibility of the water falls in Nigeria, the study of Olumirin waterfall in Erin Ijesa town in Osun State by Ajewole at al., [8] is one of the few researches in SHP.

1.2 Waterfall Power Plant

A waterfall hydropower plant harnesses the energy of falling water to generate electricity. It uses the principle of energy conversion to first convert the potential energy of water at a high elevation to kinetic energy at a lower level [6]. Next, a Pelton turbine converts this kinetic energy into mechanical energy through a rotor disk fixed with buckets on its periphery. Then, shaft couplers in the form of gear trains, are used to define the required speed and frequency matching. Finally, a generator is used to convert the rotational mechanical energy into electrical energy. Hydropower plants range in size based on power outputs from micro-hydro plants for a few homes or small settlements, to giant plants with high outputs for large settlements, cities, and industries. The amount of electricity depends on the height of the waterfall and the amount of water falling [9].

In a developing country like Nigeria, with over 200 million people, the quantity of energy required to support domestic, public, commercial, and industrial activities is enormous and grows with population size [10]. Energy in such countries is being harnessed from various sources such as hydro, gas, and solar among others. One of the biggest constraints to economic development in Nigeria is inadequate electricity supply, especially from the National grid. The on-grid energy mix is reported by [11] to be 80% thermal and 20% hydro. However, Nigeria is said to have a vast exploitable hydropower potential of more than 14,120 MW of which 3,500 MW is for small hydro potentials, such as waterfalls. Currently, only 60.58 MW (1.71%) of the small-scale hydropower potential has been developed [12]. This shows that there is big opportunity in small- scale hydropower generation, especially by harnessing the waterfall across the nation. This will remove a small fraction of power demand from the national grid [13] and also help to solve the issue of power transmission to hard-to-reach areas due to complex topographies.

1.3 An Overview of Pelton Wheel Turbine

Impulse Pelton turbine is one of the oldest methods of extracting water power [14]. The potential energy of water in hilly areas can be employed to meet the energy demands of the rural areas as well as contribute to energy development [5]. Water is one of the renewable energy sources providing about 15% of world water use for energy as reported by IEA, [12]. The outstanding feature of Pelton wheel as an axial flow impulse turbine is its capability to work under high heads up to 2,000 meters [15].

Pelton turbine is a tangential flow impulse turbine in which the potential energy of water is converted into kinetic energy in the form of a fast moving water jet that strikes the buckets on the periphery of a disk that causes it to rotate. The rotation is used to turn the rotor in a generator to produce power [16]. A Pelton turbine consists mainly of a nozzle with a flow rate regulator, a runner with buckets on its periphery, a casing for wastewater management and a breaking jet to stop the wheel from rotating. When in operation, water at high head is transferred through a conduit - known as penstock, to a nozzle at the end of the conduit. The nozzle delivers the water at high velocity and flow rate in the form of a guided jet. The jet continues to hit the splitter of the buckets which distributes it into two halves – each running along the inner circumference of the half-bucket and coming out approximately opposite to the direction of jet flow due to the spherical shape of the buckets, and finally falls into the tail race [17]. Conventionally, the jet inlet angle to the buckets is between 1 – 3 degrees and its outlet angle after the circumferential journey is 165 to 170 degrees. The force or torque that turns the runner has two components: (i) the force from momentum transfer through the loss in kinetic energy of the moving jet to the bucket in the direction of the jet, and (ii) the force of reaction of the splits moving away from the buckets in opposite direction to the jet, based on third law of motion – action and reaction are equal and opposite [18]. Two Pelton wheels on one shaft or two or three water jets on one wheel are used to produce more power from the same hydraulic configurations [19].

The use of Pelton turbine in waterfalls becomes relevant as it is an impulse device that more suitable for high pressure obtainable in waterfalls than in rivers and running streams. Secondly, recreation centers and settlements around waterfall environment are usually scanty with relatively low energy demand such as the quantity obtainable from waterfalls. Waterfall environments are mostly in hard-to-reach areas with complex topography, limiting the extension National grid supply. Such places can be powered using the hydraulic energy of waterfall to meet their lower level energy demands.

Simulation is the imitation of the operation of an existing or proposed real-world process or a physical system subject to different conditions of operation over time [20]. Simulations are usually computer based using software-generated models with both visual and interactive features to investigate the impact of different scenarios of geometric configuration, materials or changes in processes with a view to providing understanding and experimentation of the actual system. Simulation may be discrete oriented, process in form or dynamics in nature. In all cases, every simulation requires a model. A model is a mathematical, logical or physical representation of a system entity, phenomenon or process [13, 21-22]. The advantages of model and simulation include less financial risk, repeatability against the same circumstances, examination of long-term impact, gain insight for process improvement, assess random variables, encourages in-depth thinking and understanding, and improvement of stakeholders' buy-in. simulation is a non-destructive method that is used as alternative to testing theories and influence of changes in a system process. Simulation finds its application in almost all facets of life, namely: disaster preparation, Economic and financial analysis, ergonomics, satellites and space flights, marine crafts, network systems and project management, robotics and energy generation among others. The CFD software commonly used in simulation of fluid flow in Pelton turbine include I-DEAS, CFX-TASK flow solver and FLUENT [23].

1.3.1 System design and simulation

Bhuyan et al., [2] designed a Pelton turbine using SOLIDWORKS design and product development tool and simulated using Matlab Simulink environment. The design was based on the principle of operation of ocean wave energy harvesting devices. The simulation results shows an average voltages amplitudes of ± 440 V with a peak to peak current of 340 A. A maximum power output of 3.7 MW was achieved using a speed of 3,200 rpm with a constant field voltage of 11.5 V. Septa et al., [24] conducted analysis of various discharge at different nozzle angles on a Pelton wheel design and reported that the result showed that higher discharge causes runners to rotate at high speeds and an 86% efficient was reported to have been achieved using standard guidelines. The performance analysis conducted on the device include overall efficiency, shaft power with characteristics input of water heads, flow rates, injector characteristic curves and runner speeds. Chouhan et al., [13] conducted a design modification of Pelton turbine by using different material for the construction of the runners. The researchers investigated the general performance and smooth operation of the turbine by altering the force exerted by the jet at different flow rates and velocities on runners made from different materials. By altering the inertia of the runners, changes in dynamics and system performance were measured at several heads of water. The result shows that runners made from Bakelite rubber have higher performance than those of other materials. This conclusion may be linked to the material densities as lighter materials offer lesser resistance to changes in momentum. In addition, the presence of rubber additives may also have cushioned shock loads due to sudden changes in flow rate, due to the higher elastic property of rubbers. Shah et al., [6] designed a Pelton turbine with focus on the hydraulic efficiency improvement using parametric optimization method. The effects of bucket exit angle, specific speed, speed ratio and nozzle opening on hydraulic efficiency were investigated. The result shows that the hydraulic efficiency of the turbine was optimum at wide open nozzle and higher specific speed of 20.77 rpm with an exit angle of 15 degrees at 0.49-speed ratio. Thus, indicating reshaping of the bucket geometries to march high flow rate from the water in hilly areas. [15, 24] designed and analyzed a Pelton wheel of 400 W output power with a coupling driven by belt arrangement. The analyses include computation of the input power, output power, buckets and speed ratio, length of belt and efficiency. The result is a turbine with a jet diameter of 0.0254 m installed at the Mone Ta Wa Cave, Ayetharyar. The diameter of the runner is 0.254 m and the width of a bucket is 0.1143 m operating under a gross head of 20 m with a hydraulic efficiency of 96.35%. The big take in the design is the possibility of miniaturizing hydropower for very low energy appliances in remote and hard to reach rural areas.

1.3.2 System dynamics

Xinfeng et al., [23] presented a review of the penstock and nozzle erosion in Pelton turbines with highlights of some latest technical methods used. The damage of the penstock flow passage is substantially attributed to the high kinetic energy of sediment carried by high-head flows. The resultant impact is the reduction in operational benefits, safety, and stability of hydropower station. The reviewers suggested the combination of science and engineering research and development, optimization, design, and manufacturing of hydraulic machinery to minimize the impact of sedimentation as well as employing advanced monitoring technology to extend the service life of the flow passage components. Shinde and Shelke [16] reviewed the dynamic analyses of a Pelton turbine by considering theoretical, numerical and experimental methods that has been used to investigate the dynamic characteristics of Pelton Turbine. The duo concluded that the vibration produced in the system is forced vibration. The dynamic characteristics of a hydro turbine power depends heavily on changes in load disturbances causing the turbine to exhibit highly nonlinear, non-stationary system whose characteristics vary significantly with the unpredictable load which has significant effects on design and operation of turbine [16]. Thus, balancing the bucket loads on the periphery of the turbine during design is crucial. Uvaraj and Uvaraj [14] studied the suitability of Pelton turbine blades for high head energy sources. In high head and low water flows, the Pelton turbine is suitable to set up a micro-hydroelectric power plant due to its easy design and ease of development. To achieve optimum operational performance, the turbine parameters different conditions must be imbedded in the design procedure. The structural parameters considered are turbine strength, turbine torque, runner diameter, runner length, runner velocity, and bucket dimensions, bucket number, nozzle dimension, and specific velocity of the turbine. The modelling and study of the bucket was performed using SOLIDWORKS 2015 and simulated with Matlab software. The force and considering the pressure exerted on various points of the bucket with reference to the bucket geometry were analyzed to obtain the Von Mises tension, static displacement, and safety factor. The authors concluded that in the case of high head and low flow rate, the Pelton turbine is ideal for building small hydroelectric power plants [26].

1.3.3 Performance evaluation

Gupter et al., [23] reviewed the application of computational fluid dynamics for performance evaluation and design optimization. The team examined the theoretical studies conducted on the jet flow interaction with the runner buckets with focus on friction and its impact on performance and analysis of some modifications for reuse of the outlet water from the buckets. The experimental studies reported covers energy loss to cavitation in nozzle due to shapes of nozzles and jet injection position for full kinetic energy transfer. The effects of jet interference on efficiency and how it affects the geometry of the buckets were also covered. In numerical investigation, distribution of stress, flow profiles and resultant efficiencies using finite element techniques and CFD analysis at various incident jet angles and velocities were done. Results showed that the drop in performance, risk of cracking and cost of maintenance can be greatly reduced by introducing hoops around the runner where the stress is heavily concentrated. Omar et al., [27] investigated the effect of changes in operating parameters on performance of Pelton turbine. The team utilized an experimental method using different nozzle diameters, flow rates and pressure heads. The results showed that increase in diameter could lead to reduction in the input power as the water occupying larger cylindrical volume of the conduit causes decrease in height. For a given nozzle diameter, the maximum brake power was observed to have increased with an increase in flow rate which caused an increase in the applied torque. It was concluded by the team that the optimum operational condition was achieved by using a smaller diameter and with a higher flow rate. Raj, [28], designed a modified gravitational Pelton-wheel for a low-head and heavy-discharge application. The runner has bucket cups whose stored water enables the delivery of two kinds of gravitational work on the runner wheel. Firstly, in the form of kinetic energy conversion during its under-gravity free falling and secondly in the form of jet-propulsion during its discharge from bucket-cup under gravitation fall. A comparative analysis of the modified gravitation Pelton and the conventional one shows higher energy content in the new system and more effective for low head configuration. The researcher concluded that modified features provide enough promising opportunities in Mini and Micro-hydro power devices.

Several works have been done on Laboratory Pelton wheel turbines, ranging from design, modelling, and simulation, aimed at demonstrating the influence of flow rates on torque, braking force, and efficiency of the turbine. For example, Agar and Levant, [29], developed a laboratory-scale Pelton turbine for power generation using locally available inexpensive components. The apparatus was being used in the educational curriculum of the Renewable Energy Programme at the University of Jyvaskyla. The performance characteristics of a Pelton wheel turbine were demonstrated by measuring variation in power output and efficiency against the runner speed for different openings of the nozzle at a constant input head. The turbine was found to have a maximum efficiency of 47% at a flow rate of 0.171 lt/s. The duo concluded that the Pelton turbine apparatus demonstrated the principles of hydropower and is well suited for education in renewable energy programmes. Another test bench set-up by Neeraj et al., [30] aimed at experimental and numerical analysis of flow in a fixed bucket of a Pelton turbine by varying the head, jet incidence, and flow rate over a wide range of the functioning points. The setup provided measurements of pressure and torque with flow visualization. The numerical analysis was performed in FLUENT software with two-phase flow volume techniques. The outcome was reported to be consistent with experimental results. In particular, the prediction of the distribution of pressure has negligible losses outside the edge of the bucket over the range of operation for considered parameters. The team concluded that the results gave a demonstration of the steady flow optimization process of the design of Pelton turbines. A Unanimous [31] laboratory report provides a device consisting of a Pelton turbine, inlet pressure measured with a Bourdan tube pressure gauge, centrifugal pump, tachometer, calibrated orifice-meter connected to mercury manometer, brake drum dynamometer with rope and mass loading system at the end of the rope. With the nozzle wide open the inlet pressure was set to 28.5 m of water column. The flow rate was determined from a calibration chart using the reading of the mercury manometer connected to the calibrated orifice meter, as the load on the dynamometer was increased from 2 kg to 30 kg in steps of 2 kg until the drum stopped rotating. The equivalent torque corresponding to each stopping mass is used to calculate the power output and the turbine efficiency. The procedure was repeated for half and one-quarter opening of the nozzle with the pressure head kept constant at 28.5 m. The results show that the flow rate is related to the pressure drop over the dynamometer by a power function of the form $Q = 0.0003 * (\mathrm{DP})^{0.5842}$ mm of Hg. The researcher concluded that the flow rate is a central measure of the performance of a Pelton wheel turbine and that power increases with the flow rate. In another laboratory design experimented by Omar et al., [27], the effect of nozzle diameter and the water discharge on the performance of the Pelton turbine was investigated. This was done by evaluating the input power, water head, torque, brake power and efficiency for varying nozzle diameter and flow rates. It was found that the flow rate and input power increased with the water head while efficiency reached its maximum value of 37% at about 400 revolutions per minute with the least nozzle diameter of 9.7 mm. The team concluded that at constant laboratory conditions, the nozzle diameter and flow rate have substantial influences on the power generated by Pelton turbine and that the related parameters can be used to generate a higher electric power for low consuming devices. Mori [32], examined the Characteristics of the Pelton turbine as an impulse energy conversion device in which static pressure remains constant as the working fluid passes through the rotor, in a laboratory setting. The author utilized an FM3SU Pelton turbine unit which consists of a carrier base, acrylic water tank, circulation pump, driven electric motor and a pipeline network. The turbine rotor has a diameter of 70 mm with 10 blades mounted on its periphery. A needle valve of diameter 4.5 mm with an adjustable stem is installed to provide varying jets to drive the runner, and a braking system with a sensor to measure the force applied to stop the rotation of the runner. The speed of the turbine is controlled by adjusting the tape tension brake through a bolt. Mori [32], established the characteristic curves for the turbine in two different flow rates and compares the dependence of torque, braking force and the efficiency from the turbine rotational speed at a constant fluid flow rate to the operational rating information provided by the manufacturer of the device. The author concluded that the device worked adequately within fundamental characteristic of impulse turbines and can thus, be used for classical experiments in laboratories before a life system is developed.

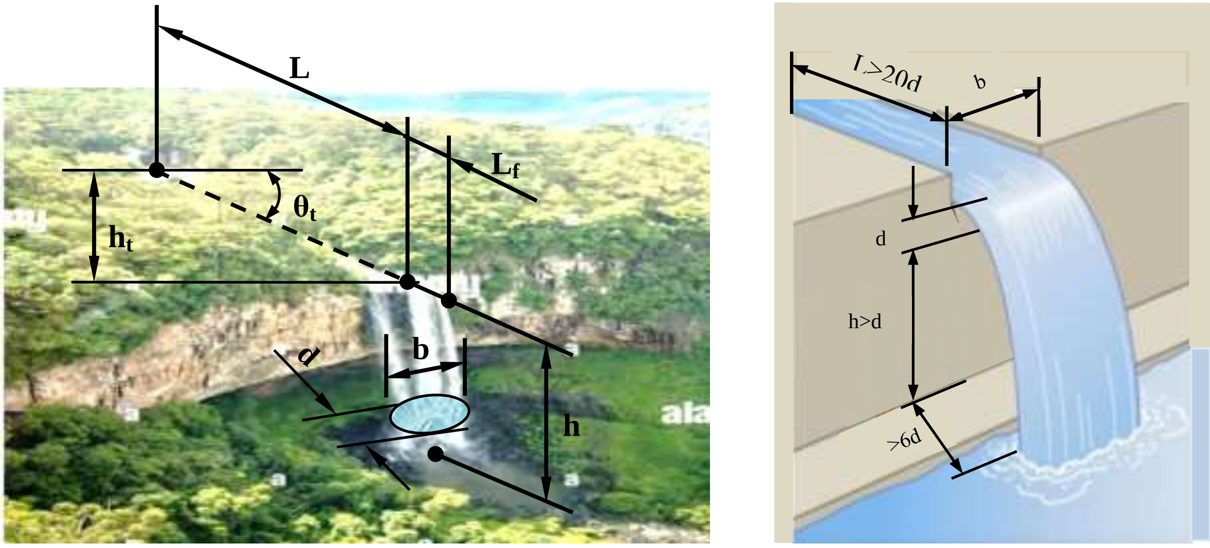
1.4 Harnessing Waterfall Hydropower using Pelton Turbine - Motivation and Aim of the Study

Due to the flexibility, sustainability, and secured nature of hydropower generation, the detailed forecast from 2020 to 2030 in IEA [12], hydropower report identified reservoirs, run-of-water, and pumped storage plants as future targets. The pumped storage resource, where water is being elevated to an upper reservoir and then released through turbines when needed is forecasted to represent 30% of net hydro additions by 2030. This claim has three embedded opportunities that can be harnessed by the Nigerian Rural Electrification Agency (REA), namely: (i) the existence of natural phenomena that could provide the required height without physical pumps is found in waterfalls across the nation, (ii) the flexibility of hydropower plants allows the development of each plant to match the topographical features of the waterfall sources, and (iii) the non-continuous use of the intended hydropower plant suggests that: demand could be occasional as it is in the use of waterfalls for tourist activities as well as lower power supply to rural areas. Nigeria has over 55 waterfalls in the rural areas with some of them over 20 m, but none has been harvested for the purpose of electricity, Makoju, [33]. There are exceeding difficulties in providing electricity in most of the rural areas due to their poor topography and high cost of transmission facilities. The studies available were mostly carried out in Asian countries and thus, lack local environmental input in terms of weather and finance and hard-to-reach conditions. This study aims at demonstrating the feasibility of producing electricity from Nigeria waterfalls using a mini-plant that utilizes Pelton wheel technology in a laboratory setting, to stimulate interest in energy generation in rural areas and recreation centers using available waterfalls and uphill streams. The knowledge of design, manufacture, installation, and maintenance of Pelton turbine using local materials is required to harness the small-scale energy potential of the waterfalls in Nigeria. It is against the need to enhance power production in Sub-Saharan African countries such as Nigeria and to establish the fundamental knowledge and capabilities required for its development that has motivated the intention of Mini-Laboratory Pelton Turbine to demonstrate its feasibility and to impart its principles.

2. METHODOLOGY

2.1 Design Concept and Specification for the Laboratory Pelton Turbine

The design of Pelton turbine is based on two principles: namely, conversion of the potential energy of a free body of water into a kinetic energy in the form of fast moving jet from a nozzle (Figure 1), and, utilization the fast moving jet on buckets firmly installed on the peripheries of a freely mounted wheel, to rotate with the shaft of an alternator to generate electricity.



(a) Critical dimension based on natural topography (b) Waterfall equivalent of Channel flow

Figure 1: The natural dimension of a waterfall and flow characteristics

Since the kinetic energy of the moving jet is obtained from the potential energy of a freely falling column of waterfall, the higher the source, the more kinetic energy is generated. In general situation, the waterfall in Figure 1 presents the main geometric dimensions that are commonly considered in waterfall modelling.

The main natural features of the waterfall are: the transition length, L_t, defined as the water run path length until it falls off the clip, the transition angle, θ_t, the angle of depression of the waterfall with respect to the horizontal plane, as it transits from the source to the cliff, H_t, is the transition height drop of the waterfall over the transition length, and H_f, is the waterfall height from the cliff to the plunge pool. Other geometric parameters are the approximate geometry of the waterfall area which is taken in this work to be elliptical, having the major axis as the width of the fall, W_f, and the depth, D_f, as the minor axis.

The Laboratory Pelton Turbine is a 1:10 scaled down prototype with six (6) basic units, namely: Water reservoir and supply unit - 1, Circulation pump unit-2, Pelton wheel unit - 3, the alternator and transformer unit - 4, Power supply and selection unit - 5, and Housing frame - 6. The schematic diagram of the turbine model is shown in Figure 2.

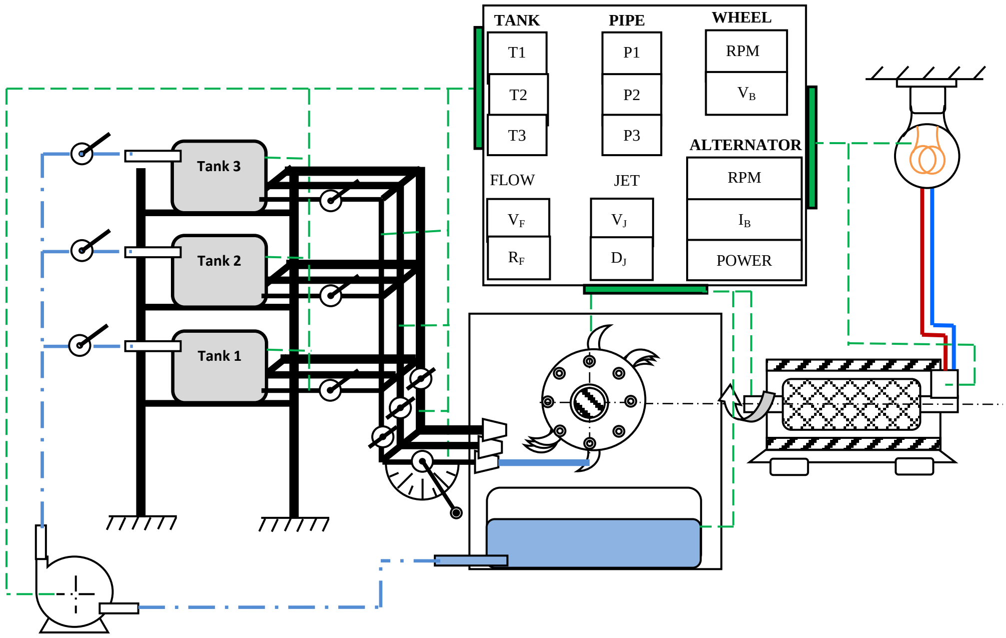


Figure 2: Schematic diagram of the design concepts for the laboratory Penton Wheel Turbine

The water reservoir and Circulation unit consists of waters tanks, pipe networks, and fittings, all made from high-density polyethylene HDPE with a density of 940 kg/m^3 and a tensile strength of 38 MPa. The material is noncorrosive and only decomposes at 300^{o}C prolonged heating [34]. A return pump which takes water from the spent water tank back to the reservoirs for continuous circulation is installed at the sump. The pump is an impeller centrifugal none-closing type with a capacity of 0.258 m^3/s, continuous duty with a single mechanical seal. The discharge pressure and suction pressure are 25.5 kN/m^2 and 56 kN/m^2. The differential pressure is 2.095 with a maximum suction of 0.752 and an average of NPSH of 35.5 m. The wheel and the buckets are made from stainless steel of density 7800 kg/m^3 and shear stress of 220 MPa and aluminium cast of density 2,680 kg/m^3 and 180 MPa, respectively. The alternator used is 1,260 winding with an output current range of 40 A to 120 A.

The Pelton turbine is intended to be a table-top type with the turbine unit and control panel stationed at a height range of 1.2 m to 2.4 m above ground level to accommodate sitting and standing posture of an average height. It is required to accommodate 2–5 students in an experiment. Fundamentally, it utilizes the head of water flow from a storage tank as a virtual waterfall with continuous flow. Three storage tanks positioned at heath intervals of 7.5, 9, and 10.5 m are used. A water sump is placed under the wheel and fed with a pipe wide enough to prevent water spill. A transparent casing is built to prevent water spills while its operation can be observed with ease. PVC pipe networks are used for the return end and cast-iron piping is for the jet unit. A matrix pipe network that combines water height and flow area consideration is used to demonstrate the principle of continuity.

In operation, water flows under gravity from any of the three tanks or a combination of two or three of them to a prefixed equivalent nozzle with a throttle valve assembly to alter the velocity of flow at will. The control panel is equipped with head meters, velocity/flow rate meter, and a tachometer Pelton wheel revolution per minute. A pump is required to return the water from the sump to the overhead tank. The output current and power are also being measured using an avometer. A throttle valve is to be produced to alter the flow rate with the aid of a protractor arranged to give six flow rate options – 0, 45^o , 90^o, 135^o and 180^o fractions of the flow at WOT for any selected pipe matrix.

2.2 Model Formulation

1) Waterfall flow dimension: The waterfall is approximated to be elliptical in its cross section, with $L_t > 20*D_f$, and $H_t > D_f$, and $L_{dp} > 6*D_f$. With these conditions satisfied, the flow rate, Q, of the waterfall is as given in Equation 1:

$$Q = C * \sqrt{gD_f} * A_f \quad (1)$$

Where $C = 1.69,$ the unconfined nap of the flow is, D_f is the depth of flow, g is the acceleration due to gravity and A_f is the cross sectional area of the flow defined in Equation 2 as:

$$A_f = \frac{\pi}{4} * (W_f * D_f) \quad (2)$$

Where W_f is the cross sectional width.

The available water power at the plunge pool is: ρgQH. Thus, the hydraulic power is given in Equation 3 as:

$$powe\ P_h = \rho g * C_v * \frac{\pi}{4} * \sqrt{g} * W_f * D_f^{\frac{3}{2}} * (H_t + H_f) \tag{3}$$

Where P_h is the available water power at the pool, ρ is the density of water, C_v is the coefficient of flow velocity, H_t is the transition height defined as $H_t = L_t * sin\theta$ and H_f is the waterfall height,

To harness this power, the gross height, width and depth as well transition slope is required.

The potential energy of the water at the clip with reference to the plunge pool is completely converted to the kinetic energy whose velocity v_f is defined in Equation 4:

$$v_f = C_v\sqrt{2g(H_t + H_f)} \tag{4}$$

And its corresponding flow rate Q_h defined in Equation 5 as:

$$Q_h = \frac{\pi}{4} * C_v * W_f * D_f * \sqrt{2g(H_t + H_f)} \tag{5}$$

2) Pelton wheel turbine dimensions: The net available head to run the Pelton wheel turbine is obtained with a percentage head loss of 6% since flow is in mainly under gravity. From this net head, all other design parameters are linked and obtained from the established formula in Equations 6 through 15 contained in Table 1.

Table 1: List of established formula for the hydraulic side of a Pelton Wheel Turbine [26, 29]

Hydraulic Parameter	Formula	Comment	Equation No.
Net height	$h_n = h_g * (1 - k/100)$	k is assumed be 6%	(6)
Flow Velocity	$v = C_v * \sqrt{2g * h_n}$	Cv is taken to be 0.952	(7)
Jet flow rate	$Q = C_d * A * v$	C_d is between 0.62 and 0.68	(8)
Velocity of wheel	$u = \varphi * C_v\sqrt{2g * h_n}$	Speed ratio, φ = 0.43 to 0.48	(9)
Number of jets	$n_j = \frac{Q}{q}$	$n_j \leq 3$	(10)
Input water power	$p_{in} = \rho * g * Q * h_n$	Power from the jet	(11)
Output water power	$p_{out} = \rho * Q * v_w(v_j - v_w)(1 + \varphi * \cos(\alpha))$	Highly dependent on α and φ	(12)
Hydraulic Efficiency	$\eta_o = \frac{P_{out}}{P_{in}}$	80 to 98 is a very good range	(13)
Jet ratio, m	$m = \frac{D}{d_j}$	The optimum ratio is m = 10 to 12	(14)
Wheel diameter	$N = \frac{60 * u}{\pi D}$	Specific speed is also being considered	(15)

In Table 1, the parameters used are: h_n = net head, h_g = gross head, k = fraction of head loss, C_v = coefficient of Velocity, C_d = coefficient of discharge, n_j = number of jets, Q = total flow rate, q is the flow rate per nozzle, p_{in} = input water power, p_{out} = output waterpower, u = the wheel velocity, φ = the speed ratio, v_w = relative velocity of the wheel, α = angle of deflection, m = jet ratio, d_j = jet diameter, D = wheel diameter, N = wheel revolution per minute, and η_o = hydraulic efficiency of the turbine.

3) Pipe Matrix for Water Flow Analysis: Flow from each tank is configured to pass through any of the three different diameter pipes or a combination of two or the three pipes. The individual or combined flow rate was determined to know the minimum time required to refilling the tank between the min control level and the maximum free surface was established in the four possible combinations presented in Equation 16.

$$\left.\begin{array}{l} \text{P1 + P2:} \quad A_{1,2} = (Q_1 + Q_1)/v \\ \text{P1 + P3:} \quad A_{1,3} = (Q_1 + Q_3)/v \\ \text{P2 + P3:} \quad A_{2,3} = (Q_2 + Q_3)/v \\ \text{P1 + P2 + P3:} \ A_{1,2,3} = (Q_1 + Q_2 + Q_3)/v \end{array}\right\} \tag{16}$$

The value of weighted area obtained from the above combination is used to determine time required to empty the tanks using the relation in Equation 17.

$$t_e = \left(\frac{2*A_T}{C_d*A_n} * \sqrt{\frac{h_n+h_t}{2g}}\right)/60 \tag{17}$$

t_e is the time required to empty the tank, A_T is the cross sectional area of the tank, A_T = is the cross sectional area of the jet, C_d is the coefficient of discharge, h_n = net head from the base of the tank and h_t head of water in the tank.
The result from this analysis will give flow with fastest time to empty the tanks. The flow rate corresponding to this minimum time is used as the flow rate specification for the required pump for recirculation.
In addition to the time of emptying and filling the tank, the principle of continuity is demonstrated as the sum of flow towards a junction is equal to the sum of flow out of it. Thus, the equation guiding the operation of the flow through the matrix pipe is given in Equation 18:

$$Q_{net} = \sum_{i=1}^{n} Q_i \qquad i = 1, 2, \dots 2, n. \tag{18}$$

Where Q_{net} is the resultant flow at any junction and Q_i is a flow in tributes pipes.

The design parameters that are critical to effective transfer of kinetic energy of jet to the mechanical energy at the runner for smooth operation of Pelton wheel are the wheel diameter, jet ratio, the number of buckets and the bucket geometry. The description, formula and range of applications of these parameters are presented in the formula in Equations 19 through 24 in Table 2.

Table 2: Pelton wheel rotor and bucket design parameters [26, 30]

Parameter Description	Formula	Range of Application	Formula No.
Jet ratio, m	$m = \frac{D}{d_j}$	The optimum ratio is m = 10 to 12	(19)
Wheel diameter	$N = \frac{60 * u}{\pi D}$	Specific speed is also being considered	(20)
Numbers of buckets	$n_b = 15 + \frac{m}{2}$	The must not be less than 15	(21)
Length of buckets	$L_b = 2.5 * d_j$	There should be provision for incoming jet.	(22)
Bucket width	$w_b = 3.5 * d_j$	Wide enough to deflect water by at least 160°	(23)
Bucket depth	$e_b = d_j$	If the material has the strength	(24)

From Table2, the parameters used are: m = jet ratio, d_j = jet diameter, D = wheel diameter, N = wheel revolution per minute, u = wheel velocity, n_b = the number of buckets, d_j = jet diameter, L_b =length of bucket, w_b = width of bucket, and e_b= depth of bucket.

2.3 Pump Selection

In a laboratory context at the same thermodynamic state, liquids will not flow from a lower to a higher potential level, without some work inputs – equivalent of 'Clausius statement' for energy transfer. Thus, a pump is used to return the water and make it available on a continuous basis like waterfall sources. For continuity, it ensured that the flow rate from the selected pump is equal to or greater than the flow rate, Q, in Equation 8.

Three water tank reservoirs are used to momentarily store the water at different heights and discharge it at the base of the tanks to demonstrate changes in velocity with height. To achieve the required power demand of the pump, three factors were considered; the total height against which the pump must deliver the water to the reservoirs, the suction lift and the desired flow rate, all of which are dependent on the piping system and the pump characteristics. The delivery head h_d, is the net head plus the head drop, representing the dynamic energy losses due mainly to friction against the walls of the pipe and the fitting accessories in the circulation circuit. The total delivery head $h_{d,i}$, given in Equation (25) is the sum of the Pumping lift, suction head, and friction head expressed as:

$$h_{d,i} = h_g + h_s + h_r \tag{25}$$

Where $h_{d,i}$ the delivery head of a tank is, h_g is the gross head, h_s is the suction head and h_r is the head loss to various resistances to flow.

To avoid cavitation, the Net Positive Suction Head (NPSH) defined as the ability of the pump to deliver the liquid to the required height is considered as in Equation 25 to be adequate when the liquid temperature remains below its flash point.

Figure 3 presents the hydraulic unit of the turbine. The pump delivers water to the tanks through the pipes shown in green, while water from the tanks is supplied to the turbine nozzle through the pipes shown in light blue.

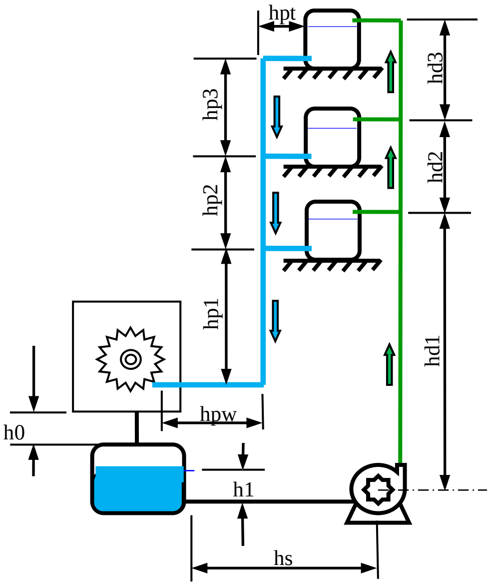


Figure 3: Laboratory Pelton Turbine water circulation systems

The design analysis for the selection of the recirculation pump was based on Equation 26 expressed in Bernoulli's as [22]:

$$\frac{p_1}{w} + \frac{v_1^2}{2g} + z_1 + H_p = \frac{p_2}{w} + \frac{v_2^2}{2g} + z_2 + losses \quad (26)$$

At any given state, p is the pressure, v is the flow velocity, z is the elevation; at states 1 and 2 and H_p is the delivery head. The basic requirement is to determine the power rating of the pump, and the pressure developed by the pump which is computed from Equations 6 and 27.

$$P_r = \frac{\omega Q H_p}{\eta_p} \quad (27)$$

Where: P_r is the power rating of the pump, ω is the impeller angular velocity, H_p is the delivery head and $\eta_p$is the pump efficiency.
The water horsepower required to deliver the head is obtained from Equation 28:

$$P_w = \frac{TDH*Q*SG}{3.6*10^6*\eta_h} \quad (28)$$

Where: P_w is the water power, TDH is the total delivery head including losses, Q is the flow rate, SG is the specific gravity of the liquid and η_h is the hydraulic efficiency.
While Equation 29 gives the pressure developed by the pump:

$$\Delta p = \left(\frac{v_2^2 - v_1^2}{2g} + H_p\right) SG \quad (29)$$

Where: Δp is the pressure developed, v is the velocity of flow from stage 1 to 2 and H_p is the delivery head.

From the dynamics of the jet flow, the force exerted by the jet on the curved vanes (buckets) as it moves in the direction of jet and gets deflected through an angle φ, is given in Equation 30 as:

$$F_x = \rho a v (v - u)(1 + cos\varphi) \quad (30)$$

Where: F_x is the hydraulic force on the wheel buckets, a is the jet cross sectional area, v is the jet velocity, u is the wheel velocity and φ is the angle of deflection of the jet.

2.4 Design/Model Simulation

Model Simulation of the Waterfall hydropower Concept was done in Matlab Environment. Simulink software integration with Matlab provides environment for designing and simulating models for dynamic systems. The incorporated Math Works is equipped with multi-domain dynamic analysis. Simulink has graphic editing tool with modifiable block library for block diagram drafting [30]. In model creation, the building blocks are dragged from the library browser to the graphic editor window and the different units of the system interconnected with directional flow link-lines. Source blocks to generate signals for the system operation are added and sink oscilloscopes produces a visualized output. The outstanding graphical visual interface of the Matlab Simulink tool makes is suitable for the modelling and simulation of the waterfall hydropower concept.

Figure 4 shows the Simulink model for the Pelton turbine with height, cross section area and exit angle as variables.

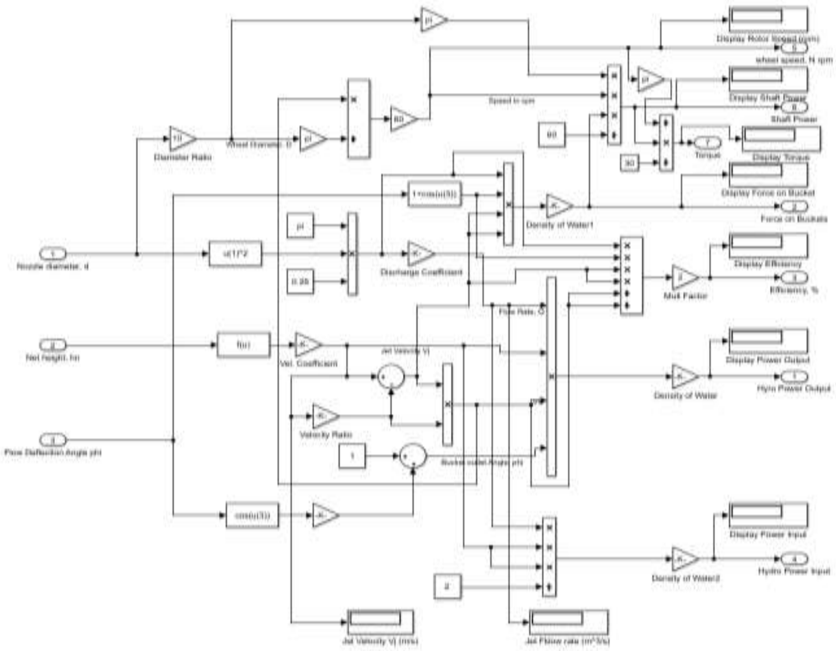


Figure 4: Detail diagram of the Pelton wheel turbine model analysis in simulink environment

The model has three major inputs, namely: the gross height - 1, the nozzle diameter - 2 and the flow deflection angle - 3. The values of pi, coefficients and ratios are represented with constants and gain blocks as the case may be. A total of nine outputs were investigated. In measuring power output from the system, electric bulbs of varying load capacities are connected to the bus of the distribution line to investigate its load characteristics. Valves and switches are provided to control the flow rate at the jet side and to regulate the electrical load at the alternator side respectively. A panel system is integrated to digitalize the control systems and provide an I/O user interface platform.

3. RESULTS AND DISCUSSIONS

The aim of this work is to model, simulate and demonstrate experimentally the concept of harnessing the waterfalls in Nigeria for energy generation in rural areas. In the models, the effects of the geometric dimensions of waterfall (height and cross sectional area of waterfall in the form of nozzle diameter), and the water discharge (in the form of flow rate from the nozzle) on the overall performance of the Pelton wheel turbine was investigated. The given conditions in the laboratory scale are power demand (750 W), water heads (7, 9 and 11m) and targeted efficiency (85%) for different nozzle diameters based on velocity of flow.

3.1 Model Parameters

The design specification for the laboratory scale turbine was an output power of 750 W with a running efficiency of 85% under a variable gross head, $h(h = 7,\ 9,\ 11\,m)$. The density of water is taken as 1000 kg/m^3 and acceleration due to gravity as 9.81 m/s^2. Table 4.1 presents the model parameter for the simulated Laboratory scale. Three Optimum nozzle diameters 0.01901, 0.02540 and 0.03810 m were used to evaluate the quantity of flow rate that will give the approximate value of the required power. Results from similar turbines with different dimension were compared to the current values as shown in the last two column of Table 3.

1) Laboratory Scale Pelton Turbine: From Table, it can be seen that jet velocity increases with height of water for a given nozzle size. This is expected as the kinetic energy of flow is obtained from the potential energy of water at higher elevation, thus, the higher the elevation the higher the velocity. This result agrees with that obtained by Ma et al., [15] (a laboratory scale) in which water at 20 m produces a proportionate velocity of 19.41 m/s. Another operation parameter of interest whose value increases with pressure head due to velocity content and diameter due to area content. For example, the flow rate increases slowly with a common difference of about 0.0003 as in d_1, 0.00045 in d_2 and 0.0011 in d_3, whereas, the difference in flow rate between d1 and d2, and d2 and d3, for a height of 11 m are 0.002 and 0.0057, thus showing that the contribution of area to flow rate has more impact than that of height. The implication of this is that it is possible to generate the same quantity of energy from a lower head by optimal selection of the nozzle diameter. This is evident from the higher ratio of power to pressure head of 58.75 W/m obtained in the current work compared to similar laboratory scale reported by Ma et al., [15], with work to height ratio of 20.12, despite a height difference of 13 m. Finally, the actual efficiency was is 82.3% as against the target of 85%. The efficiency is lesser than its laboratory counterpart by 7.7% but better than the actual life system by 4%. This may be due to the introduction of matrix pipes with many flow diversion and reducer that may not have been accounted for.

Table 3: Model parameters for the laboratory scale Pelton Turbine

Model Parameter	**Unit**	**Current Result at different Pressure heads and Nozzle Sizes**									**Existing Results**	
Optimum Nozzle Diameter	m	d1 = 0.01901			d2 = 0.0254			d3 = 0.0381			Lab scale Ma et al., [27]	Life Project Than et al., [35]
Gross height	m	$h_1 = 7$	$h_2 = 9$	$h_3 = 11$	$h_1 = 7$	$h_2 = 9$	$h_3 = 11$	$h_1 = 7$	$h_2 = 9$	$h_3 = 11$	-	213
Net height	m	6.58	8.46	10.34	6.58	8.46	10.34	6.58	8.46	10.34	20	-
Jet flow Velocity	m/s	11.02	12.50	13.82	11.02	12.50	13.82	11.02	12.50	13.82	19.41	-
Wheel Velocity	m/s	4.96	5.62	6.22	4.96	5.62	6.22	4.96	5.62	6.22	-	-
Jet Diameter	m	0.0190	0.0190	0.0190	0.0254	0.0254	0.0254	0.0381	0.0381	0.0381	0.025	0.053
Flow Rate	m^3/s	0.0020	0.0023	0.0026	0.0037	0.0041	0.0046	0.0082	0.0093	0.0103	-	0.135
Wheel Diameter	m	0.209	0.209	0.209	0.279	0.279	0.279	0.419	0.419	0.419	0.254	0.56
Water Power – in	kW	124.4	181.3	245	222	323.7	437.4	499.6	728.3	984.1	449.29	282
Output Power- out	kW	102.4	149.3	201.7	182.8	266.5	360.1	411.3	599.6	810.2	404.36	220
Hydraulic Efficiency	%	0.823	0.823	0.823	0.823	0.823	0.823	0.823	0.823	0.823	0.90	0.78

2) Optimum Diameter for the given Power and Pressure Head: For the required power of 750 W, pressure heads of 7, 9 and 11 m and target efficiency of 85%, a backward substitution using Equation 11, to determine the resultant flow rates and the value equated to the product of velocity due to height of fall and the cross sectional area of the final jet. Figure 5, presents the graph of jet velocity against range of nozzle diameters (about 0.02 to 0.07 m) that falls within flow rates obtained from backward substitution process at required heights.

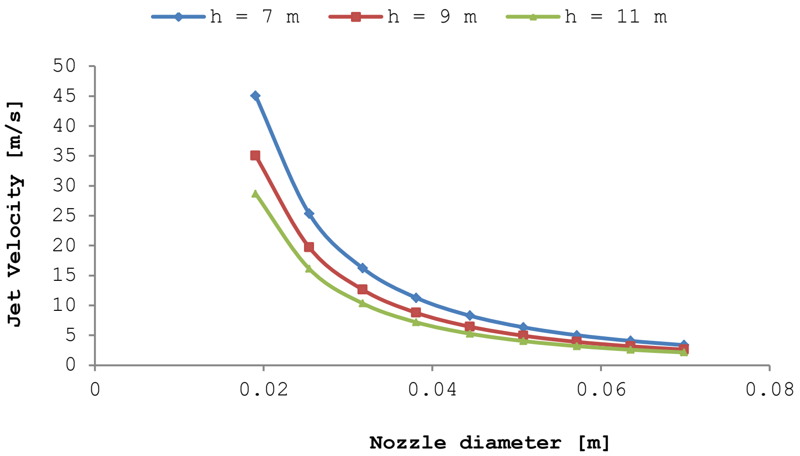


Figure 5: Determination of nozzle diameter using the effect of height on velocity

For the required power of 750 W over an efficiency of 85%, the water power input required is 750 W/0.85 = 882.35 W. Taking the specific weight of water as 9810 kg/(m^3s^2), the resulting flow rate using Equation 8 is 0.01285, 0.00999 and 0.001818 m^3/s corresponding to a height of water at 7, 9 and 11 m respectively. Since flow rate is the product of velocity and cross section area, the velocity is obtained using Equation 7 from converting potential energy to kinetic energy is used to obtain the cross section areas from which diameters were determined. The optimum diameters were found to be 19.0 25.4 and 38.1 mm. Similar method was used by Than et al., [35], in analysing the required size of conduits in real life situation for 220 kW, the result can be directly scaled down to 1:20 with similar trend as increase in diameter leads to reduction in flow velocity, but higher momentum as more cross sectional flow area is required to obtain the target power.

3) Variation of Flow Rate with Pressure Head: Figure 6 gives the variation of flow rate with height. The three optimum nozzle diameters obtained in section 3.1 were used.

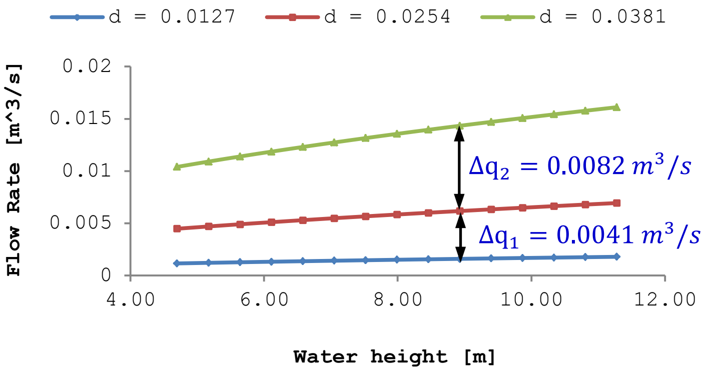


Figure 6: Variation of flow rate with water height

Since he power produced is a function of flow rate and the project is intended to demonstrate power out at different potential energy, the flow rate is plotted against height in Figure 6 for three different nozzle diameter, 12.7, 25.4 and 38.1 mm. The flow rate across all diameters increases with height of water with approximately 0.0009 m^3/s per m due to function, $k\sqrt{h_n}$. Also, the larger the diameter the higher the flow rate as observed from the differences between consecutive lines ($\Delta q_2 > \Delta q_1$), due to the square of diameter in area. Thus, the contribution area to flow rate may be higher than that of height, due to the square of diameter that produces quadratic response in flow rate. The implication of this is that, waterfall of low heights can be harnessed when flow rate are properly chosen to balance the gap in required pressure head. This result is in agreement with the findings of Omar et al., [27] who reported that though smaller nozzle diameters produces higher efficiencies against volume flow rate, more torque and hence higher power, is produced at higher flow rates.

4) Force of Jet on Buckets: Figure 7 presents the force of the moving jet on the bucket at the periphery of the Pelton wheel against height of water. Four different diameters were chosen to demonstrate the dependence of power required to drive the Pelton wheel on the pressure head and flow rate.

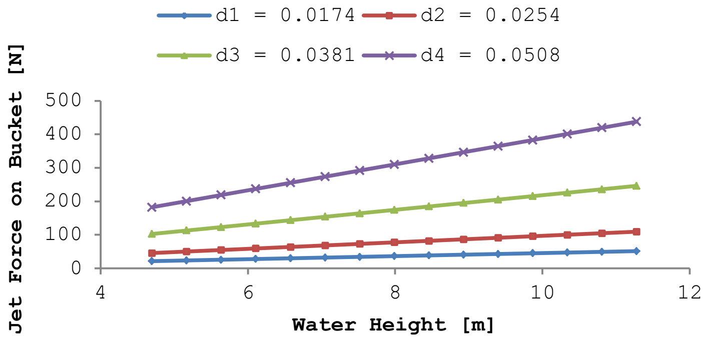


Figure 7: Variation of jet force against height of water.

In the graph of Figure 7, the force of jet on the buckets generally increases with increase in height of water, but the rate of increase is high as the diameter and hence flow rate increases. Thus, larger diameter nozzles produce more forces to turn the bucket, even at the same elevation. Also it is observed that the power rate per unit height of water is higher in larger diameters than lower diameters. This is as a result of increase in flow rate due to larger area of flow. The consequence is high power production and higher efficiency, because there is adequate torque to turn the buckets. This result agrees with the findings of Bilal, [1], Omar et al., [27] and, Than et al., [35] in which the power produced (due to the applied torque and hence, flow jet force), generally increase with height of water.

5) Rotor Speed Against Water height: Figure 8 shows the variation of the turbine rotor with water height at three different diameter ratios, 10, 11 and 12. Diameter ratio is defined as the ratio of the diameter of the wheel to the diameter of the fast moving jet. As part of the fundamental design requirement for the ratio of Pelton wheel diameter to that jet, to fall between 10 and 12 for effective operation is used to determine speed range that will not cause uncontrolled vibration due to inertia where there are sudden variation in height and hence acceleration from changes in velocity of jet.

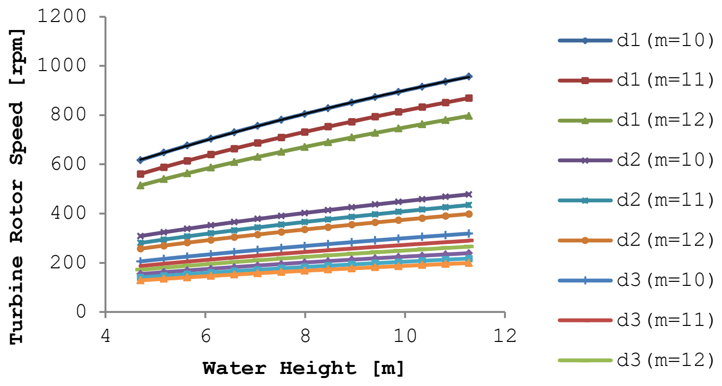


Figure 8: Variation of turbine speed with water height

The rotor speed increases with water almost quadratically, and inversely proportional with diameter. Thus, the higher the height of water the higher the speed of turbine but the larger the diameter, the lower the speed. The diameters d1 group are 17.4 mm and ranges from 514 to 916 rpm, on the other hand, the diameter d4 group is 38.1 mm and the corresponding rotor speed range is 129 to 217 rpm. This is because speed and torque are inversely proportional. Smaller diameter produces lower flow areas but higher speed and less torque while larger diameters produce high flow area to increase tor with lesser speed. It is also observed that the curves with larger diameters are more packed than the ones with smaller diameters, thus operating the turbine with higher torque and lower speed is an indication that rotation will be smoother as speed changes within the range. It also shows that at lower speeds, the difference in diameter ratio has an insignificant effect on power produced, as such at laboratory scale the chosen speed was 125 to 475 rpm corresponding to diameters d_1 and d_2. This is believed to help overcome dynamic imbalance reported by Shinde and Shelke [16].

6) Turbine Performance: Figures 9 through 11 present the simulated hydraulic power available at the incident of the water jet tricking the bucket (the blue curves) and the power produced by the turbine against the water flow rate (red curves) as well as hydraulic efficiency of the Pelton turbine (green colour), for three different nozzle diameters d1 = 19.01, 25.4 and 38.1 mm.

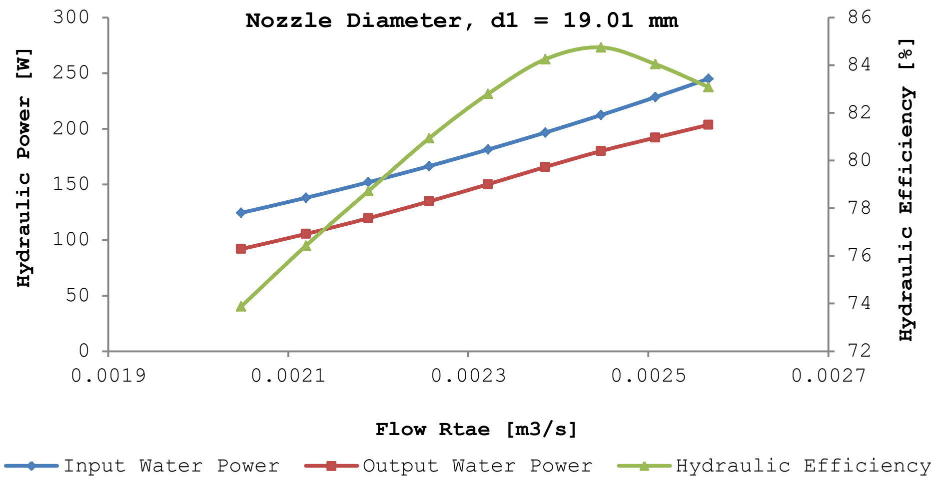


Figure 9: Variation of hydraulic power and efficiency against flow rate for d1 = 19.01 mm

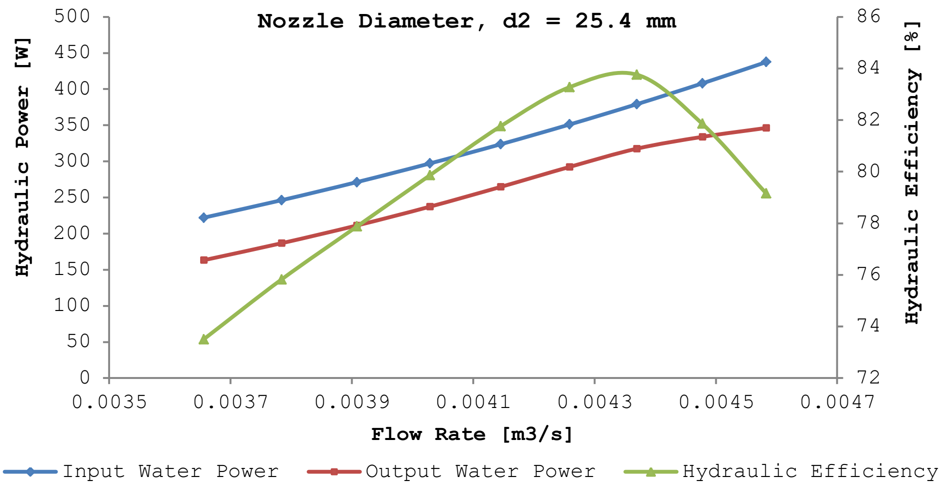


Figure 10: Variation of hydraulic power and efficiency against flow rate for d1 = 25.4 mm

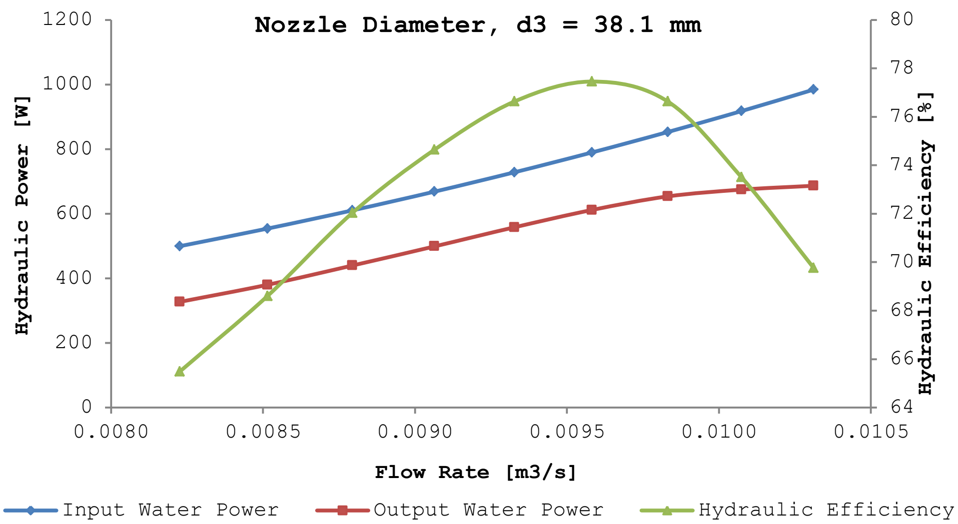


Figure 11: Variation of hydraulic power and efficiency against flow rate for d1 = 38.1 mm

From the graph of Figures 9 through 11, both input hydraulic power and turbine power are directly proportional to flow rate in all cases. As expected, the input powers are higher than the turbine powers throughout the chosen range of diameters and flow rates. In all cases, efficiency increases with flow rates until it reaches its maximum values at about 0.00245 in Figure 9, 0.00434 in Figure 10 and 0.00972 m^3/s in Figure 11, for nozzle diameters 019.01, 25.4 and 38.1 mm, respectively. In Figure 9 (nozzle diameter - d1), a maximum efficiency of about 85% was reached when the output power is 270 W. In Figure 10 (nozzle diameter – d2), maximum efficiency of 83.75 was reached at an output power of 425 W, while in Figure 11 (nozzle diameter d-3), maximum efficiency of 77.5% was reached at an output power of 1,008 W. Thus, power increases with increase in diameter and also increases with increase in flow rate. However, the power, $P_3 > P_2 > P_1$ due to a higher flow rate, as in Figures 11, 10 and 9 respectively but, efficiency in each case reduces, thus, $\eta_1 > \eta_2 > \eta_3$ as in Figures 9, 10 and 11 respectively. The reduction in efficiency as output power increases is as a result of the percentage containability of the water jet in the wheel buckets. As the jet diameter increases, part of the jet circumference may no longer be contained at the central position, thus, getting over the bucket edges. Another possible cause is that as the jet fills the bucket inlet, there is little or no space again for the jet to travel the return trip, thus leading to a reduction in the impact of jet force, as the reaction force is countered with the party of incoming jet. In all, power increases with pressure head and nozzle diameter, but, efficiency against flow rate was limited to an average maximum value of 83.2 % as against a target of 85% mainly due to bucket geometry and containability of flow, thus, in line with the results of Buhyan et al., [2] of 85%, representing a deviation of 2.14%, and lesser than the result of Ma et al., [15] (96%), by 13.3%.

4. CONCLUSION

Modelling, simulation, and demonstration of the feasibility of harvesting Nigeria waterfall for hydropower power generation were conducted using a laboratory-scale Pelton turbine. In a laboratory setting, a return pump was used to continually supply water to reservoirs at higher elevations from which the water falls under gravity to take the place of real- life waterfalls. The results obtained from converting the potential energy of water at a higher elevation to kinetic energy used to run the turbine running the turbine, closely represent the characteristics of common waterfalls and Pelton wheel turbines. It particularly demonstrates that power increases with pressure heads and flow rates and that low-pressure-head waterfall can be harnessed using Pelton wheel which is believed by almost all researchers to be the cheapest method if the flow rate and bucket geometries are managed to improve efficiency. However, the major constraint perceived lies in harvesting the water flow to achieve predetermined efficiency, since most waterfalls are in hard-to-reach environments due to poor topography.

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