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ANALYSIS AND SIMULATION ON EFFECT OF HEAD AND BUCKET SPLITTER ANGLE ON THE POWER OUTPUT OF A PELTON TURBINE

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ABSTRACT

This paper presents the effect of head and bucket splitter angle on the power output of a pelton turbine (water turbine), to harmonize the gas turbine sector to enhance the power generation by the use of efficient Hydro-electric power generation systems. Analysis and simulation using experimental data were carried out on pelton turbine head conditions, high head and low flow with increased pressure delivered more energy on the bucket splitter which then generates a force in driving the wheel compared to the result obtained from low head and high flow operating conditions. A simulation program was developed using MatLab to simulate the force generated by the bucket as the water jet strikes the existing splitter angle (10^0 to 15^0) and predicted (1^0 to 25^0) splitter angles. Result shows that as volumetric flow rate was decreasing from 0.24m^3/s to 0.06m^3/s, as the volume of water decreases the pressure is increased. This increase in pressure influences the power delivered to the wheel by the jet of water. The jet of water causes the turbine speed to increase or decrease depending on the shape, size of bucket and the splitter which the jet strikes. The specific speed of the turbine increases and the shaft output also increases. It was equally noted that as the reservoir increases in elevation from 100m to 1000m, the hydraulic power in water fall (which is given a direction in a pipe line) increases the power delivered to the wheel from (4.4 to 5.05) x $10^{17} kW$.

Keywords: ***Bucket Splitter Angle, Head, Hybrid Power, Nozzle, Pelton Turbine, Power Output, Simulation***

1. INTRODUCTION

Hydraulic turbine can be defined as a rotary machine, which uses the potential and kinetic energy of water and converts it into useful mechanical energy. According to the way of energy transfer, there are two types of hydraulic turbines namely impulse turbines and reaction turbines. In impulse turbines water coming out of the nozzle at the end of the penstock is made to strike a series of buckets fitted on the periphery of the runner. The runner revolves freely in air and the casing is not important in impulse turbine. In a reaction turbine, water enters all around the periphery of runner and the runner remains full of water every time. The water leaves from the runner and is discharged into the tailrace with a different pressure. Therefore casing is necessary for reaction turbines [1]. Pelton turbine is an impulse turbine. The runner of the Pelton turbine consists of double hemispherical cups fitted on its periphery.

The jet strikes these cups (buckets) at the central dividing edge of the front edge. The central dividing edge is also known as splitter. The water jet strikes the edge of the splitter symmetrically and equally distributed into the two halves of hemispherical bucket. Theoretically, if the buckets are exactly hemispherical, it will deflect the jet through 180°. Then the velocity of the water jet leaving the bucket would be opposite in direction to the velocity of jet entering. Practically, this cannot be achieved because the jet leaving the bucket strikes the back of succeeding bucket and the overall efficiency would decrease. In practice, the angular deflection of the jet in the bucket is limited to about 165° amount of water discharges from the nozzle is regulated by a nozzle.

The Pelton turbine has been given increasing interest by the research community within multiple fields. This is due to the increasing demand for energy on a global basis in addition to the growing focus on meeting the increasing demand by

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utilizing renewable energy resources. An increase in efficiency in the order 0.1 % would lead to large increase in electrical power production. Innovation within energy business is kept a close corporate secret and all research done on a turbine designed by commercial companies is confidential. Thus the different research communities have no common practical case with which they can cooperate within their distinctive fields [2]. In the last decade a lot of papers about numerical and experimental analysis and design of Pelton turbines have been published. A water jet from Pelton turbine injector was analyzed experimentally and numerically by Barkinson [3]. The influence of jet velocity and jet quality on turbine efficiency was investigated by Vesely and Staubli [4, 5]. A bucket simulation using three adjacent buckets was shown by Mack and Moser [6]. Unsteady analysis of a Pelton runner with mechanical simulation was presented by Parkinson [7]. A numerical analysis of water flow in a two jets. Pelton turbine with horizontal axis was presented by Jost [8]. A modification in the bucket design of Pelton turbine is suggested by SurajYadav [9] to increase the efficiency of the Pelton turbine. The effect of runner to jet speed ratio on the Pelton turbine efficiency is tested experimentally by Bryan [10].

The aim of this paper is to investigate the effect of head and bucket splitter angle on power output of a pelton turbine through experimental analysis and simulation. To investigate through simulation using experiment data, the effect of head on the power output of a pelton turbine, and to develop a program that simulates the investigation and the force generated by the bucket as the water jet strikes the splitter. The analysis was presented by Matlab Simulink computer program.

2. HEAD ANALYSIS:

2.1. Determination of Head for Micro Hydro-Power Site

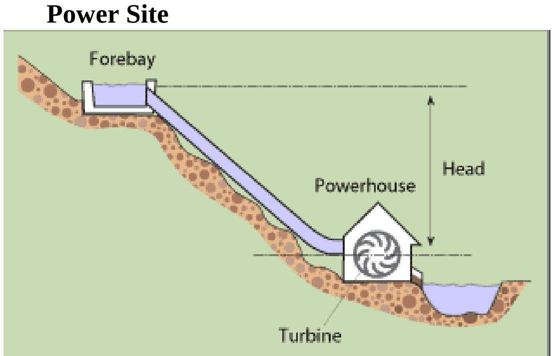

Fig.1. Pelton turbine head arrangement

In a potential micro hydropower site, head is the vertical distance of waterfall. When evaluating a potential site, head is usually measured in feet, meters, or units of pressure. Head also is a function of the characteristics of the channel or pipe through which it flows; you can use your site's head calculation along with its flow calculation to determine the site's potential power output.

Most micro hydropower sites are categorized as low or high head. The higher the head the better the output, less water is needed to produce a given amount of power and you can use smaller, less expensive equipments. Low head refers to a change in elevation of less than 3 meters (10 feet). A vertical drop of less than 0.6 meters (2 foot) will probably make a small-scale hydroelectric system unfeasible. However, for extremely small power generation amounts, a flowing stream with as little as 0.33 meters (13 inches) of water can support a submersible turbine. This type of turbine was originally used to power scientific instruments towed behind oil exploration ships [11]. When determining head, you need to consider both gross head and net head. Gross head is the vertical distance between the top of the penstock that conveys the water under pressure to the point where the water discharges from the turbine as shown in fig.1 and 2. Net head equals gross head minus losses due to friction and turbulence in the piping. The most accurate way to determine gross head is to have a professional survey the site according to Ben M. Koons, [11]. To get a rough estimate, you can use Geological Survey maps of your area or the hose – tube method.

2.2. Hose-tube method

The hose-tube method involves taking stream-depth measurements across the width of the stream you intend to use for your system – from the point at which you want to place the penstock to the point at which you want to place the turbine. You will need the following: An assistant, a 6–9 meters (20–30 foot) length of small-diameter garden hose or other flexible tubing, a funnel, a yardstick for measuring tape. Note: due to the water's force into the upstream end of the hose, water may continue to move through the hose after both ends of the hose are leveled. You may wish to subtract about 0.03 or 0.05 meter from each measurement to account for this. It is best to be conservative in these preliminary head measurement. If your preliminary estimates look favorable; you will want to acquire more accurate measurements. As stated already, the most accurate way to determine head is to have a professional survey your site.

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2.3. Condition for Head

Experiment on micro – hydropower plant site [12] have shown that the pelton turbine will give as high efficiency as any form of turbine under head as low as 3-6 meters(10-20 feet) but its construction does not admit of handling sufficient water to develop any considerable amount of power under low head within a reasonable limit of cost. It is not, therefore recommended for heads of less than 6 meters where a comparatively small amount of power is required. High head and low flow rate with increased pressure give desirable power output and could be employed when siting large scale MHPP while low head and high flow rate with decreased pressure give a lower power output and can be employed when siting a small MHPP.

2.4. Pressure Head for an Impulse Turbine System

Hydro power is obtained from the potential and kinetic energy of water flowing from a height. The energy contained in the water is converted into electricity by using a turbine coupled to a generator. The hydro power potential of a site is dependent on the discharge.

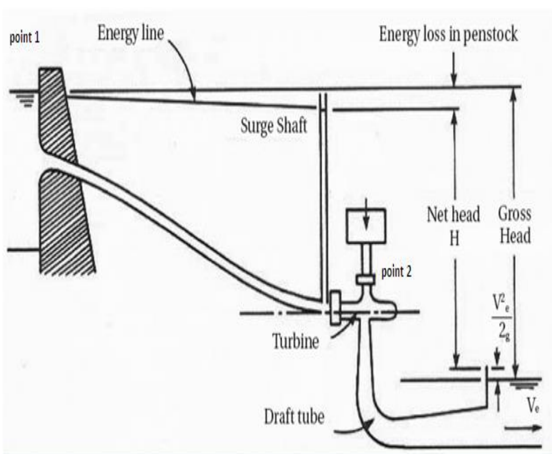

Fig.2. Components of MHPP unit

A hydro power resource can be measured according to the amount of available power or energy per unit time. The power of a given situation is a function of head and the rate of flow as shown in Fig.2. The energy in a MHPP starts out as potential energy by virtue of its height above the power house. Water under pressure in the penstock is able to do work when released, so there is energy associated with the pressure as well. The transformation of energy is from potential to pressure to kinetic energy. The power in the hydro power system strongly depends on the net head and the flow-rate of water. MMHP sites are characterized as high head or low head. The higher the head the better the power output because one would need less water to produce a given amount of power. This would mean that smaller and less expensive material could be used. A vertical drop of less than 0.6m will probably make a small hydroelectric system unfeasible. This means that head less than 0.6m would produce less power and it would not be economical.

Net head is the gross head minus the head losses that occur when water flows from the intake to the turbines through canals and penstock. Water loses energy (head loss) as it flows through a pipe, fundamentally due to:

- **Friction against the wall**

The friction against the pipe wall depends on the wall material roughness and the velocity gradient. The friction in the pipe walls can be reduced by increasing the pipe diameter. However, increasing the diameter increases the cost, so a compromise should be reached between the cost and diameter.

- **Flow turbulence**

Water flowing through a pipe system with bends, sudden contractions and enlargement of pipes, racks, valves and other accessories experiences in addition to the friction loss, a loss due to inner viscosity. This loss depends on the velocity and is expressed by an experimental K multiplied with the kinetic energy. Water flow in a pipe bend experiences an increase of pressure along the outer wall and a decrease of pressure along the inner wall. This pressure imbalance causes a secondary current. Both move together (the longitudinal flow and the secondary current), produce a spiral flow at a length of around 100meters and is dissipated by viscous friction. The head loss produced depends on the radius of the bend and the diameter of the pipe. The loss of head produced by water flowing through an open valve depends on the type of the valve.

Note: H which is the head can be gotten using Bernoulli's equation to analyze the fluid flow from point 1 to point 2 as in fig.2. Kelly. J.R [13] used the Euler's equation to obtain Bernoulli's equation by integrating along a streamline for steady, incompressible, frictionless flow which gives to Eq.1.

$$H = \frac{p}{\rho g} + \frac{v^2}{2} + z \qquad (1)$$

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Where; $\frac{p}{\rho g}$ = the head due to local static pressure, $\frac{v^2}{2}$ = the head due to local dynamic pressure, Z = the elevation head, H = the head for the flow.

From Eq.1; H = $\frac{p_r}{\rho g} + \frac{v_r{}^2}{2} + z_1 = \frac{p_n}{\rho g} + \frac{v_n{}^2}{2} + z_n$ (2a)

At the surface of the river bed, the fluid moves very slowly compared to the flow along the pipe. We say that u_r = 0, Also the pressure is atmospheric pressure, $p_r = p_n = p_{atomspheric}$. $Z_r - Z_n$ is the elevation of the river bed and the turbine.

$$Z_r = \frac{v_n{}^2}{2} + Z_n \quad (2b)$$

$$Z_r - Z_n - H_f = \frac{v_n{}^2}{2} \quad (3)$$

2.5. Turbine Power Output

Kinetic momentum theorem: Using conservation of momentum to analyze the system, Newton's second law of motion can be applied to rotational as well as linear systems, and thus "torque is equal to the rate of change of angular momentum and is expressed as: T = $\frac{dl}{dt}$ (4)

Where T is the torque, l is the angular momentum and t is the time. In linear motion, force is equal to the rate of change of momentum in the system. Angular momentum is given by the moment of momentum: L = ṁV_wr (5)

Where ṁ represents the flow rate, L is the angular momentum or angular momentum flow rate and $V_w$is the whirl velocity of the system, so at entry to the turbo machinery passage the angular momentum is ṁV_{W1}r and at exit the angular momentum is ṁV_{W2}r. So the change in angular momentum between entry and exit is: From Newton's second law applied to angular motion.

Torque = rate of change of angular momentum, Angular momentum entering the bucket per second = ṁV_{w1}r, Angular momentum leaving the bucket per second = ṁV_{w2}r.

Rate of change of angular momentum = ṁV_{w1}r - ṁV_{w2}r. (6)

ṁV_{w1}r - ṁVr = ṁr($V_{w1} - V_{w2}$) (7)

The time rate of angular momentum is equal to the torque we have; T = ṁr (V_{w1}-V_{w2}) (8)

Recall from basic mechanics that power is torque times rotational speed;

P = Tω = ṁrU/r (V_{w1}-V_{w2}) = ṁU (V_{w1}-V_{w2}) (9)

Thus; E = U (v_{w1}-v_{w2})/g (10)

This equation is known as Euler's Equation. This is also called Euler's Head which can also be determined from the elevation of pelton wheel from river bed.

From velocity diagram; $V_{w1} = V_1$

V_{w2} = U – V_{r2}cos (180 - β_2) = U + V_{r2} cosβ_2 (11)

K = V_{r2}/V_{r1} (12)

Where; K represents the reduction of the relative velocity due to friction, V_{r2}= KV_{r1} =K (V_1 - U).

E = U/g [V_1 – U – K (V_1 - U)Cosβ_2] = U/g (V_1 - U)(1 - KCosβ_2) (13)

Therefore the total power output from the flowing fluid delivered to the pelton wheel is given as: P = ṁgE = ρQgE (14)

Where; P is the power delivered to the wheel by the jet, Q is the volumetric flow rate through the nozzle, G is the gravitational acceleration, E is the energy the fluid delivers to the wheel. For maximum power output ρ,Q,g are constant. E is varying. Maximum power output will occur at some intermediate value of the vane velocity. This may be obtained by differentiation as follows: $\frac{dE}{dU}$ = 0, [(1 - Kcosβ_2)/g](V_1 - 2U) = 0.

Hence, V_1 - 2U = 0, U = 1/2V_1 and E_{max} = $V_1/2g(V_1 - \frac{1}{2V_1})(1 - kcos\beta_2)$.

Therefore; $P_{max} = \rho Q g \frac{V^2{}_1}{4g}$ (1 - kcosβ_2) (15)

The Energy arriving at the wheel is in the form of kinetic energy of the water jet and is given by 1/2$\rho Q V_1{}^2$.

The Efficiency of the wheel[14]; η_w (Max) = $\frac{\rho Q V_1{}^2(1-kcos\beta_2)}{4(\frac{1}{2\rho Q V_1{}^2})}$ = 1 - kcosβ_2/2.

η_w = Is the efficiency of the wheel, K = is the velocity coefficient, β_2 = the exit angle. The splitter angle is given as β_1 = (180 - β_2)

Considering the speed of turbine [15]; $V_{turbine}$(Ft/s) = $\omega_{turbine}$(rad/s) x $\frac{d_{turbine}}{2}$ (ft) (17)

In metric form; 0.5 X V_{jet} (m/s) = 5.235 x 10^{-5}x $\omega_{turbine}$(rpm) x $d_{turbine}$(mm) (18)

$$\omega_{turbine} = 0.5 \times 1.91 \times 10^4 \times \frac{V_1(\frac{m}{s})}{d_{turbine}(\mathrm{mm})} \quad (19)$$

2.6. Force generated by the Bucket

Flow forces and energy conversion: The energy conversion in pelton turbines takes place through the jet of water onto the rotating bucket, to show the principle of this type of energy conversion the impact of the jet onto the moving bucket is assumed to take place in a straight line. The constant jet and bucket velocities are V_1 and U respectively.

In reality the interaction between the jet and the bucket is considered in the system of the moving bucket and is expressed as: $V_{r1} = V_1 - U$. Because the bucket moves in a straight line, this relative velocity remains constant through the flow period within the bucket ($V_{r1} = V_{r2} = V_1$), if the friction is neglected. The interaction force between the jet and the bucket is considered in the U- direction and is calculated according to the momentum law which is expressed as.

Force applied by the bucket to the water stream as Eq.20 [16]: $F_b = \dot{m}\,(V_{r2}\cos\beta_1 - V_{r1})$ (20)

Assuming $V_{r2} = V_{r1}$, (elastic collision in bucket); $F = \dot{m}\,(V_{r2}\cos\beta_1 - V_{r1}) = \dot{m}\,V_{r1}(\cos\beta_1 - 1)$[14]. Where; $\beta_1 = 180 - \beta_2$.

Force of water on bucket is equal and opposite: $F_{bucket} = \dot{m}\,V_{r1}(1 - \cos\beta_1)$ (21)

Substituting (V_{r1}) into Eq.21 to get Eq.22 which is the force generated by the bucket as a result of the splitterβ_1; $F_{bucket} = \dot{m}\,(V_1 - U)\,(1 - \cos\beta_1)$ (22)

Where; F_{bucket} =is the force generated by the bucket (N), $\dot{m}$ = is the mass flow rate (kg/s), V_1 = is the velocity of the fluid jet before striking the bucket (m/s), U = is the velocity of the bucket (m/s), β_1= is the splitter angle and is always given or express as $\beta_1 = (180 - \beta_2)$ (°).

For a turbine with a single nozzle, the optimal: d_{JET}= 0.11 X PCD (23)

This constrains the pitch circle diameter (PCD). The PCD is the diameter of the runner which is measured from where the center of the jet hits the bucket as[11]: PCD = $\sqrt[3]{\frac{4.Q}{0.0121\pi\omega}}$ (24)

to have a jet as large as 20% of the PCD. All other dimensions relate to the pitch diameter (PCD) or jet diameter (d). For manufactured turbines, this has been optimized over decades of design and there is very little variation among different manufacturers.

2.7. Determination of Nozzle Velocity: V_n

The velocity v_r is the velocity of fluid particle at the water source surface fig.2. The velocity v_n is the velocity of the water jet at the nozzle. The pressure head at point 1 and 2 is equal to zero.

From Eq.3, $Z_r - Z_n - H_f = \frac{v_n{}^2}{2}$; V_n (M/s) = $\sqrt{2\,x\,g\,(Z_r(m) - Z_n(m) - H_f}$[21] (25)

Where; $V_n$is the same as V_1, H_f is equal to f L/$D_{pipe} x \frac{Vn^2}{2g}$. Therefore the flow rate entering the turbine from the nozzle is expressed as Q = AV.

$$Q = V \text{ x } A = V \text{ x } \frac{\pi d^2}{4} \quad (26)$$

$$V\ (m/s) = \frac{21.22\ x\ Q(l/min)}{d^2(mm^2)}\ [13] \quad (27)$$

The flow rate entering the turbine is influenced by the static head, pipe diameter and nozzle diameter; increase in any of these values or decrease will definitely affect the flow rate.

2.8. Developed Power

Power delivered by flowing fluid to the turbine is given in Eq.14 as P = ρgQH. Where H is the available head and Q is the flow rate from the nozzle. If we know the velocity, the power can be expressed as ½ $\rho V_1{}^2$Q where ρ is the water density and $V_1$is the water jet velocity. Either one of these expressions gives a theoretical power available from water jet.

The pelton turbine is designed to produce maximum power when the peripheral speed is ½ of the water jet speed. The power transmitted to the turbine wheel is 0.5γHQ or 0.5 ρgQH.The 50 % is theoretical and is based on the fact that water jet is reversed due to the wheel cup design180degree backward towards its source.The reversed water jet is not exactly in line so that the wheel itself has a real world efficiency of 90 % or better.

Power at the turbine wheel:
Power = 0.9 x 0.5 ρgQH (28)

Power (kW) = 0.9 x 0.5 x 1000 $(\frac{kg}{m^3})$ x 9.81$(\frac{m}{s^2})$ x Q $(\frac{L}{min})$ x $(\frac{m^3}{1000L})$ x $(\frac{min}{60s})$ x H (m)$\left[(\frac{watt}{\frac{kg-m^2}{s^3}})\right]$ x $(\frac{kW}{1000watt})$. Which simplifies to: P (kW) = 0.9 x 0.5 x 1.635 x 10^4 x H (m) x Q (l/m). If we use the formula that has the nozzle velocity then we get

$$P = 0.9 \text{ x } 0.5 \text{ x } ½ \text{ x } \rho \text{ x } q \text{ x } 1/g_c \text{ x } V_1{}^2 \quad (29)$$

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3. SIMULATION

This simulation result using prediction along with experimental data to show the implementation of the developed model which is used in predicting the power output of a pelton turbine in this study is presented. The simulation is performed for two cases: The first simulation is performed to compare the result of the pelton head conditions developed through equations to predict the power output of a pelton turbine. The result in this study was obtained on a model pelton turbine in the laboratory. The second simulation is performed to investigate the force generated when the jet of water strikes the bucket splitter.

3.1. Basic Equations

The equations used in predicting power output in this study are derived and the bucket was modeled using AutoCAD to design the shape and using velocity triangle to link with Euler's equation for turbo machinery to derive an equation to determine power delivered to the wheel, turbine speed, shaft power output, the power delivered to the generator and the force generated by the bucket. Subsequently an equation was derived using Bernoulli's equation to link the flow from the river bed to the nozzle which then generates a force to deflect the wheel backward. The equations used for writing this simulation are as stated below and the program language used is c++, on Numerical simulation of free jet in pelton wheel.

4. RESULTS AND DISCUSSION

The following graphs were obtained through the simulation.

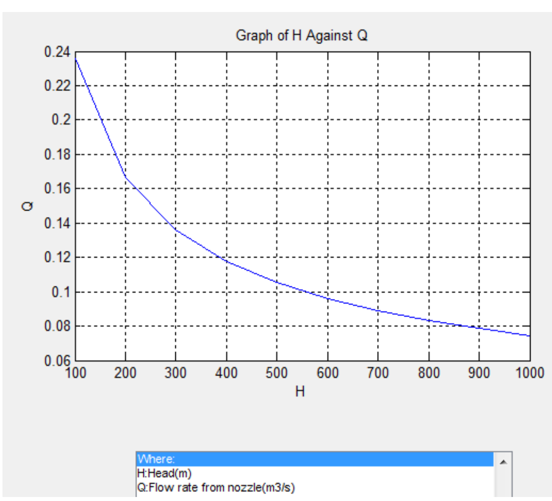

Fig.3. Graph of head Vs flow rate from nozzle

From the graph of head against flow rate from the nozzle, as the head increases from 100m to 1000m. The volumetric flow rate was decreasing from $0.24m^3/s$ to $0.06m^3/s$, as the volume of water decreases the pressure is increased. This increase in pressure influences the power delivered to the wheel by the jet of water.

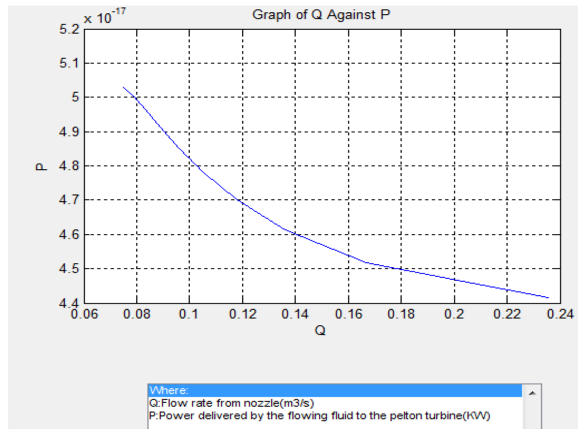

Fig.4. Graph of volume flow rate Vs power on the wheel

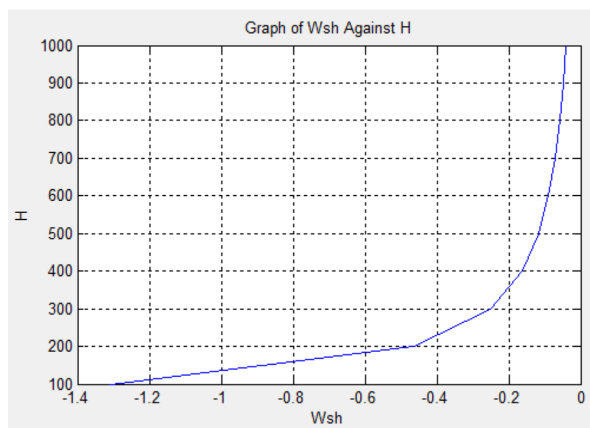

Fig.5. Graph of shaft power output Vs head.

From figs.4 and 5; As the jet of water from the nozzle strikes the bucket, it causes the wheel to deflect. Energy is delivered to the wheel by the flow rate through the nozzle. As the flow decreases with increased elevation, the power delivered to the wheel is increased, while the shaft power output reduces with positive value and increases with negative value as the elevation increases from 100m to 1000m.When the absolute velocity of the fluid exiting the turbine is zero the shaft power become maximum and the velocity of the jet is greater than that of the wheel so the value of the shaft power output becomes negative as the head increases.

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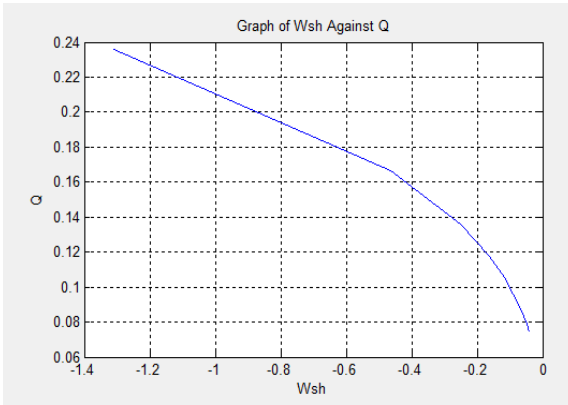

Fig.6. Graph of volumetric flow Vs shaft power output

From fig.6: The flow rate through the nozzle decreases from 0.24m^3/s to 0.06m^3/s with increased head, this decrease in the flow rate increases the negative shaft work. The power output from the shaft will increase toward the negative graph showing work was actually done on the system.

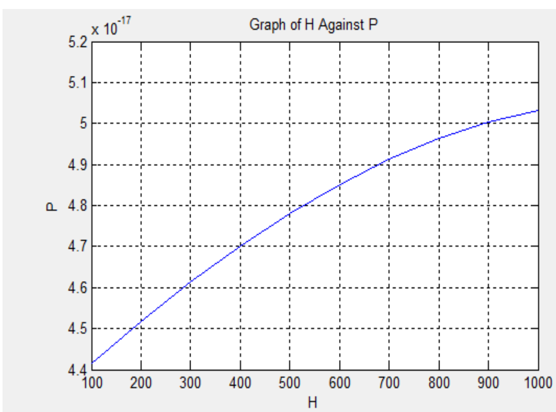

Fig.7. Graph of turbine specific speed Vs shaft work

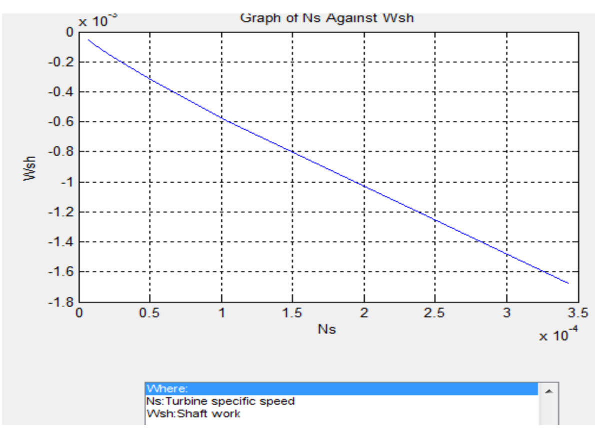

Fig.8. Graph Head Vs power to generator.

From figs.7 and 8; the jet of water causes the turbine speed to increase or decrease depending on the shape, size of bucket and the splitter which the jet strikes. As the specific speed of the turbine increases the shaft output also increases. As the reservoir increases in elevation from 100m to 1000m, the hydraulic power in water fall which is given a direction in a pipe line increases the power delivered to the wheel from 4.4 to 5.05 x $10^{17}kW$.

5. CONCLUSION

The research work investigated through simulation and experimental data, the effect of head and bucket splitter angle on power output of a pelton turbine, and developed a program that simulates the investigation and the force generated by the bucket as the water jet strikes the splitter. The analysis was presented by Matlab Simulink computer program. The following conclusions were reached based on the study: The pelton turbine operating on high head and low flow with increased pressure condition generated a power output which could be applied in siting a large hydro power plant while that of the low head and high flow with decreased pressure generated a lesser output and could be applied in siting a small MHPP.

The operating condition for the pelton turbine in the laboratory was low head and high flow with decreased pressure. As the jet of water from the nozzle strikes the bucket, it causes the wheel to deflect. Energy is been delivered to the wheel by the flow rate through the nozzle. As the flow decreases with increased elevation, the power delivered to the wheel increased. When absolute velocity of the fluid exiting the turbine is zero the shaft power becomes maximum and the velocity of the jet is greater than that of the wheel so the value of the shaft power output becomes negative as the head increases. The jet of water causes the turbine speed to increase or decrease depending on the shape, size of bucket and the splitter which the jet strikes. As the specific speed of the turbine increases the shaft output also increases. This increase in pressure influences the power delivered to the wheel by the jet of water.

The flow rate through the nozzle decreases from 0.24m^3/s to 0.06m^3/s with increased head, this decrease in the flow rate increases the negative shaft work. The power output from the shaft will increase showing work was actually done on the system. High head and low flow are recommended for power generation of a large MHPP which could help attain the level of power supply instead of low

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head and high flow which is applicable for power generation of a small MHPP. Finally further research on the effect of pelton bucket splitter angle on the bending stress on bucket is recommended.

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