AN EXPERIMENTAL PROTOTYPE FOR LOW HEAD SMALL HYDRO POWER GENERATION USING HYDRAM

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Abstract
The global rise in energy demand has resulted to the over exploitation of both renewable and non renewable energy sources. Most feasible hydroelectric power (HEP) plants sites have been exploited and the current focus is on harnessing energy from small HEP plants which have low head and flow velocity rendering them unsuitable for HEP generation. Previous research work focused on improving the turbine shape and efficiency; designing better water intake, improving the generator and development of turbines suitable for low heads. The main aim of this research was to optimize the power generated by low head small hydro plants through the use of hydraulic ram pump (hydram) to boost the water pressure before it impinges on the turbine. In the current work, a small HEP prototype system was designed fabricated and test runs conducted. The prototype comprised of; a low head water reservoir, a hydraulic ram pump which was used to increase the head of the water emanating from a low head source, a high head reservoir mounted at a the most optimal height based on the hydram flow rate and pressure considerations and a double cup pelton wheel turbine suitably designed to extract power from the water jet. A drive pipe was used to connect the hydram pump to the low head reservoir while the delivery pipe connected the pump to the high head reservoir. Water from the high head reservoir was used to turn the pelton turbine which was coupled to a generator. The flow rate in the drive pipe and the delivery pipe as well as the pressure in the hydram were optimized by adjusting the waste valve stroke length. It was observed that the hydram was able to pump water to a higher head which then increased the power produced by the turbine.

Key words: Hydroelectric power, renewable energy, hydraulic ram pump

1 Introduction

Hydroelectric power (HEP) accounts for 97.9% of the total world renewable energy [1]. Currently, most of the sites for large HEP plants have been exploited. The shift is towards the small HEP plants. Harnessing power from Pico and Micro HEP sites still remains a major challenge due to low heads and flow rates. Adequate HEP sites should have a head of at least 2 meters for significant amount of power to be generated and nearly all available sites have been exploited. Run off river plants; on the other hand, require long pipes and extensive planning for an artificial head to be created.

Previous research work on optimizing the power developed by small hydro plants has focused on improving the turbine shape and efficiency; designing better water intake and penstock, improving the generator and development of turbines suitable for low heads such as the hydrokinetic turbines. However, improving the turbine and system efficiency does not solve the problem of harnessing electrical energy at low velocity rivers. There is, therefore, the need to develop methods that can be used to increase the water pressure and head so as to maximize and optimize the power generated. The main objective of this research work was to develop a prototype system that uses a hydram pump to increase the water head and pressure before it impinges on the turbine. This would optimize and maximize the power developed by a small hydro power plant. The inherent advantages of such as system would be; the ability to generate energy at any point on the stream or river, increased HEP power production, low construction costs, negligible negative impacts, reduced installation and maintenance costs, requires less feasibility studies, reduced planning costs, can tap energy at low velocity streams and the system will be affordable and scalable to Pico and Micro hydro power systems.

1.1 HEP Generation

HEP is harnessed from flowing water. Water at inlet and outlet has different heads/height and this creates the pressure difference which in turn rotates the turbine. The turbine is then coupled to the generator via a rigid coupling or through gears. The power from the turbine is given by;

$$P = \rho g Q h_{av} \tag{1.1}$$

Where (h_{av}) is the difference between the upper reservoir level (Z_{res}) and the tailrace level (Z_{tw}) and is defined as the available head, P is the available power, ρ is the density of water in kg/ m^3, Q is the flow rate in m^3 /s.

1.2 Hydraulic Ram Pump (hydrams)

Hydraulic ram pump is an automatic pump that uses the energy of flowing water to pump water to a height above the source. The pump requires no external power source. The pump has two moving parts; the impulse valve and the delivery valve [2]. The pump is comparatively cheap, reliable and can be used to raise water to considerable height. Figure 1 in the appendices shows this pump. Its basic parts are; the Hydram body, impetus / waste valve, snifter valve, delivery valve, air chamber and relief valve. The pump operation can be divided into four main cycles. These depend on the position of the waste valve and the delivery valve and the average time –velocity variation.

1.2.1 Acceleration Stage

At this stage, the waste valve is open due to the force of gravity or due to the tension of the spring. Water flows from the river/source to the waste valve via the drive pipe. There is an acceleration effect due to the supply head (h_s) till the fluid attains a velocity (V_0). As the acceleration increases, the hydraulic pressure under the impulse valve, the drag force and the static pressure in the hydram body increases. These forces initiate the valve closure, this happens when the drag force is high enough to lift the waste valve to cause sudden closure [3].

1.2.2 Impulse Valve Closure

Due to the lifting force, the waste/impulse valve slams shut. The closure should be instantaneous and rapid.

1.2.3 Delivery

As the waste valve slums shut, it remains shut. The water flowing in the drive pipe has to lose its momentum suddenly. This sudden loss in momentum causes a large surge pressure referred to as the water hammer. As the pressure rises higher than that of the air chamber, water is forced into the non return delivery valve. The entry of water compresses the air in the air chamber while some water is forced to the delivery pipe. The delivery valve remains open until the pressure in the hydram body falls below the air chamber pressure [3].

1.2.4 Recoil

After the delivery valve shuts, the remaining water in the drive pipe and the hydram body recoils. This causes a sudden pressure drop that is low enough to open the waste/ impulse valve. The recoil also sucks some air through the snifter valve. This air sits on the bottom of the delivery valve and is pumped into the air chamber during the next cycle. This ensures that the air chamber has air all the time to cushion the pressure force [4].

2 Materials and Methods

A prototype small HEP system was designed and fabricated. Experiments were then carried out to determine performance of a prototype small HEP plant with and without water hydram pump.

2.1 Design and Fabrication of Components

2.1.1 Design and Fabrication of the Hydraulic Ram System

The hydraulic ram pumps were designed based on the head and flow rate conditions, the main parameters evaluated during the design of this pump were; the drive pipe length (L), Cross-sectional area of the drive pipe (A), drive pipe diameter (d) and thickness(t), supply head (H), delivery head (h), friction head loss in the drive pipe, friction head loss through the waste valve, friction head loss at the delivery valve, the velocity in the drive pipe when the waste valve begins to close, the steady flow velocity (VS) through the waste valve when fully open, valve weight, valve stroke, valve opening orifice area, valve cross sectional area and size of the air chamber. After design, the hydram was fabricated.

2.1.2 Design and Fabrication of the Turbine

A pelton wheel turbine was designed. The pelton wheel was selected because of its ability to; operate at varying flow rates, operate at varying heads, no need for an outside casing, ease of fabrication and assembled, less costly, ease of adjustments, Ability to deliver power even at very low flow rates and easy maintenance. One of the design constrains was the need for high pressure for it to operate. This was archived through the use of a small nozzle at the outlet. The turbine unit was then fabricated.

2.1.3 Generator Selection

A permanent magnet DC generator with variable speed was used. This generator responded to voltage and flow rate changes as these factors affected the speed of the turbine rotation and subsequently, the power generated.

2.1.4 Data Logger Programming

The data a logger was programmed to measure voltage, current and then compute the power generated. The data was collected at intervals of 15 seconds. Also recorded was the ambient temperature.

2.1.5 Design of the Support Structure

The design of the reservoir support system was done. This structure was made such that, it was possible to adjust the height of the water reservoir that acted as the dam during the experimentation. The material properties and load imposed on them were taken to consideration during the design of the structure.

2.2 Prototype Testing

Various tests were performed to attest the workability, efficiency and the performance of the developed system. The testing procedures are outlined below;

2.3 Prototype Tests with Hydram Pump

The prototype system was tested with the hydram pump as a water pressure and head boosting device. In this experimental setup, the hydram pump was used to increase the head of water before it impinged on the prototype's turbine. The voltage, current and power developed was determined and recorded for various flow rates and heads using a data logger. The experimental setup for the prototype with a hydram pump is shown in the figure 3 below.

The main materials used are;

1) The 1500 liter change over tank
2) 1500 liter reservoir tank
3) 1500 liter elevated tank
4) Hydram pump
5) Assembled HEP prototype
6) A booster pump for change over
7) Tape measure
8) Flow meter
9) Manometer Pressure gauge
10) Data logger
11) Stop watch

2.4 Experimental Procedure

The equipments were set up as shown in the figure (3) below:

1. The low head water tank (LHWT) initial height was 1.68m, the high head water tank (HHWT) was placed at a height of (5.66m), the penstock run from the HHWT to the turbine as shown in figure (1), the turbine and generator were connected via a rigid coupling.
2. The booster pump was then switched ON so as to pump water from the storage tank (ST) to the LHWT. This ensured that the LHWT remained full and thus, the data collected was based on a constant head which resembles water flow in rivers. Three pipes supplying water to the LHWT were also opened; this was to ensure that the water level in the water tank remained constant.
3. The tap from the LHWT was opened fully so that water accelerated through the drive pipe to the hydram. The hydram pump was then started by pressing and releasing the waste valve shaft several times till the waste valve oscillated automatically. This was achieved after the pump air chamber had acquired enough pressure to pump water and also cause the delivery valve to close.
4. When the hydram started pumping, the HHWT was opened so that water would run from the HHWT to the turbine unit. The system was optimized such that the flow rate at the delivery pipe and the water flowing to the turbine system equalized.
5. The water accelerating turned the turbine which then rotated the generator unit thus generating electrical energy
6. Once the turbine started running, the data logger was switched ON and the MONITOR button as well as the SCAN button activated. Once these two were activated, the data logger would record voltage generated after every 15 seconds. This data was stored in a floppy diskette. The system was allowed to run for 15 minutes.

7. After 15 minutes, the tap at the penstock was adjusted by rotating it through 180^0 so as to reduce the water flowing in the drive pipe to the hydram. Once this was done, the voltage generated was recorded for 15 minutes.
8. Step (7) was repeated six times. Each of these times, the flow through the drive pipe was varied and the voltage and power generated recorded. The variation in flow was done by adjusting the tap so as to achieve the following flow rates; $3.33 \times 10^{-4}\ m^3/sec$, $3.125 \times 10^{-4}\ m^3/sec$, $2.63 \times 10^{-4}\ m^3/sec$, $2.38 \times 10^{-4}\ m^3/sec$, $1.85 \times 10^{-4}\ m^3/sec$, $1.68 \times 10^{-4}\ m^3/sec$ and $1.00 \times 10^{-4}\ m^3/sec$.
9. After testing the power and voltage generated for seven different flow rates, the booster pump was switched OFF and its pipe reversed so that water would flow from the LHWT to the storage tank. The pump was then switched ON so as to pump water from the LHWT (empty the low head water tank) to the storage tank. When the storage tank was full, the booster pump was switched OFF and the remaining water in the LHWT tank drained.
10. The LHWT was then removed from the adjustable stand. The fastening bolts holding the tank stand were unscrewed and adjustable table lowered by 100mm. The bolts were then re-screwed. This process reduced the tank head by 100mm(0.1m)
11. The LHWT was then reinstalled back onto the adjustable stand. This time its head had reduced by 100mm or (0.1m)
12. The booster pump pipes were connected so as to pump water from the storage tank (ST) to the LHWT. Three pipes bringing water from the taps within the workshop area were also connected to refill the tank.
13. Once full, steps 2 to 13 were repeated. This was done for the heads 1.68, 1.58, 1.48, 1.38, 1.28, 1.18, 1.08, 0.98, 0.88, 0.78, 0.68, 0.58, 0.48, 0.38 and 0.28.
14. A total of 15 different height were varied, for every head there were 7 different flow rates, the total number of experiments was (15×7 = 105 experiments).
15.

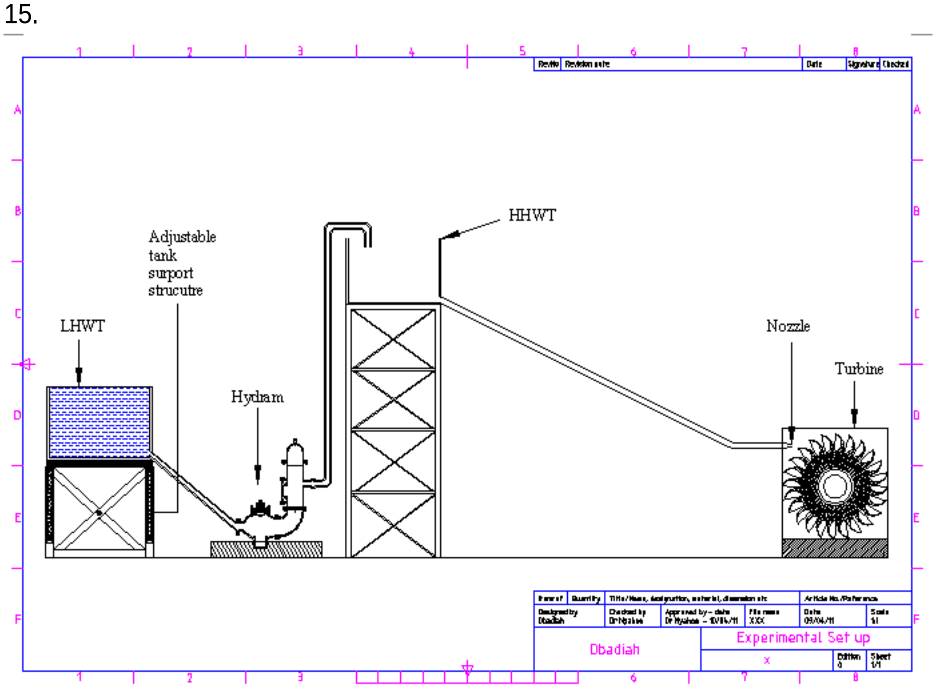

Figure 3: The experimental setup of the small HEP using the hydram

2.5 Prototype Tests with no Hydram

Tests were carried out on the prototype system without using the hydram pump. The voltage current and power developed at different heights and flow rate was recorded using a data logger. The same procedure as that described in section 3.3.1 was followed but in this case, the drive pipe from the main tank was connected to the turbine directly and the HHWT was not used. This is shown in Figure 4.

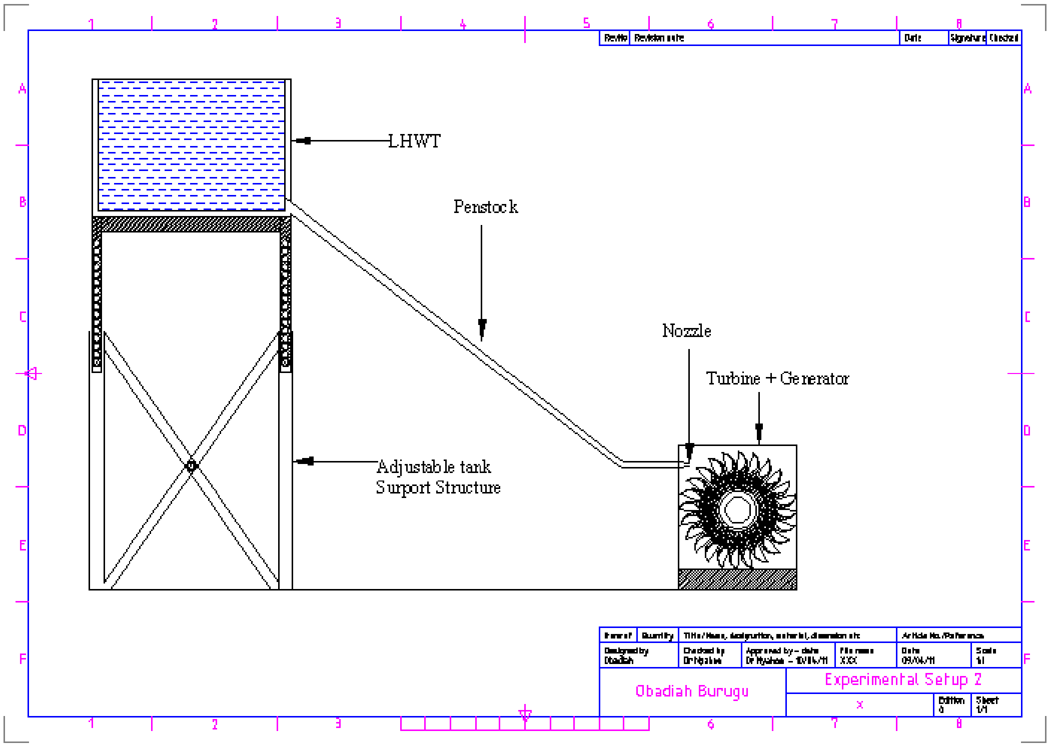

Figure 4: experimental set up of the prototype without the hydram pump

2.6 Comparative Analysis

The voltage, current and power developed by the experimental prototype when using the hydram and when not using the hydram was compared.

3 Results and Discussions

3.1 Output Characteristics of the Prototype with the Hydram Pump Booster

From the results obtained, it was found out that, changes in flow rates and head affected the generator terminal voltage as well as the power generated.

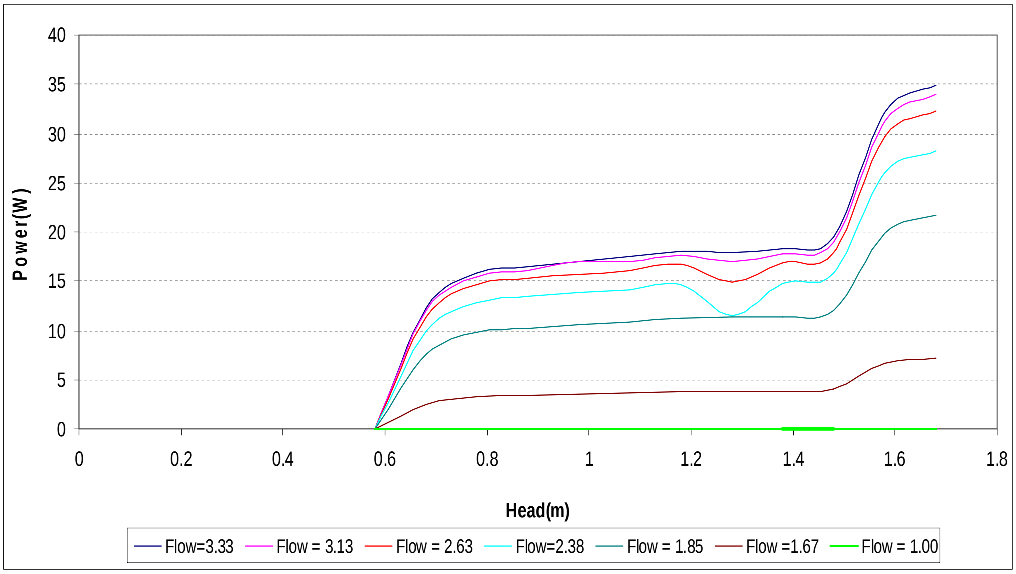

Figure 5: Changes in power generated due to change in flow rate and head

From Figure 5, it can be seen that, at very low head (0.38m to 0.78m) the power produced is directly affected by the head. The voltage then stabilizes and there is no further increase in voltage. Further increase in voltage generated occurs only at very high heads. This stabilization can be attributed to the fact that small changes affect the time it takes for the hydram waste valve to close but does not affect amount of water delivered at the delivery pipe. Generally, it can be seen that the hydram pump used could not operate at heads below 0.68m. From the literature study, the minimum head for the hydram pump is 0.5 meters. This effectively means that the hydram can be used in HEP systems with a head as low as 0.5 meters.

3.2 Output characteristics of the prototype without the use of the hydram pump

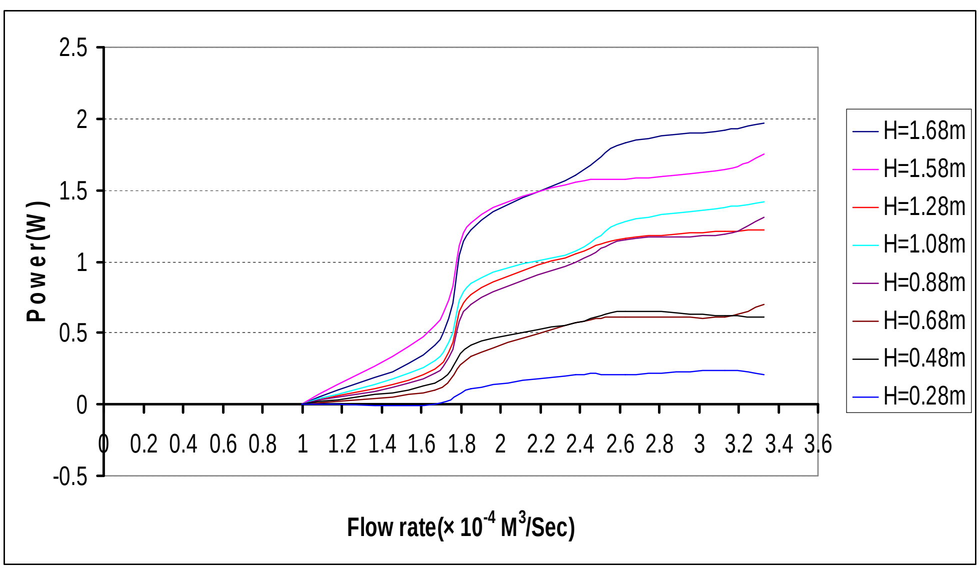

Figure 6: Changes in power generated due to change in flow rate and head (without hydram pump)

From Figure 6, it was observed that, the power generated by the prototype system without any mechanism to boost the water head pressure was generally low. The power varied with changes in flow rate and head. As the flow rate was increased from 1.00 $\times 10^{-4}$ m^3/sec to 1.85 $\times 10^{-4}$ m^3/sec, the voltage generated by the prototype system also increased. A point was reached where; further increases in the flow rate caused a slight increase in the voltage generated. Generally, increase in flow rate in a HEP system results to an increase in power generated as more water is available to propel the turbine. Hence, the results obtained were in line with convectional HEP systems. Also, as flow rate was further increased, the output power remained constant or slightly increased due to penstock constrains such as pipe friction, pipe radius, size of reservoir, the head as well as the pressure exerted by water for a given pipe radius.

3.3 Comparative Analysis

It was observed that, the power generated by the prototype system with the hydram was higher than that generated when the prototype was operated without the use of the hydram system. The power obtained when using the hydram system was approximately (15) times more than when the hydram was not used. The generator output voltage also increased 5 times when the hydram pump was used.

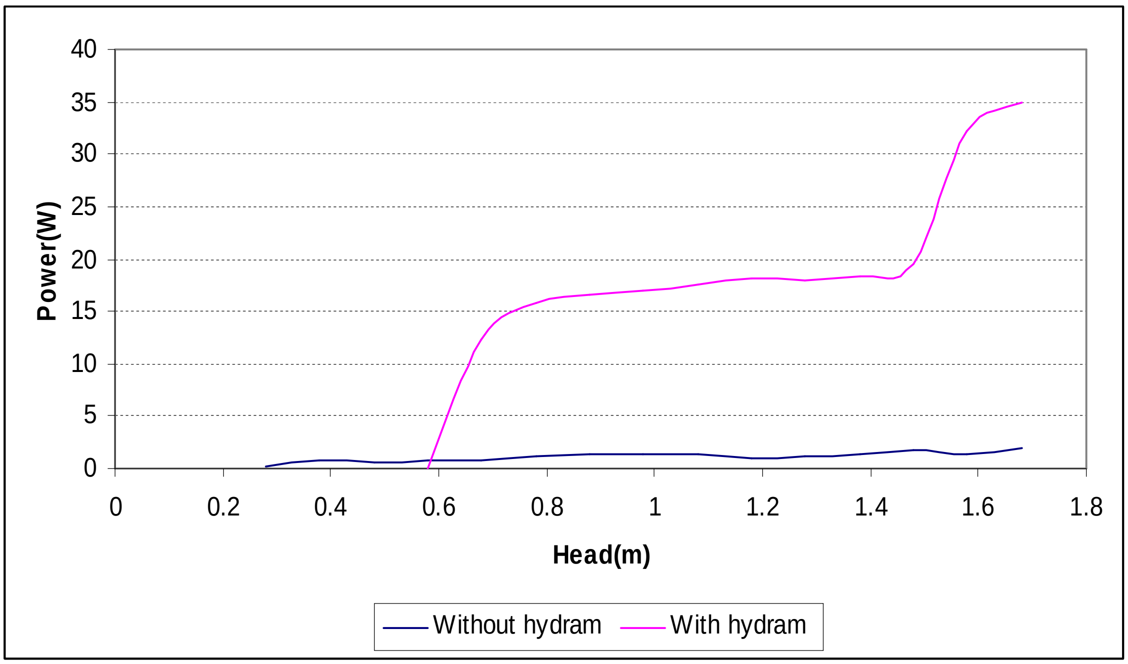

Figure 7: Comparison between the voltage generated by the prototype HEP system with and without hydram at Flow rate = 3.33 and different heads

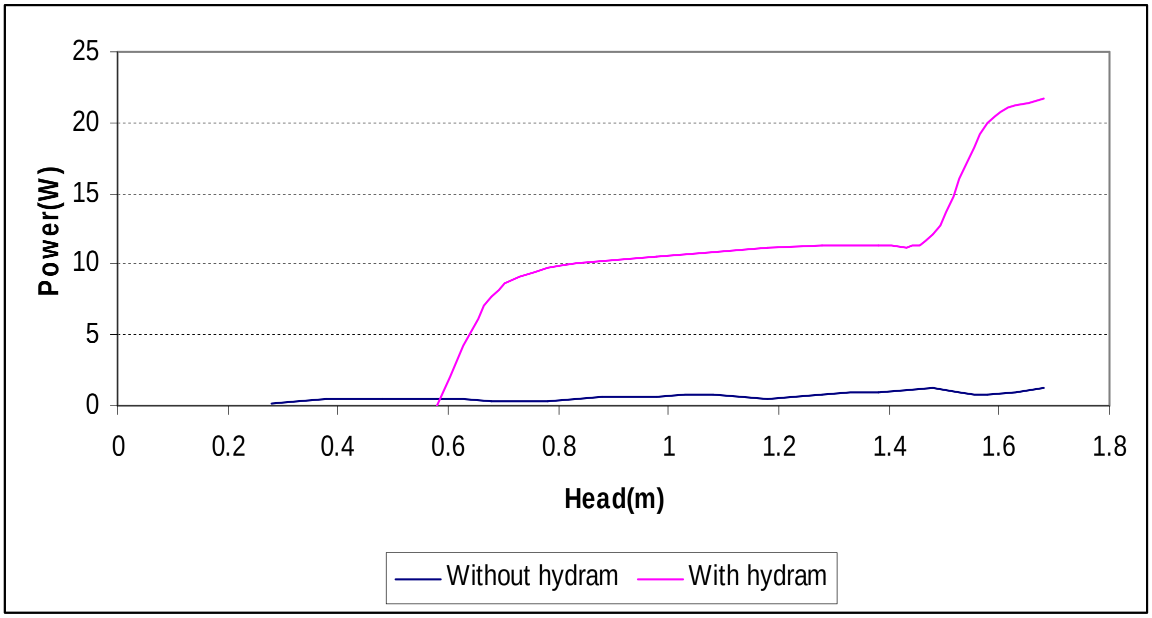

Figure 8: Comparison between the voltage generated by the prototype HEP system with and without hydram at Flow rate = 1.85 and different heads

4 Conclusions

Based on the results obtained, it can be concluded that hydram was able to operate at heads as low as 0.68m. This was done by redesigning of the waste valve and optimizing the waste valve return spring so as to archive high pumping efficiencies even at very low heads. The voltage generated by the prototype system when using the hydram pump was approximately 5 times greater than when the prototype was operated without the use of the hydram. The power generated by the prototype system when using the hydram pump was approximately 15 times greater than when the prototype was operated without the use of the hydram. The biggest disadvantage was that a lot of water was wasted in the waste valve.

5 Recommendations

Through the experiments carried out, it was demonstrated that the use of the hydram pump to boost the water head pressure in small hydro can be used to effectively harness electricity from low head rivers and streams. I would therefore recommend the use of hydram pumps to boost the power harnessed from low head rivers with high flow rates.

Based on the literature review, most of the rivers have small heads ranging from 1.5 meter to 0.2 meters. These sites have been neglected as no significant amount of electricity can be produced. It is recommended that such sites be used for harnessing HEP with the use of hydram pump to boost water pressure provided there is enough flow rate to run the hydram pump.

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APPENDICES

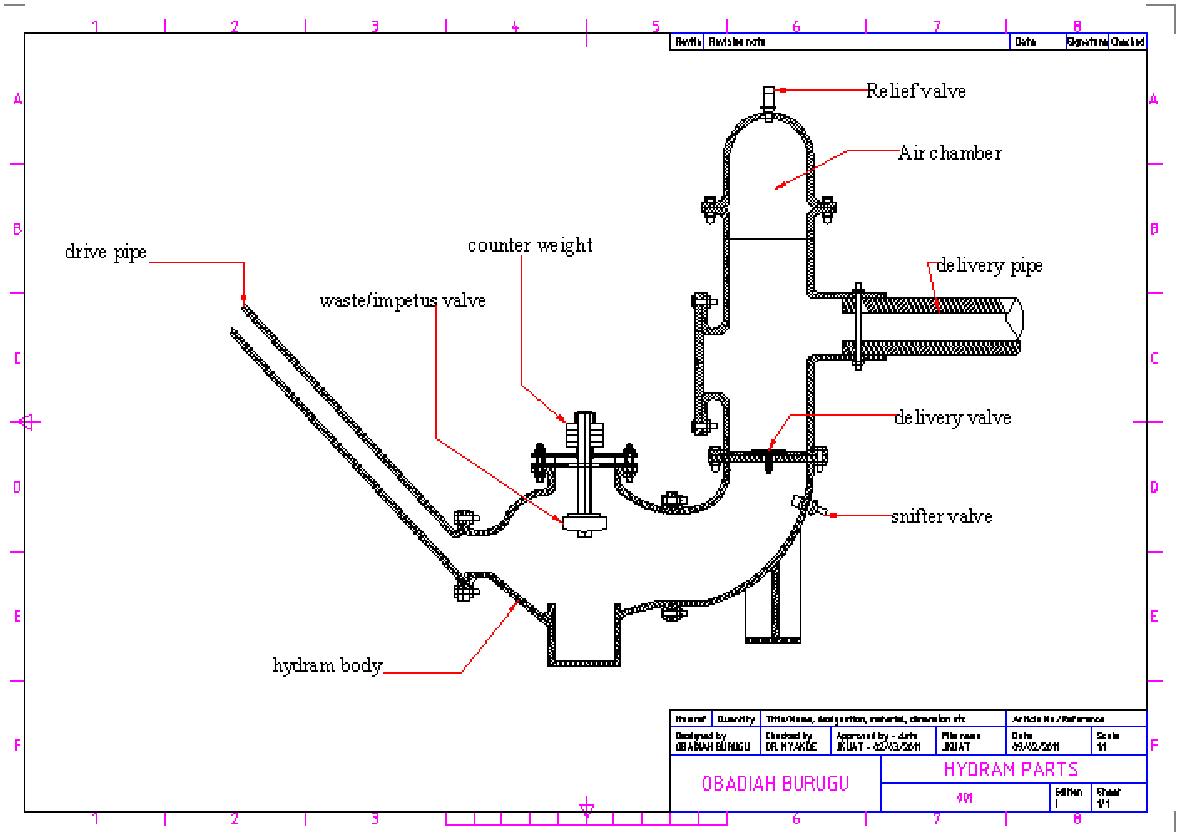

Figure 1: The main parts of a hydram pump

Figure 9: The fabricated pelton wheel turbine

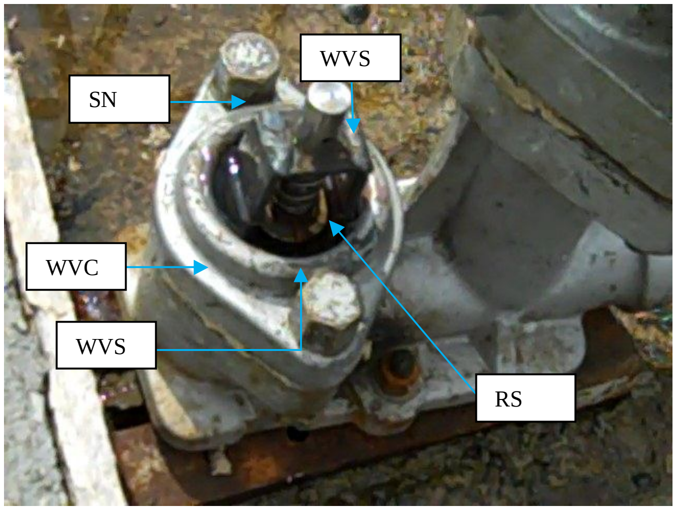

Figure 10: The fabricated waste valve to allow for low head operation

Legend SN: Stud Nut and Bolt, WVS: Waste Valve Shaft, RS: Return Spring, WVS: Waste Valve Seat, WVC: Waste Valve Casing