ISSN (Online) 2395-2717

International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)

Vol 9, Issue 9, September 2022

Design and Analysis of a Micro-Hydro Distributed Power System

[1] Muster Thivhileli Madavha, [2] Mohamed-Tariq Kahn

[1] Department of Electrical, Electronic, and Computer Engineering (DEECE), Cape Peninsula University of Technology, South Africa.
[2] Department of Electrical, Electronic, and Computer Engineering (DEECE), Cape Peninsula University of Technology, South Africa.
Corresponding Author Email: [1] 219047707@cput.ac.za, [2] khant@cput.ac.za

Abstract— ***The purpose of this study is to improve the standard way of producing electricity in a hydropower plant through the introduction of a more effective method. The aim of installing this Micro-hydro Distributed Power System is to achieve greater results in comparison to those attained with a standard micro-hydro power plant, without depending upon rainfall but upon two stored natural resources, air and water. This air supply will come from solar compressors and the water will be drawn from existing dams or runoff from rivers into storage tanks, which will generate electricity throughout the year at the same rate as the existing micro-hydropower that depends upon rainfall.***

The Micro-hydro Distributed Power System is a working pressure hydropower plant that generates electricity by compressing fluid into the system, using compressed air and is designed and analyzed in CAD design software and results are calculated to ensure the design is sufficiently durable to withstand the pressure, since the entire power system is dependent upon working pressure and how the power is generated using two major renewable sources, water and air. The Micro-hydro Distributed Power System's working principle has been adapted from hydropower plants, the system converts H-Head(m) into pressure which is then used in the formula in (P=ρgh) to determine the power of the system.

Theoretically, the findings of this study prove that the power to be generated, based upon the calculations, is much higher than expected before commencing the research, the power input needed for the Micro-hydro Distributed Power System based upon the compressor system's rated power is 11KW to produce the 13 bars of pressure needed to compress fluid for maximum power output. At 13 bars the compressor system is found to be producing 398.3MW of power but at a high rate of flow of water which is found to be 391.907 L/s. A major advantage of the Micro-hydro Distributed Power System is that this water is pumped back into the tank from which it is re-used over and over again. This system depends entirely upon compressed air which is used to compress fluid through pipes, without this compressed air the water does not flow and cannot be pumped back into the system

Index Terms— ***Micro-Hydropower plant, Hydropower, Air Compressor, Solar PV, H-Head(m), Water Consumption.***

I. INTRODUCTION

A. Motivation and the need for Micro-Hydro Distributed Power System

Micro-hydro Distributed Power System (MHDPS) is an improved hydropower energy source, a renewable energy source that uses compressed air powered by the solar system, and water drawn from rivers/dams where the system is built. It stores water in the storage designed tanks and circulates it around the system generating electricity.

In this system, the air is created by the solar compressor to create high-pressured air that compresses water, as it compresses water it creates high-pressure water that is then pushed out at a high speed to turn turbines.

This is system is considered to be renewable energy based on the sources it uses to produce electricity mainly water and air.

The main purpose of the MHDPS is to provide new ways of producing electricity in a way that will benefit both people and the environment and also have a positive impact on South Africa's economy. The use of air and water to drive the turbine brings many benefits because these two renewable sources will improve the efficiency of the system and the water is also recycled. The MHDPS, as mentioned above, will benefit both people and the environment. It is well known that micro-hydropower plants can be run efficiently and provide clean energy from upstream rivers and do not a reservoir to power the turbine [1]. What makes such power hydropower plants unique is the fact that they do not waste water. Instead, the air pressure is expended to pump back water into storage tanks and re-used to drive the turbine. The standard style pump uses a great deal of electricity and, thus, re-designing it so that it utilizes a renewable energy source to drive the turbine gives a clear indication that the output electric power may be more cost-effective compared to the normal hydropower plants that use electric pumps. This use of pressured air also gives an advantage to the MHDPS by enabling it to control the power output that the turbine produces. The power output depends upon how much air generated pressure is pumped into the water tanks.

B. Literature review

Hydropower is based upon the principle of using water falling from a certain height and flowing water that has an amount of kinetic energy and potential energy associated

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ISSN (Online) 2395-2717
International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)
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with it. Hydropower entails utilizing a turbine or water wheel to convert the energy in falling or flowing water into mechanical energy. This energy is then converted into electricity by an electric generator [5].

Micro-hydro power plants are both effective and reliable in terms of generating clean electricity. They can provide electricity from 5KW up to 100KW – a small hydropower plants can provide up to 10MW [1], while the large-scale hydropower plant can produce up to 80 TMW energy. Hydropower plants are of great importance for the current and future electricity systems since they provide electricity without emitting CO_2 and hydro reservoirs offer high operational flexibility [6]. Hydropower is one of the most well established sources of renewable energy, providing more than 16% of the world's electricity consumption from both large and small power plants [7]. Hydropower plants do not harm the atmosphere, in fact, their way of producing electricity is very beneficial to the earth, the dams created for such establishments not only benefit humans but also the various species of plants and fish that live in these dams. The use of a solar compressor (whose energy source is the sun) with an improved design that will increase pressure, will enable the enhanced hydropower system to generate more electricity using a smaller amount of water.

While many renewable energy sources have a negative effect, hydropower is still the overwhelming leading technology. Nevertheless, in the past years, other renewable energy sources, such as wind power and photovoltaic (PV) have had a much higher growth rate [2]. The MHDPS also uses a PV solar compressor to pump pressure to drive it through the system.

Through the introduction of a MHDPS that has no electric pump more results will be achieved. In a normal tested Pump-Hydro unit with two reservoirs, of hydropower capacity of 16 MW, the Pump Power capacity also is 16MW at a fall height of 200m [2], already the pump is consuming the produced energy at that tested 200m. A PHS is a clean and sustainable energy storage system that uses water to store energy. This storage system does not require any chemical substances and can store energy in a wide range of capacities. It requires two reservoirs of different heights [3]. The difference between the micro-distributed unit compared to the pump-hydro is that it does not use reservoirs of different height but uses them simply to store water and contain pressure that it mixes with air pressure from solar compressors.

Hydropower plants are environmentally friendly and do not emit CO_2, rather, they reduce the CO_2 which is deposited in the surroundings, because of the use of hydropower plants in China it was found that CO_2 emission reduction has passed 70% [8]. The recent shift to a hydropower plant type that uses only a small amount of water, in which water and air are mixed to generate electricity which is equivalent to the standard operated hydropower plant has not been done. The continuous improvement of hydropower plants, involving the use of different solutions and combinations of pipes and storage tanks, has been analyzed to identify the most convenient solutions [9]. Several design options must be taken into account when seeking to create a successful micro-hydro power plant, these design considerations are [5]:

Flow duration curve (FDC)
Flow rate measurement
Weir and open channel
Trash rock design
Penstock design
Head measurement
Turbine power
Turbine speed
Turbine selection

From the above options for a micro-distributed power system, only certain items must be considered since pressure created by the compressor eliminates most of the above items. The items to be considered are: Flow duration curve (FDC), Flow rate measurement, Turbine power, Turbine speed and Turbine selection, as well as pipe design with pipe selection for better flow.

Compressors are used widely globally, machines such as grinders and even drillers that previously utilized electricity, now are designed to use air as their source of energy. The redesigning of a pump that will use air from the solar compressor to create pressure will make the process of the pump use less electricity and the input will not be equal to the output. Centrifugal compressor which is of a small size, a simple and compact structure and a high single-stage pressure ratio, has been widely used in small and medium-sized turbo aircraft engines and almost all types of auxiliary power plants. The optimal design of a centrifugal compressor with high-pressure ratio and deficiency in air equipment tool has been the pursuing target of compressor designers for decades [10].

C. Contribution of the system

Small hydropower is one of the renewable energy technologies that have great potential within the Sub-Saharan African region, with a high potential of improving quality of life (12).

Almost a fifth of the world's electrical supply depends on potential energy, and the government has seen hydroelectric dams as a means of stimulating economic growth through the provision of clean energy(13). Since Micro-hydro The advantages of a micro-hydropower plant over the same size wind, wave and/or solar power plants are [1]:

- High efficiency of 70%-90% and, thus, by far the best of all energy technologies.
- High capacity factors of >50% compared with 10% for solar and 30% for wind power plants.
- A slow rate of change; the output power varies only gradually from day to day and not from minute to minute.
- Power output is maximum in winter.

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ISSN (Online) 2395-2717
International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)
Vol 9, Issue 9, September 2022

This system will not only contribute to providing electricity but also to the conservation of rainwater since the storage tanks will be drawing water from the nearby dams or rivers which will then be used or be benefiting in farming. South Africa's economy also depends on farming, and the agriculture sector is one of the main pillars of the country's economy and is one of the largest sectors that consumes water, with about 62% of the annual useable runoff rainwater (14). This system is going to contribute to the energy sector, agricultural sector, and the improvement in the small hydropower generating method.

II. PROCESS FLOW

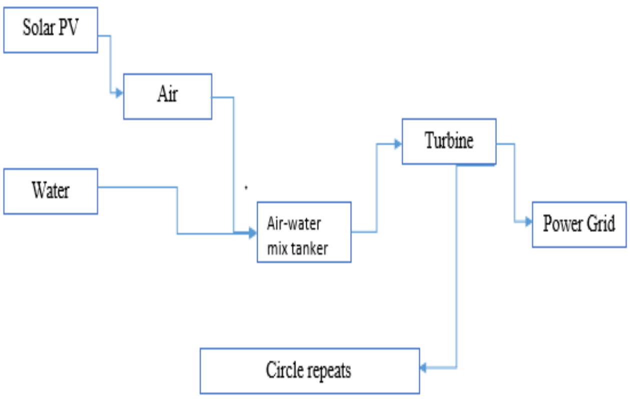

Figure 1 a simple flow chart

The use of air and water has been done and analyzed in form of exploitation of low-head hydropower by pressure interchange with air, using siphons, with careful design of the flow passages to minimize losses, air-pumping efficiencies of 70 percent (15).

Applying the principle of air pressure and using that air pressure to push water at high speed, without considering the siphons and using different designs to produce more power is what the diagram shows.

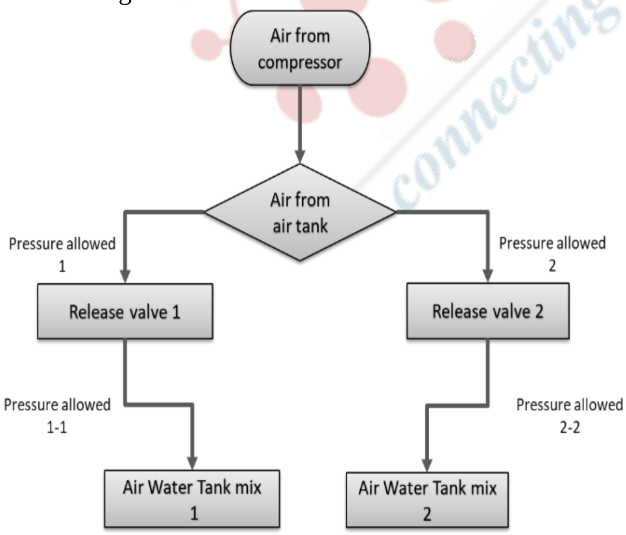

Figure 2 Air process from a compressor to mixing with a water tank

Table 1 Pressure Release work process

Working pressure on a pipeline to Release Valve 1	3bar	3bar	Working pressure on a pipeline to Release Valve 2
	0bar	0bar	
Pressure allowed 1	yes	no	Pressure allowed 2
	no	yes	
Pressure allowed 1-1	yes	no	Pressure allowed 2-2
	no	yes	

The label "Pressure allowed" in Figure 8 above indicates that the valve allowing pressure is open, as shown by yes (green) and when the required pressure is reached, it closes that main release valve 1 and opens release valve 2.

The main purpose of the release valve for the MHDPS is to allow and reject the air needed to the mix tank and to allow or reject the air (pressure) needed on release valve 1, since this release valve does not work simultaneously wih release value 2. If release valve 1 is working and needs 3000 Kpa, release valve 2 will not work during that time. As soon as release valve 1 has acquired the allowed pressure of 3000 KPA then the release valve 2 will repeat the process that with release valve 1. Before release valve 1, there is a computerized valve that allows the change of pressure to be directed to a single line on release valve 1, this process is termed the "breathing method".

III. DESIGN ANALYSIS

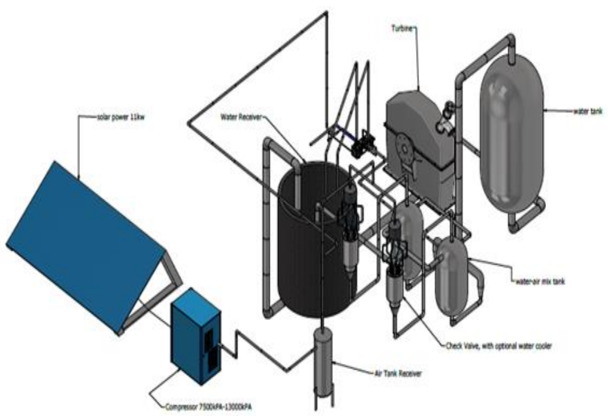

Figure 3 3D View of Micro-hydro Distributed Power System

This **air tank** is an air receiver, it accepts air from the pumps and compressor and discharges the air to the check valve. The air tank is used to store air at a higher pressure than what is needed for the MHDPS and creates a favourably high pressure when it is needed for the system [11].

The **released valve design**, only allows air to pass through, it doesn't allow air to flow back, or reverse pressure. The release valve at certain pressure releases air to the other tank. And when the pressure is reached its maximum operation point it goes to the other release valve to do the

ISSN (Online) 2395-2717

International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)

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same process at release valve 1. Refer to *Table 1 Pressure Release work process.*

The **air-water tank,** allows air to build up as it creates high pressure, the reason for two air-water tanks is to allow each tank to clear, for water which will be pumped in to be pumped in without a push back pressure which will make the water fill in slow. The principle to this is the breathing method as one release valve releases, the other release valve is working on filling the tanks.

Theoretical pressure will always be the same as per a single release valve, with the assumption that in the process of the working release valve there are no pressure losses which are due to:

- Leakage of a pipeline.
- Valve leakage
- Friction losses
- And other minor unplanned losses which might occur.

The main pressurized tank, the main pressurized tank is the last in the process of this power system, which discharges the pressure created by the air-water tank. The water comes at high pressure, which is then directed to the turbine.

Water Reservoir, collects water from the river or dam and water from turbines after generation process is pumped back to this Water Reservoir,

Pumps

Pumps are custom made for this power system, it uses air. The air used in the pumps is air from the ***Air-Water tank-mix*** which is released into the pumps. The pumps are also responsible to pump water to the ***Air-Water tank mix.*** There is also an optional pipeline in the case where the pressure from the ***Air-Water tank mix*** is not meeting the required pressure to pump water into the tanks. The optional air pipe is from the main compressor tank that will supply Air from the compressor to the Pumps.

Pump working principle

- **Water to Reservoir tank (Main water Tank)**

Water is drawn from the river or nearby stream/dam to the first tank, as water is passing through Air vanes water is drawn by Water vanes to the Reservoir Tank. The Reservoir Tank is an open tank, the pressure on top is atmospheric (101.323KPA).

- **Water to Air-water Tank Mixture**

Water is pumped again to the Air-water Tank Mixture at a lower pressure when check Valve A is open, Check Valve B is closed allowing water in at lower pressure, as soon as water required is in the Air-water Tank Mixture B, Pumps stop working on Air-water Tank Mixture A, and move to pump water at Air-water Tank Mixture B, pumping water at the same rate, and same conditions from Air-water Tank Mixture B. this process is the working principles of the Air-water Tank Mixture A and B.

1. Off-shelf sources.

GA-11 compressor is an oil-injector rotary screw compressor type. The calculations used to determine how much pressure is needed and how much power will this power system needs are referenced from this ***GA-11 Compressor***. The other reason to consider an oil-injector rotary screw compressor type is this compressor type has only two moving parts compared to the piston air compressor which has many moving parts. And the rotary screw compressor operates at lower temperatures and has a good cooling integrated system (16).

solar energy for the design Micro-hydro power system must be able to provide 11KW to 25KW for effective production or desired air at all times, for both air tanks and pumps. The air will be recycled during times when the system needs to be strained. Solar energy must meet the demand. Compressor selected needs a minimum of 11KW to produce 7bars to 13 bars, solar energy between 11kw to 25kw will allow the power system to have access energy which will also be used as for back up to the system and to other electrical components the power system requires.

The homer is the most popular tool for sub-national level planning energy distribution, The software has been extensively used in many studies for a cost comparison of investment decisions (17). Homer reduces the complexity by producing worldwide databases for solar PV radiation and the ability to design and choose industrially available components, and the option to model PHS as a storage type along with other technologies (18). Using the software to simulate how much power can I extract from the all-season climate, will help in deciding how much solar PV and storage I need for the system.

Kaplan Turbine is a reaction turbine type that Micro-hydro Distributed Power System will run with, Kaplan Turbine allows water to flow both in and out in the axial flow. What makes the Kaplan Turbine during the demand is the blades can be changed angle for maximum efficiency for different flow rates of water (19)

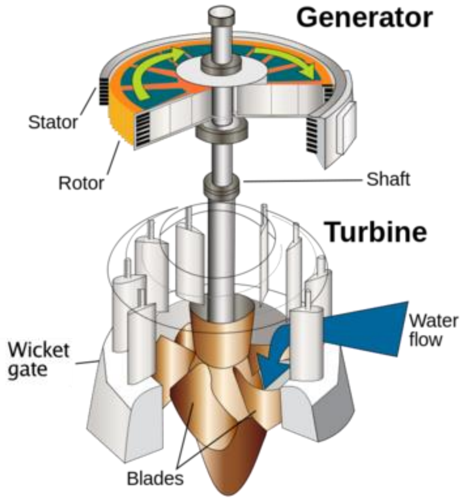

Figure 4 Kaplan turbine (19).

ISSN (Online) 2395-2717
International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)
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Since water has to be in axial flow, the water from the turbine will enter the turbine in radial flow. Kaplan's design is different compared to other turbines, it allows water to first enter through radial then exit axial unlike other turbines (20). This will not anyhow make water to turn the turbine lose pressure because the water in the line to the turbine is already pressure raised from the water-air tank mixture.

IV. RESULTS

Pressure in the water is to Pressure Head (H).

H_{net} is the gross head and head losses can be assumed to be 10% (21).

$H_{net} = H_{gross}$ X0.9

or

$H=\frac{P}{\rho g}$

The efficiency being used is in reference to some conducted experiments on the small hydropower plant since generating of the power was not practically done.

Therefore, the overall efficiency of a small hydropower plant is found to be its drive efficiency is 95%, generator efficiency is 93%, and turbine efficiency is 85% (21).

Therefore the overall system efficiency of small hydropower which is the Micro-hydro Distributed Power adapted will be as:

$\eta_{overall\ eff} = \eta_{Drive\ eff} X\ \eta_{Generator\ eff} X\ \eta_{Turbinel\ eff}$

=0.95X0.93X085

=0.75 or 75%

Mass flow rate ($\dot{m}$) = l^{-1} or kg^{-1}

Therefore the power output base on different heights will use the following formula

$P_{power} = \dot{m}X\ H_{net}\ Xg\ X\eta_{overall\ eff}$

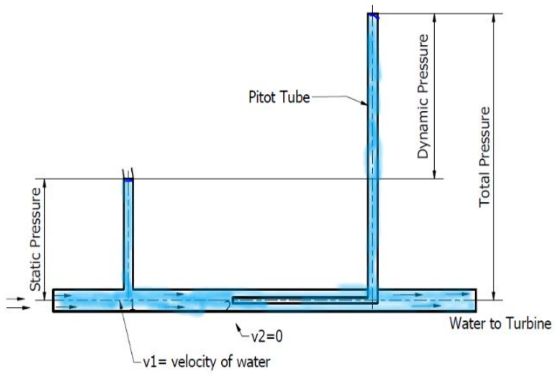

Figure 5 Velocity of fluid to the turbine.

Benoli Equation

$$\frac{P1}{pg}+\frac{V1^2}{2g}+Z1=\frac{P2}{pg}+\frac{V2^2}{2g}+Z2$$

Z_1 and Z_2= 0

P1 =(Ps) static pressure

P2=(Pt) (total pressure)

$$\frac{P1}{pg}+\frac{V1^2}{2g}=\frac{P2}{pg}$$

$$P1+\rho\frac{V1^2}{2g}=P2$$

$$V1^2=\frac{2(pt-ps)}{\rho}$$

Table 2 Pressure supplied by the compressor and generation of power

P(kpa)	volume flow	power(W)	Power(MW)
0	0	0	0
50	0	0	0
100	74.48118	8660.34155	0.00866
150	108.2402	16644704.3	16.6447
200	133.7328	25579810.5	25.57981
250	155.0901	35480837.6	35.48084
300	173.8432	46290196.8	46.2902
350	190.7615	57948691.9	57.94869
400	206.297	70404135.4	70.40414
450	220.7419	83611621.6	83.61162
500	234.2978	97532458.9	97.53246

V. DISCUSSION

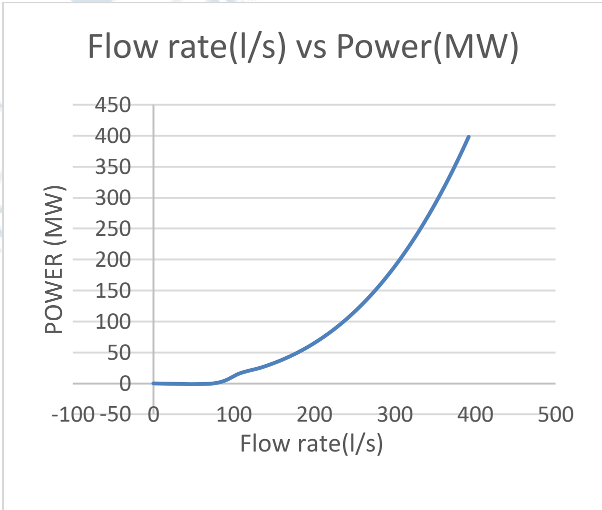

Figure 6 Water consumption vs power production

According to the calculation and graph presented, the greater the power output, the more water is needed in the system as the pressure increases in the air-water tank (air compressor filling the release valve). From 0L/s to 75L/s, as indicated in the graph, theoretically there is no power being generated due to Pressure P from Table 1 of the theoretical calculation being pressure from the compressor, Ps is static pressure and Pt is the total pressure inside the water-air mix tank, Table 9's theoretical calculation from the main table, the zeros(0) from dynamic pressure to Power.

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International Journal of Engineering Research in Electrical and Electronic Engineering (IJEREEE)

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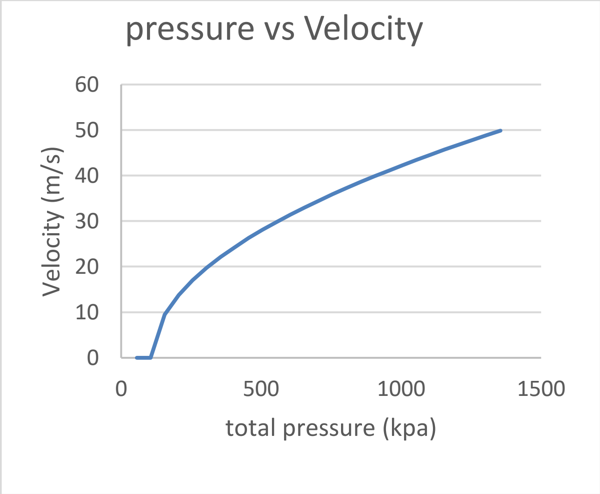

Figure 7 Pressure(kpa) vs velocity (m/s)

The pressure created in the main pressurized water storage exits the tank at high speed to the turbine, and as the pressure increases the velocity of water increases, and more pressure is added the greater the flow rate.

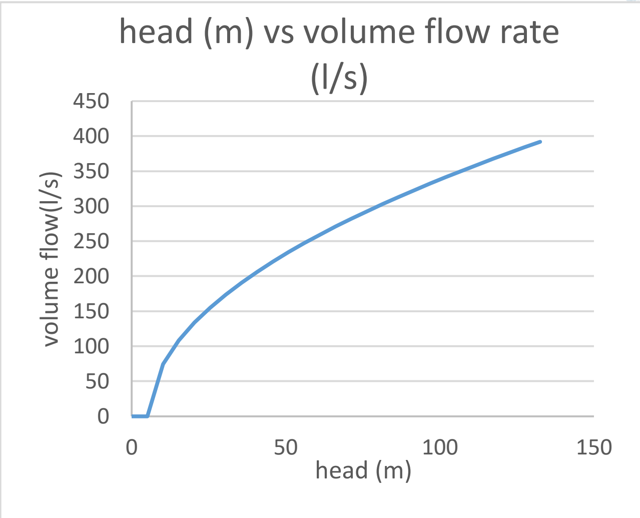

Figure 8 Head (m) vs Volume flow rate (l/s)

This graph shows a pressure converted to a pressure head (m) from a hydro pressure (P=ρgH) used to calculate the height. For instance, if 555.0341 KPA for this pressure the head is 50.9684m, the more head increases the more this power system uses or discharges water to the turbine.

VI. CONCLUSION

The MHDPS represents theoretical research undertaken with a design to support the theoretical results. It was proposed originally as falling under the category of the small hydropower plant, but due to the results obtained, it can be categorized as a large power plant. The only problem with the MHDPS is the amount of water it consumes while producing electricity, bearing in mind that the more the flow rate the greater the electricity generated. To solve the water crisis associated with the MHDPS, the design is designed to recycle water by using air pumps to drive the water back into the system. At 13 Bar pressure from an 11KW rated solar compressor, 398MW of electricity theoretically can be produced from the proposed MHDPS.

As stated and shown above 398MW is a theoretical calculation, and the efficiency of the generating stage is not calculated for the said MHDPS due to the research not being implemented practically. The overall efficiency used for this system is of a small hydropower plant that was used based upon the initially proposed idea that this system will be categorized as a small hydropower plant, based on the nature of the design and capacity of the source (solar energy for compressor, size of compressor and the amount of water needed to operate the envisaged MHDPS).

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