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DEVELOPMENT OF A PEDAL POWERED WATER PUMP (PPWP)

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ABSTRACT

Water is highly essential for domestic, agricultural and industrial use; the supply of water to these various places of use has posed a significant challenge. This is because, most rural households and farmlands especially in western Africa finds it difficult to purchase expensive pumping devices which can only be operated by using either electrically operated motor or prime mover and requires special repair, installation and maintenance by technically oriented personnel. The inconsistency of electricity, unavailability of fuel and inadequate or lack of technical oriented persons renders the pump incapacitated in these rural areas. The developed Pedal Powered Water Pump (PPWP) successfully provides reliable and consistent water pumping and distribution means for general and even for small scale industries uses and; at the same time, serves for health fitness. The PPWP is a manually operated pumping machine to pump water from a sump as deep as 11 foot (2.5m) to a desired height of at least 21 foot (6.4m) by the application of a significantly magnified human energy through pedalling. The pedal powered water pump comprises of a fabricated pedal and crank connected to a large rim which in turn, is connected to a very small centrifugal pump pulley. The velocity ratio of the pedal crank to the rim's sprocket and from the rim to the pump's pulley facilitates the pumping operation. The materials for the construction of the pedal powered water pump is solely obtained from locally made metals and scraps, thereby providing a means of recycling metal wastes, obtaining an income from such wastes and preventing the littering of scraps in the society which are positive ways of improving on the economy. The efficiency of the machine is obtained to be 69%.

KEYWORDS: Machine; Pedal; Power; Pumping; Water

INTRODUCTION

Water is one of the most important and commonly used natural resources. It needs to be extracted from its sources, such as rivers, ditches, sky and beneath the ground for man's regular use. The task of fetching water by local means using a pail tied to a rope is quite stressful and it wears out the person fetching the water. A standard family with six persons will require an average quantity of water of 100 litres per day (Neelesh, 2013). In transferring water from one point to another a pumping device is required. Pumping is a vital method for supply of water from some resources, which the gravity system cannot be enough due to the effect of topography and side level (Dhaimat & Al-Helou, 2004). Pump is a mechanical or electro-mechanical device that adds energy to a fluid (liquid or gas) either by rising, accelerating or pressuring the fluid and also transfers liquid at the expense of power input (Akinwonmi et al., 2003).

Pumps are designed to raise or move liquids (load) through certain distance or height by suction or pressure. Pumps serves numerous purposes especially in the transportation of liquid from one part to another for example, crude oil and natural gas are transported from distance via pipeline by means of pumps (Calvert, 2007;

Kumar, 2010). Water Pump is a device that is used to transport water from one place to another (Emiliawati, 2017). Depending on the application, the pumping system can be selected from surface, submersible or floating pump types. Pumps can be class. Mainly, there are Centrifugal pump and positive displacement pump (Mohammedi et al., 2013). The centrifugal pump is positioned on its stand and the driven shaft of the centrifugal pump is connected to the bicycle-like wheel with the help of either a belt or a chain. By pedalling it, the wheel rotates, thereby rotating the centrifugal pump which in turns discharges water from the sump. Pedal Powered Water Pump (PPWP) is an eco-friendly water pump system that is used to pump or extract water from well or sump to a desired height and also serves as a means of exercise for the body without necessarily run around, thereby giving fitness to body at the same time. Also, studies have proved that an average human needs to exercise the body in any possible means at average of 1 to 2 hours daily for healthy living (Zarkadoulas et al., 2008). The PPWP works on mechanical energy without electricity.

MATERIALS AND METHOD

The pedal powered water pump basically explains a simple energy conversion (that is, the kinetic energy of a pedalling which is converted to a fluid potential energy in the impeller and finally back to a fluid kinetic energy from the suction to the delivery)

An incorporation of a rim which is rotated by a crack and chain assembly is used to amplify the minute rotational inertia of the human pedalling operation. This amplified speed of the rim is directed by means of a belt from the rim to the pulley attached to the shaft of the centrifugal pump. It is noteworthy that the minimum revolution per minute (rpm) required to successfully lift the water from the suction to the delivery is equal to the mean pedalling speed of the operator. This can conveniently be achieved by calculating the velocity ratio between the rim and the pulley as well as the number of stride pedalling between each pedal to the crank. The feasibility of this project setup on a real life application requires the pedal powered water pump be position on castor wheels which can easily be moved to any desired place. A sample well of 8 meters was selected having an average groundwater level at 6 meters' depth during the dry season and 3.5 meters during the rainy season. The suction pipe is designed to reach two-third of the water level at any height, but not too low as to touch the bed of the well or too high to be above the water level. The pedal powered pump is set up as shown in Figure 1 and an operator performs a couple of pedalling. It is imperative to note that the amount of water pumped during rainy season can be different from the dry season, consequently both seasons or any time depends upon the pedalling ability of the operator. At normal pedalling speed, more water will be pumped during rainy season and less during the dry season because the level of water drops lower in the dry season thereby increasing the suction head.

The important factors considered in development and construction of the pedal powered water pump includes;

a. Pump capacity, pump power, impeller size and speed as well as the type of pump suitable for the needed job
b. The suction height and discharge head which will dictate the length and diameter of pipe and hose to use
c. The rim and pulley diameter which determines the velocity ratio in line with

the pump's required revolution per minute

d. The dynamics of the bicycle frame and the base frame
e. The general design and drafting
f. The safe working load

Working Principle of the Pedal Powered Water Pump (PPWP)

The operational rule of the project can be divided into three distinctive categories viz;

a. Operational principle of the pedal-crank and rim
b. Working principle of the rim and pulley
c. Working principle of the centrifugal pump

DESIGN ANALYSIS

Design Analysis for the Bicycle Frame

The bicycle frame forces in each member is derived so as to determine the forces which will be concentrated at strategic points on the base frame of the structure. The maximum weight exerted on the structure is 160 kg as measured, to establish the weight in Newton, equation 1 as given by Ejiko et al., (2015) was utilized.

Force = mg (1)

where;

Mass (m) = 160kg

Acceleration due to gravity (g) = $9.81ms^{-1}$

therefore, force = 160 x 9.81 = 1569N.

considering a free body diagram of the bicycle frame in Figure 2.

By resolution using methods of joints as given by Khurmi and Gupta (2005)

$$\longrightarrow \sum fx = 0 \qquad (2)$$

$1673 \cos 75^o + F_{ac} - F_{ab} \cos 56^o = 0$

$433 + F_{ac} - F_{ab} \cos 56^o = 0$ (3)

$$\uparrow \sum fy = 0$$

$-1673 \sin 15^o - F_{ab} \sin 34^o = 0$

$-433 - F_{ab} \sin 34^o = 0$

$$F_{ab} = -\frac{433}{\sin 34^o} = -774.33$$

F_{ab} = 774.33N (C).

$433 + F_{ac} - F_{ab} \cos 56^o = 0$

$433 + F_{ac} - (-774.33) \cos 56^o = 0$ (4)

$433 + F_{ac} + 432.99 = 0$

$F_{ac} =$ 865.99N (C)

Design Analysis for the Base Frame

The base frame in Figure 4 has points 1, 2, 3, 4 and 5, which indicates the load distribution on each point through which the shear force and bending moment is calculated. The forces are determined by resolving on a straight line whose free body diagram is presented in Figure 5.

Known parameters:

Standard number : STN 42 5550
EN 10024

Mass of pump = 6.7kg

Force exerted by the pump = 6.7 x 9.81 = 65.73N

Point 5,

$$\text{Concentration per beam} = \frac{65.73}{2} = 32.865N$$

$$\text{Concentration per } N/mm \ \frac{32.865}{251} = 0.131N/mm$$

Point 4-3,

Mass concentration at DE = 2.3kg

Force = 2.3 x 9.81 = 22.563N

Concentration per N/mm = 0.1359N/mm

Finding R_1 and R_2 (reaction at both ends)

Taking moment about point, G,

R1 x 1935 = 836.5 x 0 + (836.5 x 275) + (0.1359 x 166)(1079) + (0.131 x 251)(1845)

R1 x 1935 = 315044.54

$$R_1 = -\frac{31504454}{1935} = 162.8N$$

$R_1 + R_2$ = 836.5 + 836.5 + (0.1359 x 166) + (0.131 x 251)

R_2 = 1565.64N

Calculating for shear force

$S.F_A = 162.8N$
$S.F_{B-C} = 129.9N$
$S.F_{D-E} = 129.9 – (0.1359 X 166)$
$S.F_F = -729.14N$
$S.F_G = -1565.64N$
Calculating Bending moment
B.M = F X D
$B.M_A = 162.8 x 0 = 0Nmm$
$B.M_{B-C} = 51388.2Nmm$
$B.M_{D-E} = 137990.64Nmm$
$B.M_F = -220983.37Nmm$
$B.M_G = 5972.46Nmm$
The maximum bending moment can be obtained from the highest point on the graph in Figure 7.
Maximum bending moment, taken as $B.M_H$
$B.M_H$ = 162.8 (939) – (0.131 x 251 x 723.5) - (0.1359 x 83 x 41.5)
= 128611.69Nmm
Maximum Bending moment is obtained as 128.12KNmm

Calculating Moment of Inertia for the Base Frame

Taking a cross sectional area of the base frame,
Moment of inertial according to Engineersedge

$$I = \frac{1}{3}\left[(ty^3 + a(a-y)^3 - (a-t)(a-y-t)^3\right] \quad (5)$$

Where y is the distance from the centroid

$$y = a - \frac{a^2 + at - t^2}{2(2a-t)}$$

$$y = 50 - \frac{50^2 + 50(5) - 5^2}{2(2(50)-5)}$$

y = 35.66mm
therefore moment of inertial is calculated thus,

$$I = \frac{1}{3}\left[(5(35.66)^3 + 50(50-35.66)^3 - (50-5)(50-35.66-5)^3\right]$$

$$I = \frac{1}{3}\left[22673263 + 14744073 - 3666512\right]$$

$$I = 11250275mm^4$$

A. Calculating the Working Stress for the Structure

Formula for the working stress as given by (Ejiko et al., 2015)

$$f = \frac{My}{I} \quad (6)$$

where;
f is the working stress
m is the mass in kg
y is the distance from the centroid
I is the moment of inertia.

$$f = \frac{128111.69 \times 35.66}{11250275}$$

F = 40.766KN/m^2
Therefore, the working stress for the base structure is derived to be 40.766KN/m^2
From standard steel table ultimate stress for mild steel = 390N/m^2
And tensile stress = 560N/m^2
Hence, the design is safe

Design Analysis of the Hub and Rim

Known parameters:
Length of hub = 160mm
Total weight of the wheel = 2kg = 19.62N
The free body diagram of the hub and wheel is presented in Figure 9;
Calculating for R_1 and R_2 taking moment at D,
R1 x 160 = (9.81 x 50.25) + (9.81 x 105.25)
R1 x 160 = 1525.455

$$R1 = \frac{1525.455}{160} = 9.534Nmm$$

$R_1 \approx 10N$
Calculating for shear force
$S.F_A = +10N$
$S.F_B = 10 – 9.81 = 0.19N$
$S.F_C = 0.19 – 9.81 = -9..62N$
$S.F_D = -9.62 + 10 = 0.38N$
Calculating for bending moment
$B.M_A$= 10 x 0 = 0Nmm
$B.M_B$= (10 x 50. 25) – (9.81 x 0) = 502.5Nmm

$B.M_C = (10 \times 105.25) - (9.81 \times 55) - (0) = 512.95Nmm$

$B.M_D = 0Nmm$.

Design Analysis for the Centrifugal Pump

Pump ratings and parameters:
Power : 1Hp
R.P.M : 2850rpm
Maximum Discharge (Q.max) : 120L/min
Maximum Head : 34 m
Maximum Suction head/lift : 9m
Pipe diameter:25.4 mm
Diameter of rim : 650 mm
Diameter of crank : 200mm
Diameter of sprocket : 80mm
Length between sprocket and crank : 500mm
Pedal dimension : 10 x 7.5mm
Pedal stroke length : 200mm
Diameter of pulley : 50mm

Operational principle of the pedal-crank and rim

The crank comprises of a toothed sprocket and a pair of pedals which are at 180^o to each other. The sprocket runs a chain to the front end which is held by a hub. The hub at the front end of the crank serves as the central shaft for the rim. The hub and rim are held concentrically by spokes. Therefore, the torque exerted by foot to the pedal is converted directly to rotational motion which in turn is conveyed by the chain towards the hub and hence, to the rim.

The tooth ratio between the crank and the hub facilitates an increased speed of the rim

Working Principle of the Rim and Pulley

Basically, the advent of the rim connected to the pulley is to increase the revolution per minute of the speed coming from the crank. Equation7 was used to determine the rim diameter according to Ejiko et al., (2018a and 2018b) and Khurmi (2005).

$$\frac{d_1}{d_2} = \frac{N_2}{n_1} \qquad (7)$$

n_1 = speed of rim
N_2 = speed of pulley
D_1 = diameter of rim
D_2 = diameter of pulley

Working Principle of the Centrifugal Pump

A centrifugal pump is one of the simplest pieces of equipment in any process plant. Its purpose is to convert energy of a prime mover (e.g. bicycle wheel, electric motor or turbine) first into velocity or kinetic energy and then into pressure energy of a fluid that is being pumped. The energy changes occur by virtue of two main parts of the pump, the impeller and the volute or diffuser. The impeller is the rotating part that converts driver energy into the kinetic energy. The volute or diffuser is the stationary part that converts the kinetic energy into pressure energy.

The process liquid enters the suction nozzle and then into eye (centre) of a revolving device known as an impeller. When the impeller rotates, it spins the liquid sitting in the cavities between the vanes outward and provides centrifugal acceleration. As the liquid leaves the eye of the impeller a low-pressure area is created causing more liquid to flow toward the inlet. Because the impeller blades are curved, the fluid is pushed in a tangential and radial direction by the centrifugal force. This force acting inside the pump is the same one that keeps water inside a bucket that is rotating at the end of a string. Figure 12 depicts a side cross-section of a centrifugal pump indicating the movement of the liquid.

Conversion of Kinetic Energy to Pressure Energy:

The key idea is that the energy created by the centrifugal force is kinetic energy. The amount of energy given to the liquid is proportional to the velocity at the edge or vane tip of the impeller. The faster the impeller revolves or the bigger the impeller is, then the higher will be the velocity of the liquid at the vane tip and the greater the energy imparted to the liquid. This kinetic energy of a liquid coming out of an impeller is harnessed by creating a resistance to the flow. The first resistance is created by the pump volute (casing) that catches the liquid and slows it down. In the discharge nozzle, the liquid further decelerates and its velocity is converted to pressure according to Bernoulli's principle (Okeke & Anyakoha, 2008).

This head can also be calculated from the readings on the pressure gauges attached to the suction and discharge lines. Pump curves relate flow rate and pressure (head) developed by the pump at different impeller sizes and rotational speeds. The centrifugal pump operation should conform to the pump curves supplied by the manufacturer.

RESULTS AND DISCUSSION

Result and Performance Evaluation

After conducting extensive test-running on the pedal powered water pump from a desired height, the various height and discharge heads required to be met were satisfactorily obtained. The maximum suction depth is established is 8 ft (2.5m) and the maximum delivery head is established to be 21 ft (6.4m).

Table 1 to 4 shows the discharge volume in litres per minute with varied suction depth and delivery head

Efficiency of the Pump

Efficiency of the pump is calculated using the equation (8) as stated by Kumar (2010).

Efficiency

$$\eta = \frac{\text{energy developed by the pump}}{\text{energy supplied to the pump}} x100\%$$

$$\eta = \frac{\ell gQH}{Pw} x100\% \qquad (8)$$

Where;

Power supplied = 1118.55kw

Density (ℓ **)** = 1000kg/m^3

Acceleration due to gravity (g) = 9.81m/s^2

Discharge volume (Q) = 199.42 L/m = 11.97 m^3**/s**

Maximum discharge head = 6.4m

Power, P_w= ℓgQH (9)

P_w= 1000 x 11.97 x 9.81 x 6.4 = 751 kw

$$\eta = \frac{751}{1118.55} x100\%$$

Efficiency (η) = 62%

CONCLUSIONS

Based on the experimental results obtained from the designed, fabricated and tested project a clear inference can be drawn that the pedalling operation was sufficiently able to pump water from a desired depth to a height for the transfer and distribution of water to municipalities and for small scale industrial uses.

RECOMMENDATIONS

Though, the development of a pedal powered water pump was able to pump water from a sump to a desirable height of 21 ft, some constraints were encountered during the course of development. These constraints were addressed. Below is some noteworthy recommendation for improved design efficiency and better output of the machine; speed increasing gears can be incorporated so as to reduce the pedal reaction to the operator. This is imperatively essential if the machine is to be used for deeper suction lifts. It can also be redesigned so as to allow incorporation of other types of couplings in order to transmit the energy produced from the rim for other uses like generating electricity using the alternator or for washing machine.

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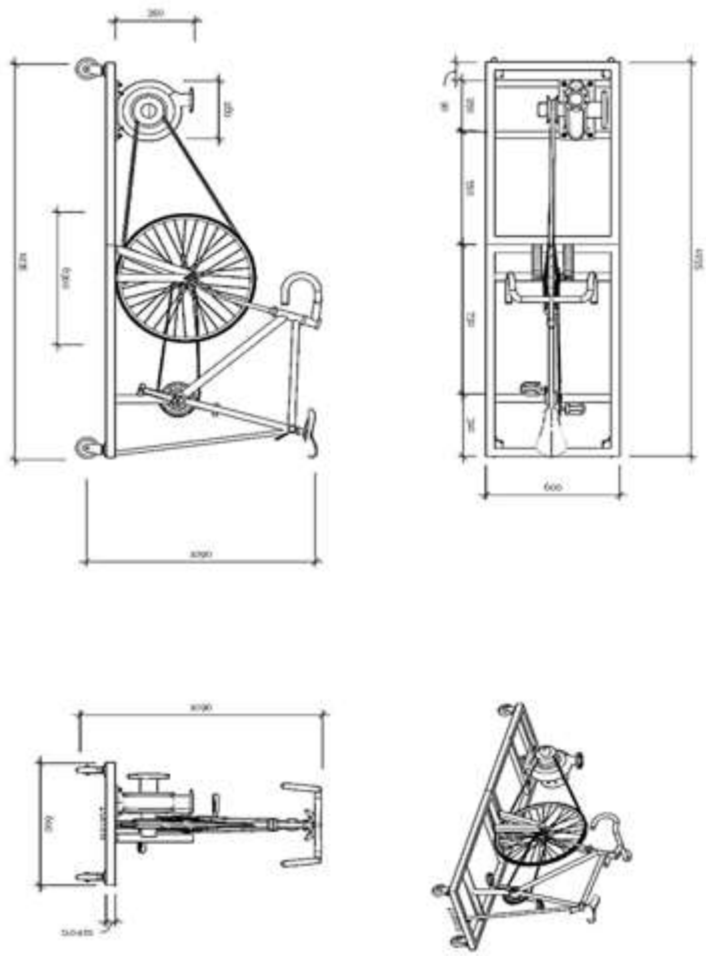

Figure 1. The Overview of PPWP

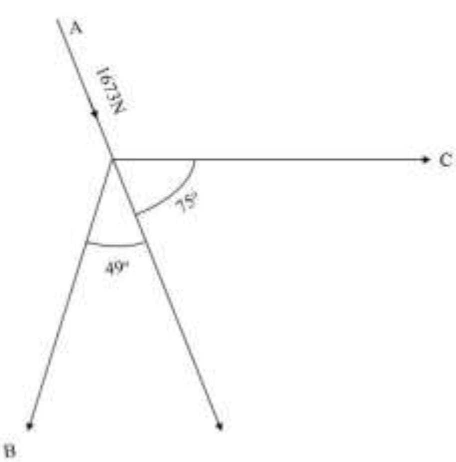

Figure 2. Resolution of Horizontal Bicycle Frame Forces

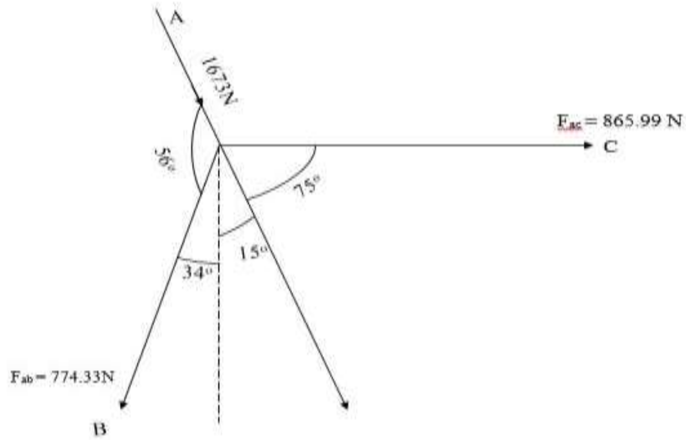

Figure 3. Resolution of Vertical Bicycle Frame Forces

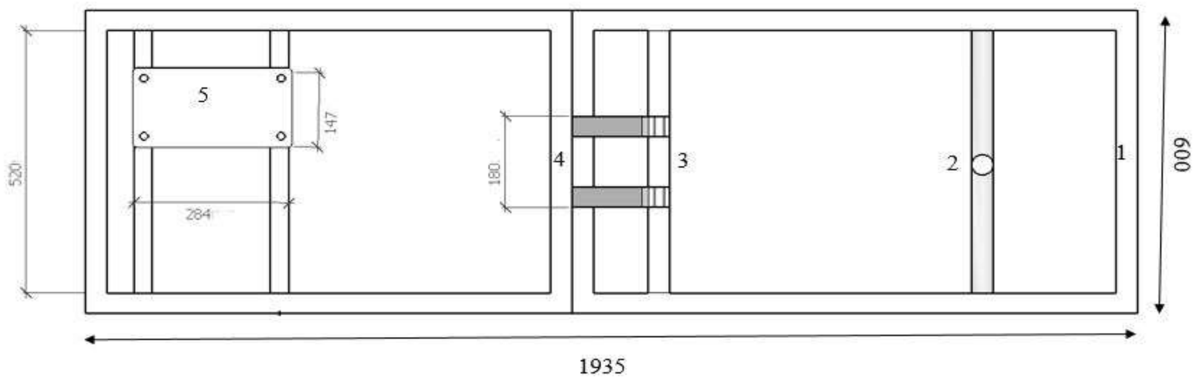

Figure 4. The Base Frame

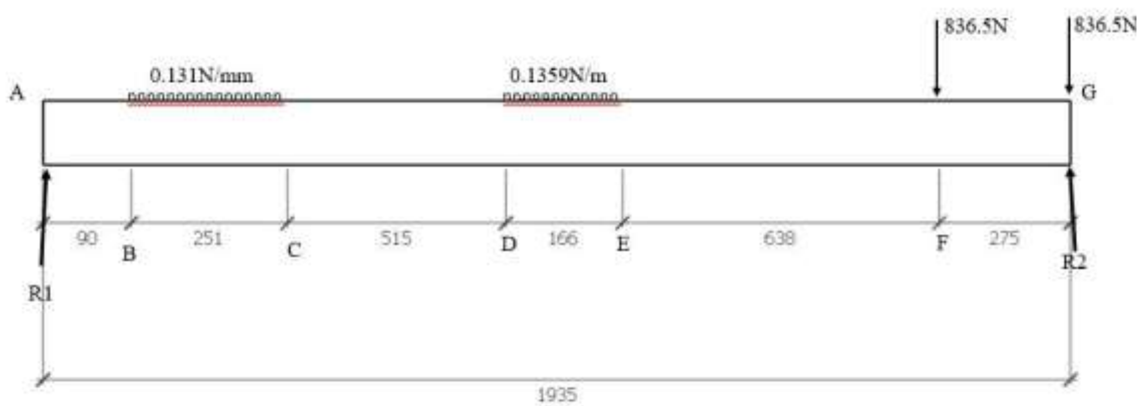

Figure 5. Line Diagram for the Base Frame

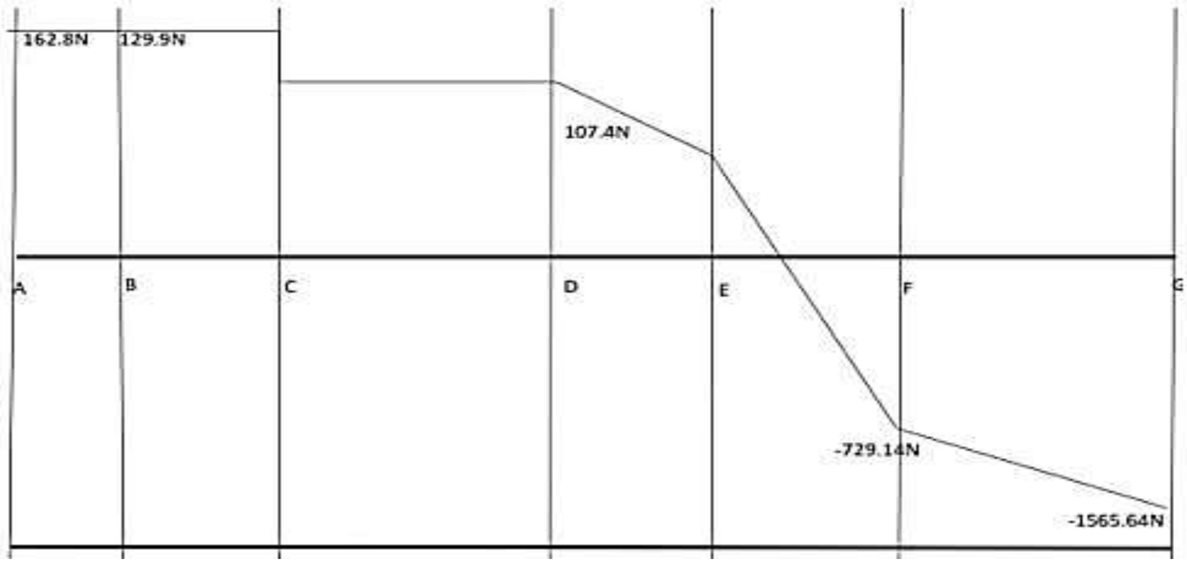

Figure 6. Shear Force Diagram

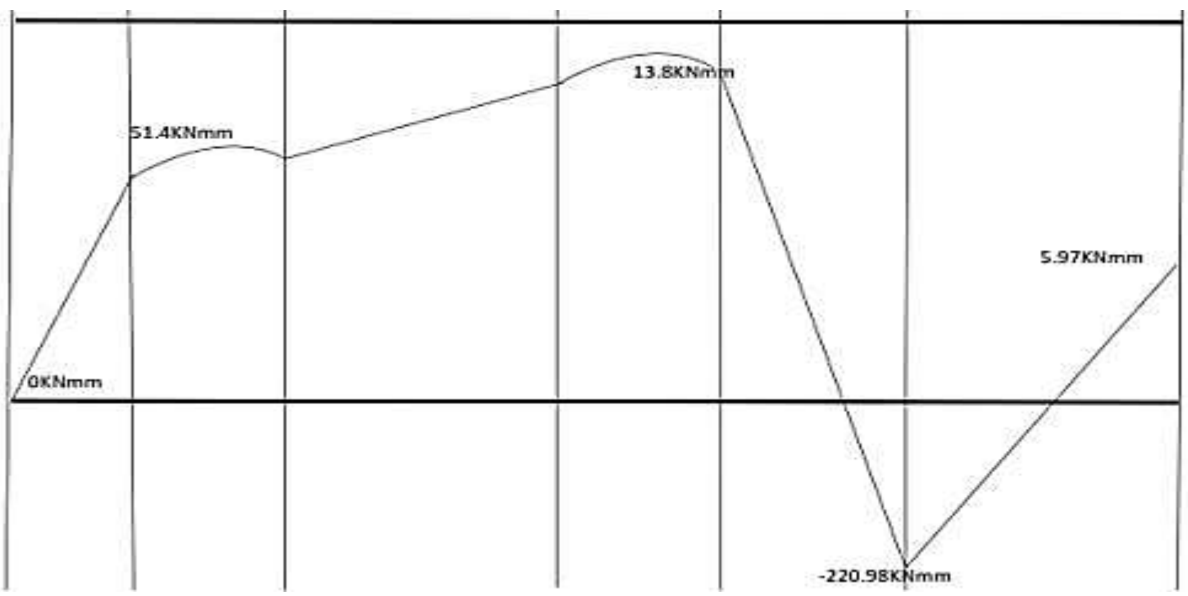

Figure 7. Bending Moment Diagram

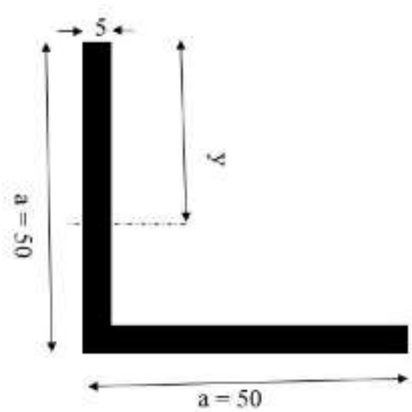

Figure 8. L Cross Section of the Base Frame

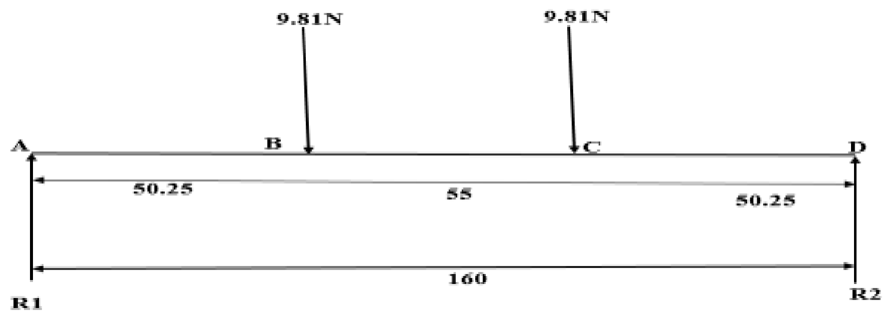

Figure 9. Line Diagram of Hub and Wheel

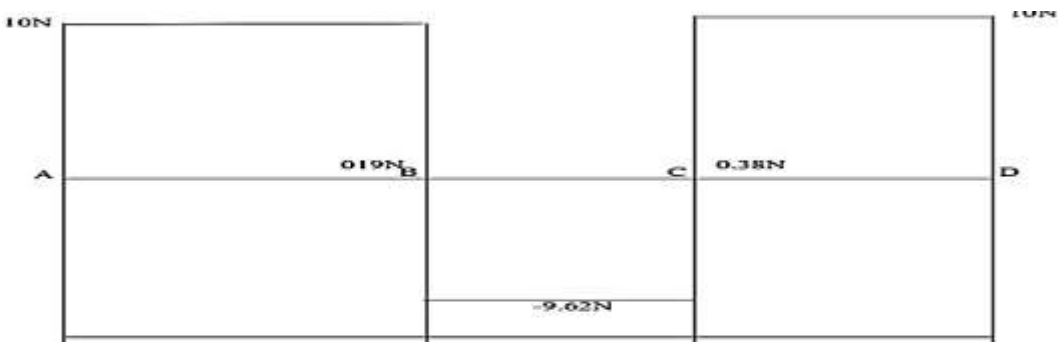

Figure10(a). Shear Force Diagram of the Hub

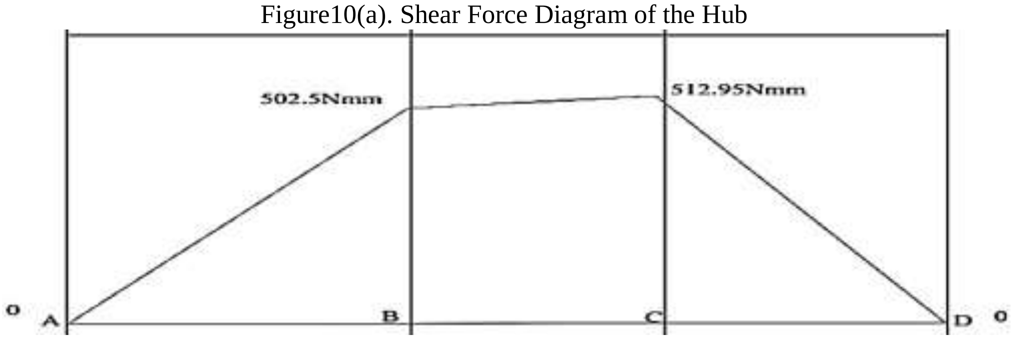

Figure 10(b). Bending Moment Diagram of the Hub

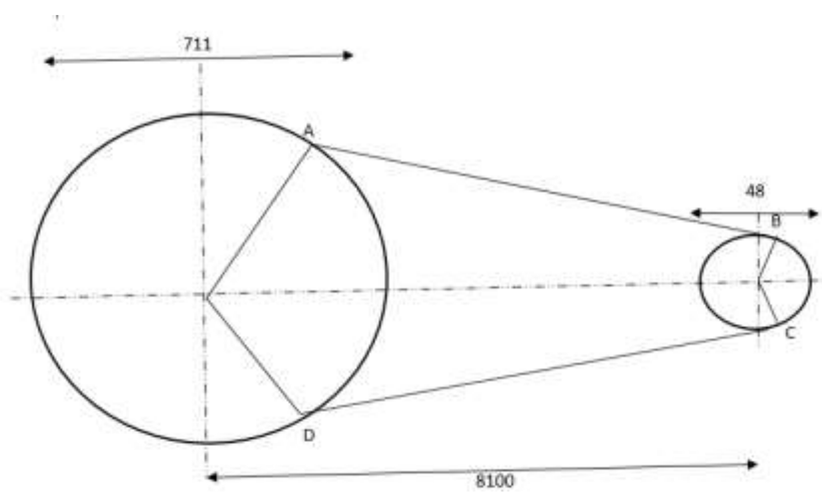

Figure 11. The Rim and Pulley

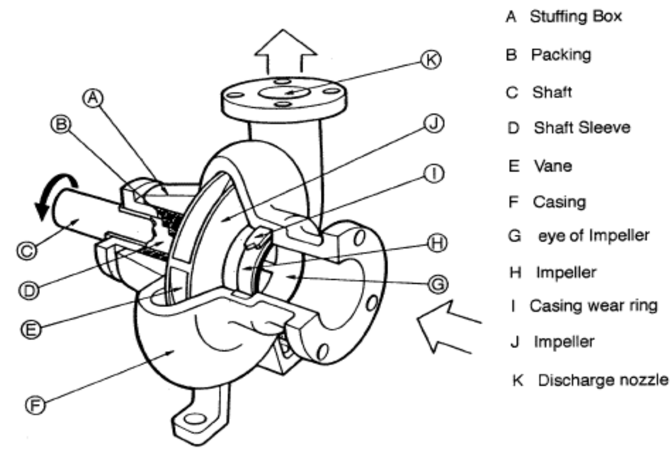

Figure 12. Sectional View of Centrifugal Pump

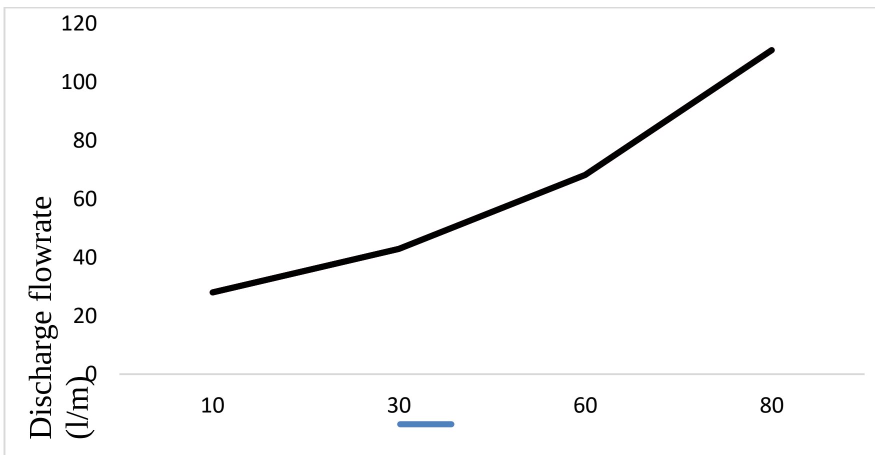

Figure 13. Graph of discharge Flow rate against Speed at a Depth of 4 ft and Head of 8ft

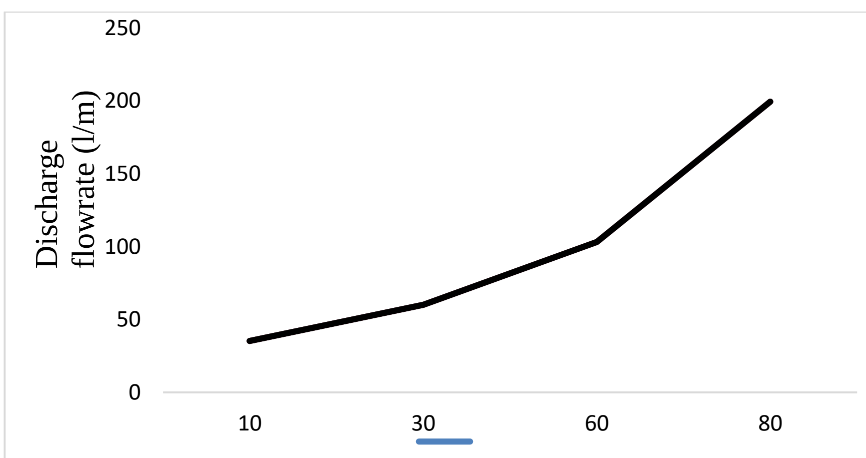

Figure 14**.** Graph of discharge Flow rate against Speed at a Depth of 2 ft and Head of 2ft

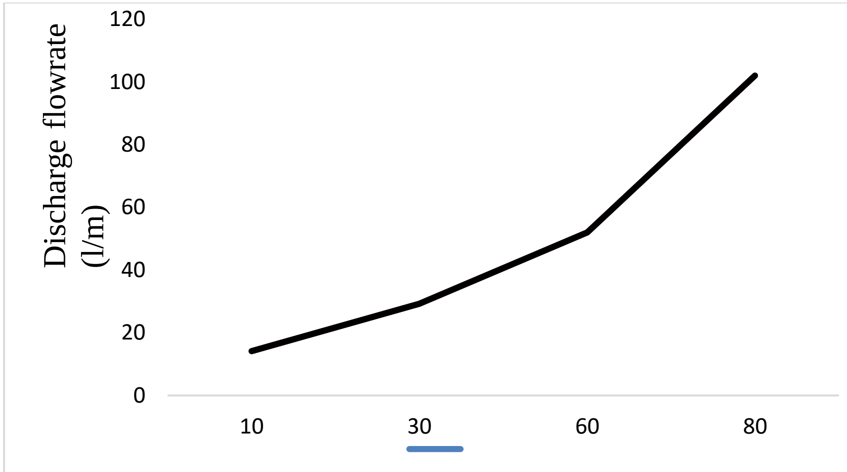

Figure 15. Graph of Discharge Flow rate against Speed at a Depth of 6 ft and Head of 4ft

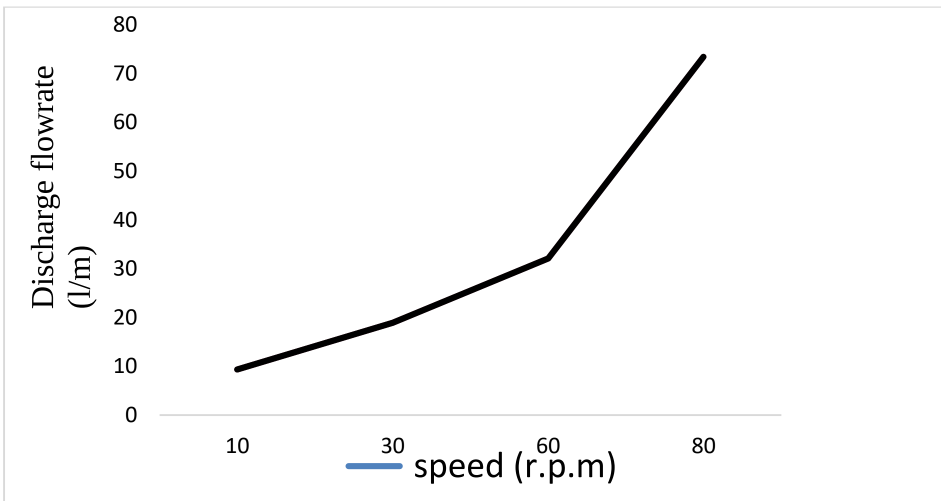

Figure 16. Graph of Discharge Flow rate against Speed at a Depth of 7.6ft and Head of 18 ft

Table 1: Performance at a Speed of 10 r.p.m

s/n	Suction depth (ft)	Delivery head (ft)	Discharge(litres/min)
1	1	3	28.25
2	4	8	28.04
3	2	2	35.3
4	6	4	14.1
5	7.9	18	9.3

Table 2: Performance at a Speed of 30 r.p.m

s/n	Suction depth (ft)	Delivery head (ft)	Discharge(litres/min)
1	1	3	49.02
2	4	8	42.9
3	2	2	60.08
4	6	4	29.3
5	7.9	18	18.9

Table 3: Performance at a Speed of 60 r.p.m

s/n	Suction depth (ft)	Delivery head (ft)	Discharge(litres/min)
1	1	3	79
2	4	8	68.2
3	2	2	103.25
4	6	4	52.03
5	7.9	18	32.1

Table 4: Performance at a Speed of 80 r.p.m

s/n	Suction depth (ft)	Delivery head (ft)	Discharge(litres/min)
1	1	3	152.9
2	4	8	110.9
3	2	2	199.42
4	6	4	102.1
5	7.9	18	73.4