Development and Performance Evaluation of a Low Head Hydro Turbine for Rural Electric Power Generation

B. N. Nwankwojike, S. K. Ogbansiegbe, O. F. Oti, I. F. Onuoha

Abstract

A micro hydro turbine used for harnessing hydropower potentials of low head water bodies in rural areas was developed from locally soured materials and evaluated at Anya River in Umudike. Its major components include the base, strut, rotor (runner assembly) and its scroll casing. The performance evaluation result indicates the optimal power output of the turbine as 4.30kW at 80.34% efficiency, 0.42m^3/s discharge rate and runner shaft speed of 60rpm. The micro turbine was developed at a cost of two hundred and thirty thousand, six hundred and forty naira (₦230,640.00) only.

Key Words: Environmental friendly power generation, hydropower, low head water bodies, micro hydro turbine, renewal energy, rural electrification

1.0 Introduction

Nigerian rural areas have been much behind in the provision of electrification despite that rural electrification is one of the basic infrastructures for socio-economic development and industrialization. According to Okonkwo (1995), rural electrification has multiplier effect on this nation's economy and this usually manifests in the form of springing up of small and medium scale industries, which in turn provides employment opportunities to the rural dwellers and transforms their economic life as well as checks rural-urban migration. Thus, the desire for electricity in our rural areas is so high that today, one easily finds small electric generators in many homes and business outfits. The problems of this small scale self electricity generation such as limited capacity, high energy and exergic losses, high cost of production, hazardous gases and noise emissions have been acknowledged [1], [2], [3] and [4]. Although, these authors collectively emphasized 24-hour uninterruptible public electricity service of satisfactory quality as the sure measure to avert these problems associated with rampant use of individual electric generators in this country, [5], said that this is not likely to be met in the near future. This is because the installed electric power capacity of Power Holding Company of Nigeria (PHCN), which only a percentage is actually being produced is grossly inadequate for over 150 million people living in this nation [5]. Therefore, one of the major challenges of the government and people of Nigeria today is how to bring up this very low production/consumption level to match the internationally advocated minimum electricity consumption of 6.5MWH per head per year as applicable to developed countries [5].

Electricity generation is basically conversion of other energy forms into electrical energy. According to [5], electrical generator is the only practical device currently available in Nigeria for large scale conversion of energy from other sources into electricity and this is a rotational device. Thus, other energies are normally converted into intermediate turning energy (mechanical torque) using turbines before final transformation into electrical form as the turbine drives the generator. Globally, the major sources of energy required for driving the turbine are fossil fuels, nuclear fuels, wind, solar and force of moving water (hydro power) [5], and [6]. Presently fossil and nuclear fuels have wider utilization globally, but they are non renewable and their continuous use poses dangerous threat to the world ecosystem. Thus, the world is redressing to hydropower energy driven sector because it is renewable and has minimum impact to the environment [7], [8]. According to [7] and [8], hydro energy should contribute significant portion of world's energy need if the aim to tackle climate change must be achieved. Another outstanding features of hydropower driven electrical energy generating sector include that it is immediately (within seconds at least) available where as thermal sources can meet demand at a much slower rate [5]. Although, the successful operation of hydro-electric power scheme is dependent on sufficient and predictable rainfall in a region, it is easily and economically storable for use when necessary unlike its sister natural energy sources, solar and wind that cannot be stored in large quantity at an economic rate especially with respect to the budget of rural dwellers. Compared with other energy driven power plants, hydro power plant goes with long life span (40 to 80 years) and low operating and maintenance cost [7], [9]. In addition, renewal of hydro energy resources occurs free of cost and all equipment required in setting up this power scheme are usually available locally except the turbine. Hence, development of hydraulic turbine from locally sourced materials in Nigeria is paramount for significant assess to enormous micro hydro power potentials of small water bodies such as streams, small lakes and rivers in our rural communities and this is highly necessary in addressing the nation's present electrical energy crisis at minimal adverse environmental effects.

Hydropower scheme may be large or small depending on the water discharge rate and height of fall (head) [9]. Large or high head hydropower scheme goes with high flow rate and large reservoir built on a higher height from which water flows through pressure pipes to the turbines and discharges at the tailrace. The high level reservoir is usually formed by constructing a dam on a river valley. Since construction and maintenance of this dam involves intensive investments, the scheme is not adequate for low income rural dwellers. Medium head scheme is also not suitable for rural application even though the river is used unaltered as reservoir because design of penstock used for conveying water from the river to the turbine is expensive. Small hydro power can be mini when its power output fall between 1MW and 30MW or micro producing between 5kW and 100kW [7], [8]. The later scheme is the most suitable for powering rural communities because it requires low head micro turbines and little civil works, thus its cost of establishment and operation is relatively very low and at the tune of individual and group of individuals/ rural community funding. Also a minimum of 1m head and small water bodies that can maintain at least 0.01m^3/s discharge throughout the year is adequate for the micro scheme and such water source is usually found in regions of medium to high annual rain fall (for up to seven months in year) as obtained in Niger Delta area of Nigeria. Hence, the micro hydro power potentials of various streams and small rivers in this area if well integrated as part of the nation's energy plan and harnessed will go a long way in improving the availability of electricity in Niger Delta region.

Umudike is one of the rural communities in Niger Delta with many water bodies (such as Anya, Akpatalamgbaja, Iyiukwumgbaja, Iyiamaya, Iyiocha, Mmiriohii etc) that have micro hydropower potentials and yet suffers epileptic public electric power supply despite that it hosts two federal research based institutions, Michael Okpara University of Agriculture (MOUAU) and National Root Crops Research Institute (NRCRI). Available records shows that Umudike located within latitude 05^0 29$^/$ North and longitude 07^0 33$^/$ East has a flat topography with height of less than 140m above the sea level and sporadic hills at greater distances apart [10]. The same record also indicates that watershed between the Cross River and Kwa-Ibo River basins is located in this area signifying the presence of hydropower resources. Thus, there is need to develop a low head turbine that can be used to assess the micro hydro resources in this area from locally sourced materials to bring environmental friendly electricity production at the tune of individual and rural community funding. Hence, the objective of this work, development of a low head micro turbine for harnessing the micro hydropower potentials of small water bodies with Anya River as a case study to serve as a model for others.

2.0 Materials and Methods

2.1 Hydro Power Potential of Anya River

Anya River is a tributary of Kwa-Ibo River which in turn took its roots around MOUAU land and empties into the Atlantic Ocean [10]. Though the river flow varies with season, its flow for over 70% of the year has harnessable hydropower potential. Since this is a small water body, the regular flow (or discharge) rate of this river was determined using Weir method as ranging between 0.04m^3/s and 0.59m^3/s. The irrigation site of NRCRI Umudike was used as the test site for this investigation. The breadth of the provisional weir of this facility was measured as 0.60m using a leveling gauge while 1.3m was determined as the water head at the site using the Dump level and Theodolite methods [8]. Thus, the theoretical hydropower potential of this river was estimated as 3507.075W using Equation (1) given by [11] as;

$$P = \rho g H_G Q \qquad (1)$$

Where; P = Hydropower in watts, (W)

ρ = Density of water = 1000 kg/m^3

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

H_G = Maximum height (head) of fall = 1.3m

Q = Design discharge rate = 0.275m^3/s (mean discharge)

The water from this river is soft with relatively low suspended solid levels and this feature makes it suitable for micro hydro power scheme since there is no fear for abrasive corrosion on the turbine vanes and sedimentation tank will not be required.

2.2 Design Considerations

The design, selection of materials and development of this low head micro turbine was based on the following considerations;

1. All materials for the fabrication were non toxic to ensure that the use of the turbine does not contaminate the water because of heavy demand on it for both irrigation and community use.
2. The turbine was developed based on run-of-river system with locally sourced standard materials to ensure low cost of production and operation as well as maintainability of the system.
3. A slope of 0.05 corresponding to a vertical and horizontal distance of 0.2mm and 4m was used in the diversion channel design to ensure effective flow from the intake structure into the turbine.

2.3 Description of the Micro Hydro Turbine

The major components of the developed low head hydro turbine (Fig. 1) are its base, strut, turbine inlet, rotor (runner assembly) and its scroll casing. The base upon which the strut was mounted was fabricated from a 75mm-section angle iron (thickness = 5mm) while the strut was made from a 100 by 50mm U-channel of the same thickness. The turbine inlet is an aperture at the top of the strut through which water from the diversion channel flows into the runner. It is made from a 5mm thick mild steel plate and angle iron of the same specification as that of the base. The runner assembly was covered with a scroll casing (made from a 5mm thick mild steel plate) whose cross-sectional areas decreases proportionally from the turbine inlet to the exit in order to ensure constant velocity of the water along the path.

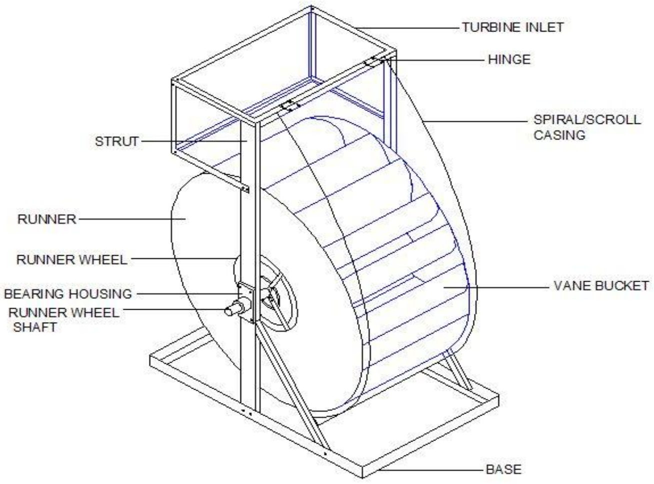

Fig. 1: The developed low head micro hydro turbine

The runner is made up of two separate circular disks connected by the runner wheel and vane buckets, this assembly was mounted on a 35mm diameter shaft made from mild steel supported at both ends using thrust bearings. Each of the disks was fabricated from 5mm thick mild steel plate while the runner wheel was made from a mild steel plate of thickness and external diameter of 10mm and 600mm respectively. In between the disks are twelve vane buckets fastened on both the wheel periphery and the disks. Each vane bucket was fabricated using 10mm thick mild steel plate with 260mm, 170mm and 160mm as axial width, radial and circumferential lengths respectively.

2. 4 Design Analysis of the Low head Micro Turbine

The velocity of approach of water entering into the turbine, V and the runner velocity, U were determined as 4.55m/s and 3.25m/s respectively using the relations given by [11] and [12] as;

$$V = K_v \sqrt{2gH} \quad (2)$$

$$U = K_u \sqrt{2gH} \quad (3)$$

Where; $K_v =$ Coefficient of velocity = 0.98

$K_u =$ Peripheral coefficient = 0.7, since flow is natural and does not employ a jet

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

The effective head, H under which the turbine operates was determined as 1.1m using the following Equation (4);

$$H = H_G - hf \quad (4)$$

Where the total head loss between the head race on turbine entrance, hf was determined as 0.2m. The mean diameter, D of the runner wheel was determined as 0.828m using Equation (5) thus, the turbine was developed with a runner wheel diameter of 0.83m and width of 0.26m [9].

$$D = \frac{60U}{\pi N} \quad (5)$$

Where N, the design speed of the runner shaft = 75rpm.

In accordance with [11], a rectangular channel is adequate and economical for conveying water into this turbine. Thus, each runner vane-bucket is of a rectangular profile with axial width and circumferential length of 0.26m and 0.16m respectively. In order to ensure maximum hydraulic efficiency of this turbine, the jet ratio, m representing the ratio of the runner's pitch circle diameter to the jet diameter was taken as 12 [11]. Hence, the cross-sectional area of the portion through which the water flows into the turbine, a. was determined as 0.0451m^2 using the following relation.

$$a = \frac{A}{m} \quad (6)$$

Where A, the area of the runner was computed from Equation (7) as 0.5411 m^2.

$$A = \frac{\pi D^2}{4} \quad (7)$$

Therefore, the number of vane buckets, Z required in this turbine and the radial length, L of each vane bucket was determined as 12 and 0.17m respectively using the following relations[11];

$$Z = \frac{360}{\theta} \quad (8)$$

$$L = \frac{a}{b} \quad (9)$$

Where b is the runner's width (0.26m) while θ constitutes the sum of the angles subtend by the profile of a vane bucket (18^0) and the space between two successive buckets (12^0).

The force, F_n exerted by the water jet on the moving vane-buckets, work done on the runner wheel due to this force, W_1 and the kinetic energy of the issuing jet on the vane bucket, KE were determined as 266.77N, 867Nm/s and 2124.13Nm/s respectively using the following the relations based on the principle of impulse momentum [12].

$$F_n = \rho a V (V - U) \quad (10)$$

$$W_1 = F_n U \quad (11)$$

$$KE = \frac{1}{2} \rho a V^3 \quad (12)$$

The potential energy, PE of the water momentarily held by the vane-bucket and work done, W_2 on the runner wheel due to the weight of this water were determined as 1872.15Nm/s and 1444.44Nm/s from the following equations given by [12] as;

$$PE = \rho a V g h \quad (13)$$

$$W_2 = T\omega \quad (14)$$

$$h = R_1 + R_2 + r_c \quad (15)$$

$$T = \rho a V^2 L \quad (16)$$

$$\omega = \frac{V}{R_1} \quad (17)$$

Where; T = Torque on the runner wheel
ω = Angular velocity of the runner
h = Total height of water in a vane-bucket above the ground
R_1 = Radius of the runner at the outer periphery of the vane-bucket = 0.5m
R_2 = Radius of the runner at the base of the vane-bucket = 0.33m
r_c = Runner clearance above ground = 0.1m

Therefore, the efficiency of the vane-bucket was determined as 57.84% using Equation (18) given by [12] as;

$$\eta = \frac{100(W_1 + W_2)}{(PE + KE)} \quad (18)$$

The turbine's runner wheel shaft diameter, d was determined using maximum stress relations given by [13] and [14] as;

$$d = \left[\frac{16}{\pi\tau}\left(\sqrt{(K_b M_b)^2 + (K_t M_t)^2}\right)\right]^{\frac{1}{3}} \quad (19)$$

where:
τ = Allowable stress for steel shaft with provision for key ways = 42N/mm^2
M_t = Maximum twisting moment on the shafts = 158.73N-mm.
M_b = Maximum bending moment on the shafts, N-mm.
k_b = Combined shock and fatigue factor for bending.
k_t = Combined shock and fatigue factor for twisting.

The applied loads on this runner wheel shaft are shown in Fig. 2, thus, the bending moments on the shaft were determined as follows;

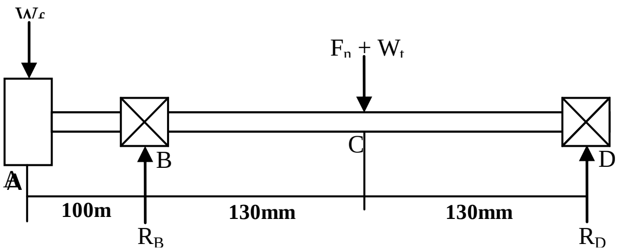

Fig. 2: The runner wheel shaft showing forces acting on it

Where the measured weight of the runner flywheel, W_f is 200.124N. The number of vane buckets that will hold water at the same time during the turbine operation is three, thus, the weight of the water, W_t momentarily held by three vane-bucket was determined as 212.37N using Equation (20) [11].

$$W_t = \rho a g L_c \quad (20)$$

Where circumferential length of the vane-bucket, L_c is 0.16m. Hence, the total force at point C (Figure 2) is 479.14N
The reactions, R_B and R_D were determined by taking moment about D
$\Sigma M_D = 0$; R_B (0.26) = 200.124(0.36) + 479.14(0.13); R_B = 516.66N
Also $\Sigma F_Y = 0$; 200.124+479.14 = 516.66 + R_D; R_D = 162.60N
The shear forces acting on this shaft were computed as follows;

F_{D-C} = 162.60N
F_{C-B} = 162.60 − 479.14 = − 316.54N
F_{B-A} = 162.60 − 479.14 + 516.66 = 200.12N
F_A = 162.60 − 479.14 + 516.66 − 200.12 = 0N

Also, the bending moments on this shaft are as follows;

M_D = 0N-m
M_C = 21.138N-m
M_B = −20.01N-m
M_A = 0N-m

Therefore, the maximum bending moment on the shaft of the runner wheel is 21.138N-m. Water flow into the turbine is steady with minor shock, hence, K_b = 2.0 and K_t = 1.5 [13]. These values were used to compute the diameter of the runner wheel shaft as 30.84mm from Equation (19). Thus, a standard 35mm diameter solid mild steel shaft was selected and used as the runner wheel shaft.
The rectangular channel inlet water flow rate, Q_1 and velocity, V_1 were respectively determined as 0.95m^3/s and 5.2m/s using the following relations given by [11] as;

$$Q_1 = \frac{A_1 R^{2/3} S^{1/2}}{n} \quad (21)$$

$$V_1 = C\sqrt{RS} \quad (22)$$

$$C = \frac{1}{n} R^{1/6} \quad (23)$$

Where; A_1 = Cross-sectional area of the channel at inlet = 0.18m^2
R = Hydraulic radius, = 0.15m
S = Slope of the channel = 0.05
n = Manning's coefficient, (0.012 for well finished concrete material) [8]
y = Water depth in the channel = 0.3m
C = Chezy Coefficient

The exit flow velocity, V_2 of the channel was also determined using Equation (24) as 8.14m/s.

$$V_2 = \frac{Q}{A_2} \quad (24)$$

Where; A_2 = Cross-sectional area of the channel exit = $0.0338m^2$.

The Q_1 >> Q indicates that the channel inlet will be effective in conveying water from the weir into the channel even in excess of the design discharge rate. Also, excess water conveyed during high flow rate at the inlet structure will be effectively channeled back to the river through the provisional spillway of the channel.

2.5 Performance Evaluation Procedure

The efficiency and power output of the hydro turbine developed were evaluated using constant head and speed characteristics tests with eight experimental runs in each case. As the names imply constant head characteristic investigation involved operating the turbine at varied speeds and discharge rates at a constant head of 1.1m while in constant speed test, only discharge rate was varied at a constant speed of 60rpm. The mechanical power output at the runner wheel shaft was measured in each test using a band and drum dynamometer. In determining the turbine power output, the scale differential, (ΔT) which is the difference between the friction tensile force on the tight side and that on the slack side of the dynamometer were first evaluated and recorded for each experimental run, then the load, (F) on the turbine and the actual torque, (T_a) developed on its shaft for each experimental run were computed using Equations (25) and (26) respectively and tabulated. Thereafter, the brake power (the actual power output of the turbine) P_B, discharge power P_Q and the efficiency of the turbine were respectively computed in each case using Equations (27), (28) and (29).

$$F = \frac{\Delta T_a}{\mu} \quad (25)$$

$$T_a = Fr \quad (26)$$

$$P_B = \frac{2\pi N_s T_a}{60} \quad (27)$$

$$P_Q = \rho g H Q_2 \quad (28)$$

$$\eta(\%) = \frac{100 P_B}{P_Q} \quad (29)$$

Where; $\mu =$ Coefficient of friction between the band and drum of the dynamometer under wet condition = 0.42

$r =$ Drum radius, 0.115m

N_s = Shaft speed in rpm

Q_2 = Discharge rate, (m^3/s)

Results and Discussion

Table 1 and 2 show the results of the turbine performance when operated under constant head and speed respectively. It is obvious from Table 1 that the brake power developed by this turbine increases proportionally with the shaft speed and discharge while its efficiency increases progressively from 60.39% at a shaft speed and discharge of 30rpm and $0.05m^3/s$ respectively to a maximum of 78.78% at 60. 03rpm and $0.42m^3/s$ and drops as the speed increases. Table 2 also shows similar trend with maximum efficiency of 80.34% at 60rpm speed and discharge rate of $0.42m^3/s$. Thus, the developed turbine performs optimally at the shaft speed of 60rpm and discharge rate of $0.42m^3/s$ with a power output 4.30322kW.

Table 1
Results of Performance Evaluation of the Turbine under Constant Head

S/No.	Discharge (m^3/s)	Shaft Speed (rpm)	Scale Differential (N)	Load (N)	Torque (Nm)	Brake Power (W)	Discharge Power (W)	Efficiency (%)
1	0.05	30.00	447.65	1065.83	122.57	385.08	637.65	60.39
2	0.11	34.83	885.65	2108.69	242.50	884.48	1402.83	63.05
3	0.20	41.60	1402.64	3340.09	384.11	1675.74	2550.60	65.70
4	0.27	50.48	1763.49	4198.78	482.87	2552.53	3443.31	74.43
5	0.35	55.80	2024.40	4820.00	554.30	3500.76	4463.55	78.43
6	0.42	60.03	2412.18	5744.78	660.65	4220.20	5356.26	78.79
7	0.50	66.53	2548.74	6068.43	697.87	4862.08	6376.50	76.25
8	0.58	73.46	2683.25	6388.70	734.70	5651.85	7396.74	76.41

Table 2

Results of Performance Evaluation of the Turbine under Constant Speed

S/No.	Discharge. (m^3/s)	Shaft Speed (rpm)	Scale Differential (N)	Load (N)	Torque (Nm)	Brake Power (W)	Discharge Power (W)	Efficiency (%)
1	0.05	60	75.27	179.22	20.61	129.51	637.65	20.31
2	0.11	60	363.17	864.70	99.44	624.82	1402.83	44.54
3	0.20	60	869.07	2069.22	237.96	1495.16	2550.60	58.62
4	0.27	60	1255.11	2988.35	343.66	2159.30	3443.31	62.71
5	0.35	60	1940.90	4620.00	531.30	3338.29	4463.55	74.79
6	0.42	60	2501.30	5955.48	684.88	4303.22	5356.26	80.34
7	0.50	60	2724.23	6486.26	745.92	4686.73	6376.50	73.50
8	0.58	60	3036.27	7229.22	831.36	5223.58	7396.74	70.62

4.0 Conclusions and Recommendations

A low head micro hydro turbine was developed using locally soured materials at Michael Okpara University of Agriculture, Umudike for harnessing micro hydropower resources of small water bodies. The turbine optimal power output is 4.30kW at 80.34% efficiency, $0.42m^3/s$ discharge rate and runner shaft speed of 60rpm. Since the development, operation and maintenance of this system is within the context of rural technology and funding, and also that its operation is environmentally friendly, it is therefore of economic sense if the production of low head turbine is integrated into Nigerian energy development plan. This will not only facilitate effective taping of enormous micro hydro power potentials of our rural small water bodies but help to bring to an end the Nigerian electrical energy crisis in the nearest future.

References

[1] R. C. Okonkwo, Rural Electrification in Nigeria: Strategies and Problems; In Eboh, E. C., Okoye, C. U. and Ayichi, A. edited *Rural Development in Nigeria.Concepts, Processes and Prospects.* Auto-Century Publishing Company limited, Enugu, Nigeria, pp. 119-126, 1995.

[2] C. D. Okereke, *Environmental Pollution Control*, Barloz Publishers, Inc. Owerri, Nigeria, pp. 22, 239-245, 2006.

[3] E. J. Ekoi and K. Onyenobi, “Energy and Economic Losses due to Constant Power Outages in Nigeria”, B. Eng. Project Department of Mechanical Engineering, Michael Okpara University of Agriculture, Umudike, 2011.

[4] B. N. Nwankwojike, “Comparative Analysis of Noise Levels of Different HouseholdElectric Power Plants Use in Nigeria”, *West African Journal Industrial* and *Academic Research,* Vol. 3, No. 1, pp, 15-24 2012.

[5] ESHA. U. Anih. Electric Power Generation in Nigeria. Agunwamba J. C.and Eze- Uzoamaka O. J. edited *Introduction to Engineering.* De- Adroit Innovation, Enugu, Nigeria, pp. 167-177, 2008.

[6] O. L. Iloeje. Resource Potentials for Power Generation in Nigeria. *National Electricity Regulatory Commission (NERC) Annual Magazine.* pp. 17-36, 2008

[7] *Guide on How to Develop a Small Hydropower Plant*, European Small Hydropower Association. (ESHA), 2009.

[8] S. Dilip. *Micro Hydro power Resource Assessment Handbook.* Prepared for Asian and Pacific Centre for Transfer of Technology (APCTT) of the United Nations – Economic and Social Commission for Asia and the Pacific (ESCAP), 2009.

[9] C. C, Warnic, H. A. Mayo Jr, J. L Carson, and L. H Sheldon. *Hydropower Engineering,* Prentice Hall, NJ. 1984

[10] Michael Okpara University of Agriculture Umudike Master Plan Report. Somieb Consortium, Enugu, Nigeria, 2004.

[11] Rajput. R.K. *Fluid Mechanics and Hydraulic Machines Textbook.* S Chand and Company New Delhi India, 2006.

[12] D. S Kumar. *Fluid Mechanics and Fluid Power Engineering Textbook.* S. K Kataria & Sons, New Delhi, India, 2008.

[13] Sharma, P.C. and Aggarwal. D.K. *Machine Design.* S.K. Kataria and Sons, Nai Sarak Dechi. Katra, 2006.

[14] Khurmi, P. S. and Gupta J. K. *A Textbook of Machine Design.* First Multicolour Edition, Eurasia Publishing House Ltd. 7361, Ram Nagar, New Delhi-110055,

Authors’ Affiliations

Nwankwojike B. Nduka, **Ogbansiegbe S. Kelechi, and Oti F. Onyedika** *are with Department of Mechanical Engineering, Michael Okpara University of Agriculture, Umudike, Nigeria while* **Onuoha F. Ijeoma** is with *Department of Mechanical Engineering,* African Institute of Science and Technology, *Nguru Mbaise also in Nigeria.*
Correspondence:-
PH : +23480375178939; E-mail: jikeobodo@yahoo.com