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Design Development of a Mixed-Mode Reciprocating Pumping System for Small Scale Rural Water Supply

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Abstract
The strenuous stress involved in manual water supply especially in rural communities is usually very frightening, with some, trekking kilometres in search of sources of portable water for domestic uses. Scarcity of water has also hindered small scale local irrigation farming in communities around Federal University of Technology Ikot Abasi, making most farm produce seasonal. The use of pumps are costly because of importation, encouraging continued foreign dependability and innovative redundancy. Consequently, it is needful to develop an alternative, sustainable and economical pumping system to cushion the problem of water supply in rural communities. The system is pioneering with a uniquely adapted combined mechanisms for both manual and electrical operations. The pumping system is designed with a crank and lever mechanism that converts the rotary motion of the crank to the reciprocating motion of the plunger for pumping cycles. Proximate resources designated for assembly, primarily encompassing cylinder, piston, suction valves, delivery valves, suction and deliver pipes, crank and lever mechanisms, mast, links, electric motors, pulleys, idlers, sprockets, gearbox, belt drives, guards and hand wheel are the main pumping components. The system is predictable to deliver a capacity of $5\ litres/min$ *at angular speed of* $0.333\ rad$ *for an optimal output (workdone) of* $1.3443\ J/s$*. It can thrust to any head since positive displacement pump is relatively suitable for small capacities and high heads, with reduced production and maintenance costs.*
Keywords: Manual water supply, Rural communities, Pumping system, Pioneering, Proximate resources

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I. Introduction

Water is essential to human life, serving as body lubricant and temperature regulator, and as fluid of all known living organism, among other functions [1]. Its uses are enormous spanning domestic, environmental, agricultural, as well as industrial, having applications in all spheres of life [2],[3]. Portable water should be tasteless, colourless and odourless [4]. Most rural communities face significant problem accessing portable water due to limited infrastructure, financial constraints, and technical challenges, leaving them with the option of reliance on unsafe water sources. These conditions usually result in waterborne diseases, illnesses and hindrances to livelihood, and it necessitates government optimum and timely interventions [5].

For communities with streams and springs, the bottleneck becomes the countless efforts of trailing long distances every day to fetch water against the use of pumps [6]. Unavailability of sustained sources of water has also hampered both the economy of subsistence farmers and the practice of local irrigation farming [7].

A pump which is a major part of hydraulic system, converts mechanical energy into hydraulic energy [8]. The mechanical energy is delivered to the pump via a prime mover such as an electric motor. Due to mechanical actions, the pump creates a partial vacuum at its inlet, and this permits atmospheric pressure to force the fluid through the inlet line and into the pump, where the pump then pushes the fluid into hydraulic system [9]. The design development of a simple reciprocating positive displacement pump is a significant research in engineering especially because they are widely used in various industries, including oil and gas, water treatment and food processing. [9],[10].

The history of positive displacement (PD) pumps dates back to the early 19th century, with the development of the first reciprocating pump [11],[12]. Since then, various types of these pumps have been designed including rotary and gear pumps [13]. However, reciprocating positive displacement pumps remain widely used due to their simplicity and ease of maintenance [14].

Generally, PD pumps compress the liquid from suction conditions to discharge conditions and can achieve this at any speed. In fact, velocities tend to be low so there are no problems in ignoring the kinetic energies in the suction and discharge pipes. On the other hand, the pressures developed tend to be very large in comparison to the physical dimensions of the pumps; so there are no problems in ignoring the potential energy due to elevation in the suction and discharge systems [15],[16]. Although there are variations within the counter force, the PD pumps deliver an approximated steady flow at a speed. They have cyclic pumping action and are driven by either screws, pistons, rollers, gears, diaphragms, or vanes [17].

The working principle of a PD pump is that the flowing liquid in the pump may be collected inside a cavity and discharged in a predetermined quantity. A few parts, including the piston, diaphragm, and plunger, might cause liquid dislocation. The pumps have an expanding cavity on the suction side and a diminishing cavity on the discharge side. The liquid is usually sucked on the inlet side as the cavity expands and then released when the cavity shrinks [18]. These pumps operate by trapping a fixed amount of fluid and displacing it from the inlet to the outlet [19].

With a definite volume of fluid delivered by PD pumps for each cycle of pumping operation, the volume is constant regardless of the resistance to flow offered by the system the pump is in, provided the capacity of the power unit driving the pump or the component strength limits of the pump are not exceeded. The PD pump delivers fluid in separate volumes with no delivery in between, although a pump having several chambers may have an overlapping delivery among individual chambers, which minimizes this effect. The PD pumps differ from centrifugal pumps, which deliver a continuous flow for any given pump speed and discharge resistance [19],[20],[21]. Basically, this principle can be most easily demonstrated by considering a reciprocating PD pump consisting of a single reciprocating piston in a cylinder with a single suction port and a single discharge port [22].

The reciprocating pump is a positive displacement pump that sucks and raises the liquid by actually displacing it with a piston or plunger that executes a reciprocating motion in a closely fitting cylinder. The amount of liquid pumped is equal to the volume displaced by the piston [23], [24]. The pump designed with disk piston creates a pressure up to 25 bars and the plunger pumps built up higher pressures, and discharge from these pumps is almost wholly dependent on the pump speed. The total efficiency of a reciprocating pump is about 10 to 20% higher than a comparable centrifugal pump [22],[23],[24].

Reciprocating pumps for industrial uses have become obsolete owing to their high capital cost as well as maintenance cost compared to that of a centrifugal pumps. Nevertheless, small hand operated pumps such as cycle pumps, football pumps, kerosene pumps, community well pumps and pumps used as important parts of hydraulic jack, and so on still find wide applications. Reciprocating pumps is best suited for relatively small capacities and high heads [23],[24],[25],[26] [27].

Assuming that initially the crank is at the top dead centre (TDC) and the crank rotates in a clock wise direction. As the crank rotates, the piston moves towards up and a vacuum is created on the down side of the piston. The vacuum causes suction valve to open and consequently the liquid is forced from the sump into the down side of the piston. When the crank is at the bottom dead centre (BDC) the suction stroke is completed and the bottom side of the cylinder is full of the liquid [23],[24]. When the crank further turns from TDC to BDC, the piston moves inwards to the bottom and the high pressure is built up in the cylinder. The delivery valve opens and the liquid is forced into the delivery pipe. The liquid is carried to the discharge tank through the delivery pipe. At the end of delivery stroke the crank comes to the bottom dead centre and the piston is at the extreme bottom position [27], [28].

It is widely used in various applications, including internal combustion engines, pumps and compressors, presses, robotics, toy cars, and in steady state rod bending vibration investigation [23],[27]. However, despite their widespread application, PD pumps have numerous limitations, including low efficiency and high energy consumption [28]. To address these bottlenecks, researchers have explored new designs and materials, such as the use of composite materials and optimized pump geometries [29].

This research is intended to develop an affordable and a more efficient reciprocating PD pumps for small scale applications, offering solutions to rural water supply at homes and communities, general fluid transfer problems and expansion of the economy of subsistence farmers via local irrigation farming. This innovative design has handled the difficulties of high energy consumption, high cost of importation and foreign dependability, by adopting simplified geometry and minimal material requirements easing maintenance and repair and limiting downtime. The design equally has potentials for scalability, mass production and commercialization.

II. Materials and Methods

2.1 Design Concept / Theory of Operation

Crank and lever mechanism is an arrangement of mechanical parts designed to convert straight-line motion to rotary motion, as in a reciprocating piston engine, or to convert rotary motion to straight-line motion, as in a reciprocating piston pump [24]. Link mechanisms are interconnected for necessary relative motions [25].

2.2 Design Standards

The idea of the design is to use the crank and lever mechanism of a beam engine such that the rotary motion of the crank will be converted to the reciprocating motion of the pump plunger for pumping operations. The design will have a pulley system with an electric motor for ease of pumping and will as well incorporate a manual handle in case of power failure.

2.3 Design Considerations

The following considerations will be understudied in the design of the mixed-mode pumping system:

i. Type and working of the pumping system.
ii. The size of the cylinder for the top dead centre (TDC) and the bottom dead centre (BDC).
iii. Amount of water to be discharged.
iv. Power required to drive the pump.
v. Co-efficient of the discharge and the slip of the reciprocating pump.
vi. Velocity of the electric motor.
vii. Pressures in the suction and delivery pipes
viii. Sizes of pipes, base plate, crank and lever mechanism.
ix. Sealing needed for pressure build up
x. Corrosion inhibitor required
xi. Sizes of valves and online strainers

2.4 Design Calculations

The procedures followed during design calculations are as presented;

2.4.1 Discharge:

The discharge of pump per second;

$$Q = \frac{AL\,N}{60} = \frac{VN}{60}\, m^3/s \qquad 1$$

Where Q = discharge, A = area, L = length of stroke**,** N= number of crank, V= volume of liquid

2.4.2 Weight of water delivered:

This is calculated thus;

$$W = \frac{WALN}{60} \qquad N/S \qquad 2$$

2.4.3 Workdone per second:

The workdone is given as;

$$K = (h_s + h_d)\ \text{J/s} \qquad 3$$

Where K= workdone, h_s= height of centre of suction pipe, h_d = height to which the water will be raised

Power required:

$$P = \frac{wALN}{60000}((h_s + h_d)\ \text{J/s}) \qquad 4$$

Where = power required

2.4.4 Coefficient of discharge;

$$C_d = \frac{Q_{act}}{Q_{th}} \qquad 5$$

Where C_d = coefficient of discharge, Q_{act} = actual discharge, Q_{th} = theoretical discharge

2.4.5 Slip:

$$\text{Slip} = Q_{th} - Q_{act} = (1 - C_d)\ 100 \qquad 6$$

2.4.6 Velocity of flow:

This is calculated using the expression:

$$V = wrcoswt \qquad 7$$

Where V = velocity of flow, w = angular velocity, t= time of flow, r = radius

2.4.7 Pressure head due to acceleration:

The pressure head due to flow acceleration is given thus;

$$P_a = \frac{LA\omega^2 rcos\theta}{ga} \qquad 8$$

Where a = Acceleration

For velocity and acceleration relations, [18], [20], [23], [24] present thus;

Maximum velocity of the of the crank during its discharge (outstroke)

$$V_0 = \frac{\pi\omega S}{2\theta_O} \qquad 9$$

Maximum velocity of the crank during its suction (return stroke)

$$V_R = \frac{\pi\omega S}{2\theta_R} \quad 10$$

Maximum acceleration of the crank on the discharge (outstroke)

$$a_0 = \frac{(\pi\omega)^2 S}{2\theta_O{}^2} \quad 11$$

Maximum acceleration of the crank on the suction (return stroke)

$$a_R = \frac{(\pi\omega)^2 S}{2\theta_R{}^2} \quad 12$$

For shaft design, the equation of maximum shear stress theory for the maximum shear stress on the shaft is given thus;

$$\tau_{max} = {}^1/_2\sqrt{\delta_b{}^2 + 4\tau^2} \quad 13$$

where τ_{max} = maximum shear stress, δ_b = bending stress and τ = torsional shear stress

But the twisting moment on the shaft and torsional shear stress are related as shown;

$$^T/_J = {}^\tau/_r \quad 14$$

where T = twisting moment acting upon the shaft, J = polar moment of inertia of the shaft about the axis of rotation and r = distance from the neutral axis to the outer fibre ($^d/_2$ but d = diameter of the shaft).

Recall, $J = \frac{\pi d}{32}$ 15

Equation (14) now becomes

$$\frac{T}{^\pi/_{32d^4}} = \frac{\tau}{^d/_2} \quad 16$$

$$\therefore\ \tau = \frac{16T}{\pi d^3} \quad 17$$

In the case of belt drive, the twisting moment (T) is givrn by;

$$T = (T_1 - T_2)R \quad 18$$

where T_1 and T_2 = tensions in the tight and slack side of the belt respectively and R = radius of the pulley.

Moreover, bending moment and bending stress are related thus;

$$\frac{M}{I} = \frac{\delta b}{y} \quad 19$$

where M = bending moment, I = moment of inertia of cross sectional area of the shaft, δb = bending stress and y = distance from neutral axis to the outermost fibre.

Maximum shear stress is given by;

$$\tau_{max} = \frac{1}{2}\sqrt{32M/\pi d^3 + 16T/\pi d^3} \quad 20$$

The equivalent twisting moment and bending moment was obtained using (21);

$$T_e = \sqrt{(MK_m)^2 + (TK_t)^2} \quad 21$$

where K_m = combined shock and fatigue factor for bending for a rotating shaft taken as taken as 1.5 and K_t = combined shock and fatigue for torsion for a rotating shaft taken as 1.0

$$M_e = \frac{1}{2}[M + \sqrt{(MK_m)^2 + (TK_t)^2}\ ] \quad 22$$

where T_e = equivalent twisting moment, M_e = equivalent bending moment, T = torque and M = bending moment.

For pulley system;

Velocity ratio is given by;

$$\frac{\pi D_1 N_1}{60} = \frac{\pi D_2 N_2}{60} \quad 23$$

Since it is assumed there is no slip between the belt and pulley then:

$$\frac{D_1}{D_2} = \frac{N_2}{N_1} \quad 24$$

where D_1 = diameter of driving pulley, D_2 = diameter of driver pulley, N_1 = speed of electric motor and N_2 = speed of camshaft.

The tension on the tight and slack sides of the belt represented respectively by T_1 and T_2 were determined following (25) and (26):

$$P = (T_1 - T_2)V \quad 25$$

Additionally, $2.3\log\left(\frac{T_1}{T_2}\right) = \mu\theta$ 26

where P = power of the electric motor (1.5 KW), V = velocity of rotation and μ = coefficient of friction (0.3).

2.5 Features of the Pump System

The components of the pump system is summarized as follows;

i. Cylinder

ii. Piston
iii. Suction valve
iv. Delivery valve
v. Suction pipes
vi. Delivery pipes
vii. Crank
viii. Lever
ix. Link mechanisms

2.6 Materials Selection

The healthy condition of the materials as well as the resistance to fatigue, stresses and high compression pressure were considered, thus the following materials were suitable during the selection processes:

i. Galvanized plate: This was introduced at the base of the pumping system to house every other components.
ii. Galvanized pipe: Considering the high pressure of the plunging force, a thick galvanized cylindrical pipe was selected for the cylinder.
iii. Mild steel: The crank and lever were made of a mild steel plate, with attention to their thicknesses to withstand bulging and wobbling.
iv. PVC pipe: Polyvinyl chloride pipes were used as suction and delivery pipes, because of its reduced drags and flow friction.
v. Sealing material: O-ring sealant of different sizes were introduced to prevent pressure loss. Seal tape was also used while installing valves and online strainers.
vi. Steel rod: Steel rods were used as link mechanisms and connecting rod to be sturdy
vii. Rubber studs: For proper padding and shock absorbing, rubber studs were prominent for these purposes

2.7 Design Construction

Standard construction procedures with appropriate material selection, safety and good aesthetics were followed [23], [24], [25], [30], [31].

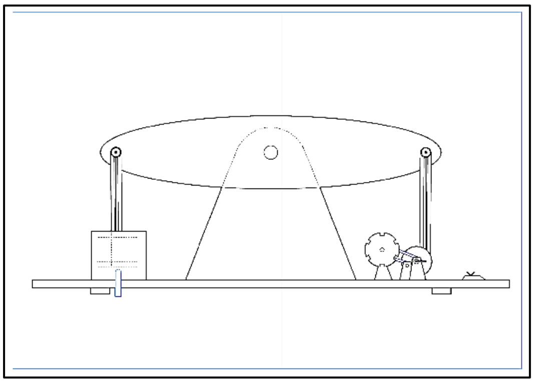
2.8 Experimental Analysis

The experimental analysis of the pumping cycle was modelled and calculated in terms of system discharge, pumping heads, pipe losses, electric motor capacity and temperature variations.

III. Results and Discussions

3.1 Results

The results are presented as working drawings, in Figure 1, 2, 3, 4, 5 and 6, including orthographic elevations, detailed labelled illustrations and 3D modelling;



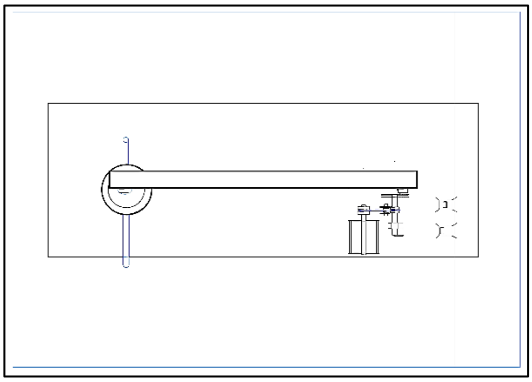
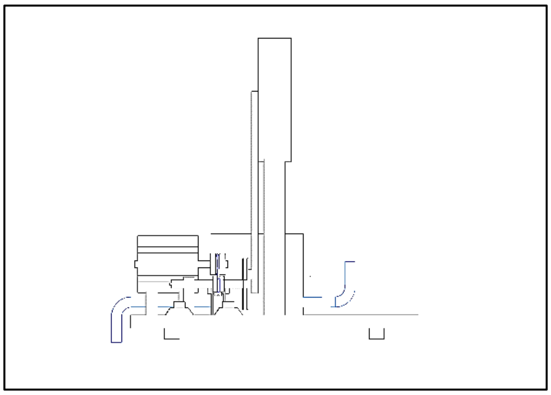
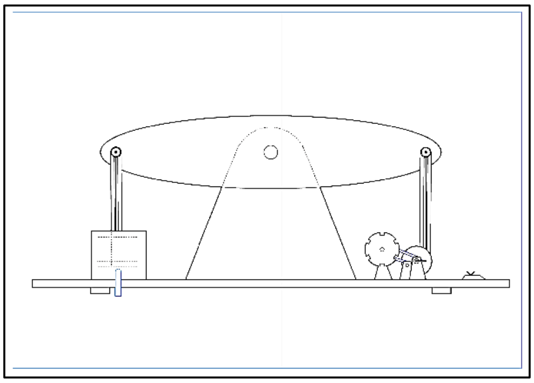


Figure 1: Front orthographic elevation Figure 2: Plan (orthographic)



Figures 3: End orthographic elevation



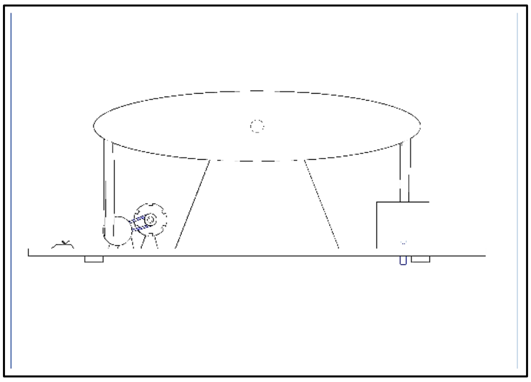


Figure 4: Front elevation (main)   Figure 5: Front elevation (rear)

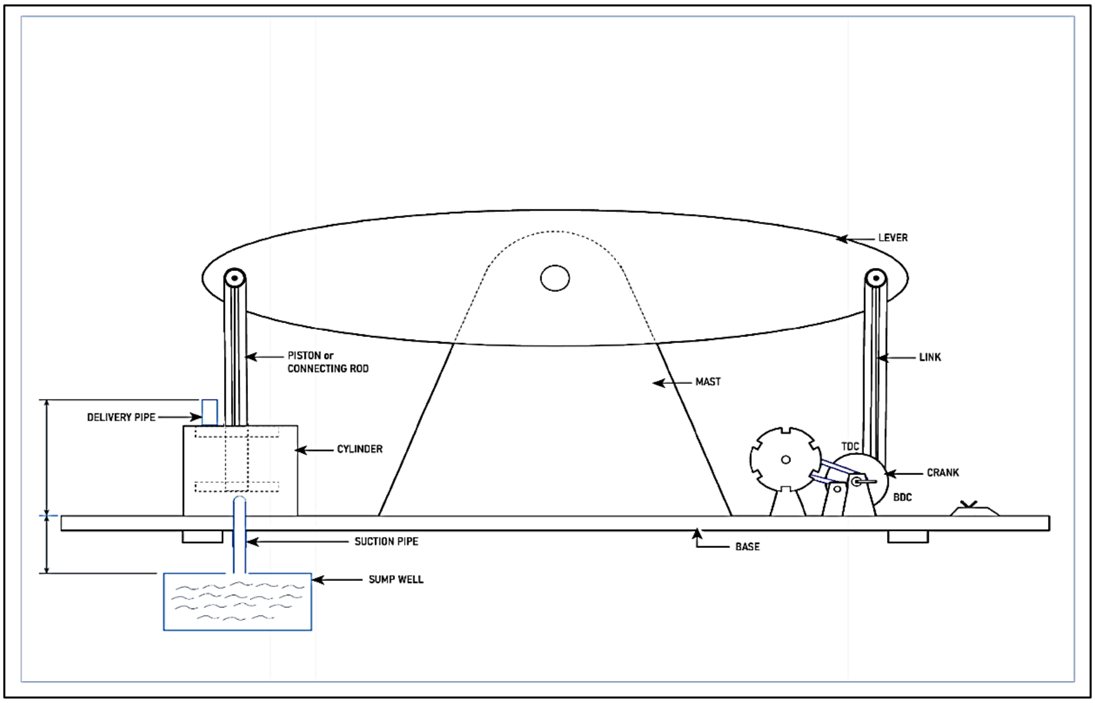


Figure 6: Detailed labelled illustration

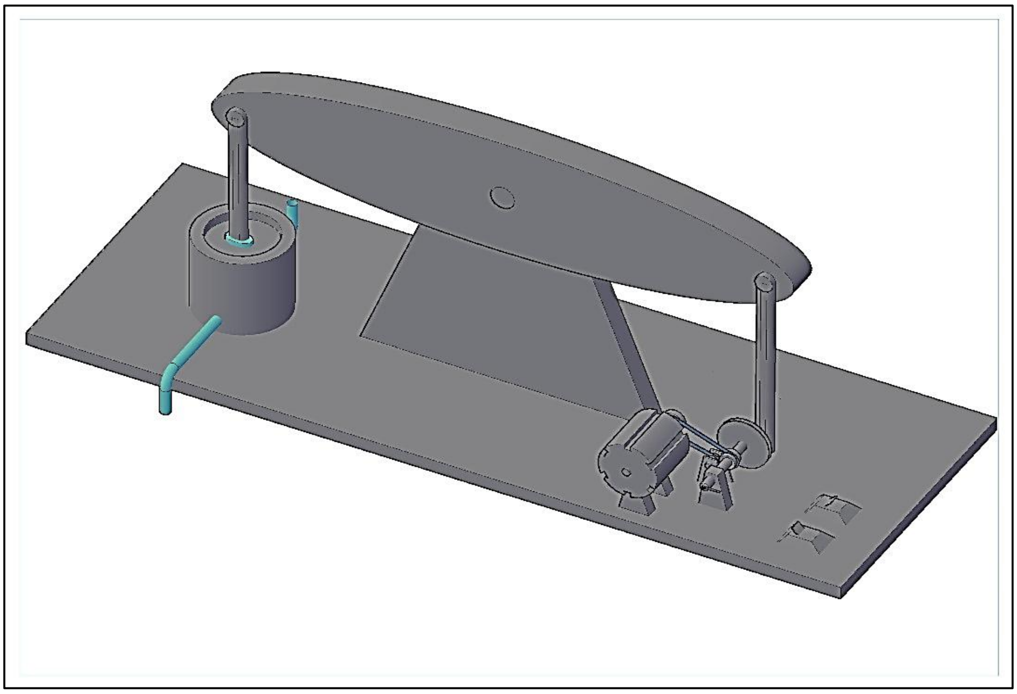


Figure 6: Design 3D modelling

3.2 Discussions

The model provided an inventive, simple and adaptable mixed-mode system which is capable of discharging pumping cycle for fluid motion. The pump design is special with a mask mounted on the thick base to support the lever fixed to a rocking bushing. The crank is connected to a belt drive to ensure a continuous rotary motion and also carries a hand wheel for manual operations, in cases of power failure. Idlers are introduced for change in flow cycle, together with a speed control system for thrust safety. Appropriate sealant is introduced to guarantee an air/water tight assembly, and to minimize pressure losses. The fused circuit controls the power intake, as well as electric surges, promoting both human and equipment safety. The crank at TDC, the pump completes the intake cycle and delivers completely when the crank returns to BDC. Short links adopted in the design prevent material bulging and safeguard maximum pressure during the plunging stroke.

With a suction cross sectional area of $3.1416 \times 10^{-4} m^2$, the pump delivers at $1.1689 \times 10^{-3} m^3/s$ with energy consumption of $1.3443 \times 10^{-3} KW$. The discharge has efficiency drop due to a general slip of 20%, falling within the design range for pumps maintained in good condition at optimal usage

IV. Conclusions

The design of the mixed-mode pump was conceptualized, developed and produced as presented in the study. Its design components offers easy conveyance with rolling drive. The crank is coupled on a thrust bearing, to ease adaptability and manual operations.

It is simple, compact and stress-free to be used, giving further benefit to its design for rural communities. The hypothetical minimum and maximum designed crank speeds are reasonable. For every one (1) second with an angular speed of $0.333\ rad$, the piston travelled the distance between TDC and BDC, giving a theoretical discharge of $1.1689 \times 10^{-3} m^3/s$, for a crank radius of $0.09\ m$. The power consumption was kept at $1.3443 \times 10^{-3} KW$. Flow losses due to frictional force in pipes, head loss in pipe bends, and workdone against rotating and reciprocating parts were accounted for. These influenced the overall system efficiency to 80.0%. Generally, resultant effect of the pumping system include minimized stress of water supply in the rural communities, enhanced irrigation farming and improved economic activities.

References

[1] Kilic, Z. (2020). The Importance of Water and Conscious Use of Water. *International Journal of Hydrology*, 4 (5).

[2] Arora, K. R. (2007). *Irrigation, Water Power and Water Resources Engineering*. Fourth Reprint Edition. A. K. ain for Standard Publishers Distribution 1705-B, Nai Sark Delhi – 110006, Pp 133-167.

[3] Ezugwu, M. O. and Akhimien, F. O. (2022). Review of the Effects of Water Characteristics and Quality on Human Health. *International Journal of Current Science Research and Review 05 (03), 673-685.*

[4] Ocheri, M. I., Odoma, L. A. and Umar, N. D. (2014). Groundwater Quality in Nigeria Urban Areas: A Review. *Global Journal of Science Frontier Research, Environment and Earth Science 14 (3) Version 1.0.*

[5] Ihunwo, C. C. (2021). Exploring the Importance and Impact of Quality Water on Human Health. *International Journal of Academic Health and Medical Research, 5 (10), 90-96.*

[6] Çepel, N. and Ergün, C. (2003). *The Importance of Water and its Ecological Problems*.

[7] Hashemi, S., Darzi-Naftchali, A., Karandish, F., Ritzema, H. and Solaimani, K. (2024). Enhancing Agricultural Sustainability with Water and Crop Management Strategies in Modern Irrigation and Drainage Networks. *Agricultural Water Management, 305 (6), 829-842.*

[8] Watton, J. (2007). *Modelling, Monitoring and Diagnostic Techniques for Fluid Power Systems*. Springer; Berlin, Germany.

[9] Bensaad, D., Soualhi, A. and Guillet, F. A. (2019). A New Leaky Piston Identification Method in an Axial Piston Pump Based on the Extended Kalman Filter. *Measurement*, 148 (106921)

[10] Johnston, D. N. (1991). Numerical Modelling of Reciprocating Pump with Self Acting Valves. *Proceedings of Institute of Mechanical Engineering,* 205, 87-96.

[11] Anthony, E. (2014). *Fluid Power with Applications* (Seventh Edition) London: Pearson Education Limited.

[12] Rayner, R. (1995). *Pumps Users Handbook*, 4th ed., Elsevier Advanced Technology, Pp. 131-170.

[13] Menkara, A., Faryami, A., Viar, D. and Harris, C. (2022). Applications of a Novel Reciprocating Positive Displacement Pump in the Simulation of Pulsatile Arterial Blood Flow. *PLoS ONE* 17(12):e0270780

[14] Li, R., Wei, W., Liu, H., Ye, J., Wang, D., Li, S. and Wang, W. (2022). Experimental and Numerical Study of the Dynamic and Flow Characteristics of a Reciprocating Pump Valve. *Processes*, 10(7), 1328

[15] Brain, N. (2006). *Handbook of Pump and Pumping: Pumping Manual International*. London: Elsevier Science & Technology Books.

[16] Igor. J. K., Joseph, P. M., Paul, C., and Charles, C. (2001). *Pump Handbook* (Fourth Edition). New York: McGraw-Hill.

[17] Lev, N. (1999). *Centrifugal and Rotary Pumps Fundamentals with Applications*. New York: CRC Press.

[18] Tackett, H. H., Cripe, J. A. and Dyson, G. (2008). *Positive Displacement Pumps Fundamentals – Power and Direct Acting Types*, Texas A&M University Turbomachinery Laboratory, Pp. 3-11.

[19] Wang, G., Zhong, L., He, X., Lei, Z., Hu, G., Li, R.and Wang, Y. (2015). Dynamic Behaviour of Reciprocating Plunger Pump Discharge Valve Based on Fluid Structure Interaction and Experimental Analysis. *PLoS ONE*, 10, e0140396.

[20] Committee, E. T. (2007). *Positive Displacement Pumps, A Guide to Performance Evaluation.* New York: Wiley-Interscience.

[21] Jekayinfa, S. O. and Bamgboye, A. I. (2006). Development of Equations for Estimating Energy Requirement in Palm Kernel Oil Processing Operations. *Journal of Applied Science*. 2, 2-5

[22] Rudolf, J., Ted, R. H., Brian, A. F. and Rajan, V. S. V. (2005). Optimum Design Parameters for Reciprocating Pumps used in Natural Gas Wells. *Journal of Energy Resources Technology*, 127 (4), 285-292

[23] Khurmi, R. S. and Gupta, J. K. (2005). *A Textbook of Machine Design*. 5th Edition, SChand & Co. Ltd New Delhi, India. Pp. 774-779.

[24] Khurmi, R. S and Gupta, J. K. (2007). *Theory of Machines. Multi-colour Edition*, S. Chand Publishers, India. Pp. 504-509.

[25] Khurmi, R. S and Gupta, J. K. (2004). *Mechanics of Machines. 3rd Edition*, S. Chand Publishers, India. Pp. 368-382.

[26] Rajput, R. K. (2007). *Fluid Mechanics and Hydraulic Machines. 2nd edition*, S. Chand Publishers, India.

[27] Irving, H. S. and Rao Mohana, G. K. (2006). *Engineering Mechanics (Statics and Dynamics)*. Pearson Education.

[28] Tang, S., Zhu, Y. and Yuan, S. (). An Improved Conventional Neural Network with an Adaptable Learning Rate towards Multi-signal Faults Diagnosis of Hydraulic Piston Pump. *Advance Engineering Information*. 50, 101406.

[29] Li, X., Cao, Z., Wei, Z. and Ren Q. (2025). Theoretical Model of Energy Conversion and Loss Prediction for Multi-Stage Centrifugal Pump as Turbine. *Energy Conservation Management*, 325, 119379.

[30] Chapman, W. A. J. (1974). *Workshop Technology Part 1. Fifth Edition*. Edward Arnold (Pub) Ltd.

[31] Tharaja, B. L. (2000*). Fundamentals of Electrical Engineering and Electronics*. Edward Arnold Publishers Ltd.