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Electromagnetically-Actuated Double-Acting Reciprocating Pump for Industrial Applications

Ishola Ademayowa Afiz, Obasa Abdul-Hafiz and Adekunle Gideon

Abstract -- This study presents the design of an electromagnetically-actuated double-acting reciprocating pump for industrial applications. This concept was developed to replace the conventional rotating crank principle traditionally used to actuate a double-acting reciprocating pumps. An electromagnetic oscillator is designed using two linearly placed electromagnets. The electromagnets are designed to achieve translational and oscillatory motion by means of a circuit designed to alternate the polarities of one of the electromagnets and control the speed of oscillation. The electromagnetic oscillator is coupled to a double-acting reciprocating pump for which pump rate, fluid discharge and pressure are measured at the pump outlet. The purpose of this model is to achieve compactness in line with versatility.

Index Terms: Astable multivibrator, double-acting reciprocating pump, electromagnetic oscillator, density, micro pump, pressure, relay, switching circuit.

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1.0 INTRODUCTION

The advancement in electro-mechanical systems has greatly influenced industrial growth and production plants in recent times. Improved technical designs of industrial equipment has also favored output and overall performance of industries. Virtually all industries require a pumping system either for hydraulic or pneumatic purpose and as such this model will be a discrete phase in advancing and improving the industrial process of pumping fluids. Pumping system has overtime served as a means of conveying fluid from a source to a destination for various purpose. Several types and classification of pumps have been developed over centuries, also, they have been designed from different concepts but they ultimately serve similar purpose. Pumps have been majorly classified into positive displacement and rotodynamic based on the theory of the moving fluid [1].

The integration of electronics, electrical and mechanical applications for developing engineering systems is a scheme of mechatronics [2]. The scope of this study is to design an electromagnetic oscillator coupled to a double-acting reciprocating pump that will be used to pump fluids of various densities from a reservoir through a flow system to a destination or to power other hydraulic devices.

The principle of electromagnetism is produced by allowing electric current to flow through a coil wounded on an iron core. This induces north and south polarities on the electromagnet [3]. In this study, oscillation is achieved by placing two electromagnets beside each other which induces magnetic characteristics of like poles to repel and unlike poles to attract. A shaft is coupled to a piston to reciprocate within a cylinder barrel. This advancement effectively replaces the rotating crank as displayed in figure 1 and due to its design it is viewed as a compact model and can be assembled in one single unit. Also, due to its compatibility, it can be further scaled into a micro pump suitable for medical applications. This will be the next phase of advance study and design model to be achieved.

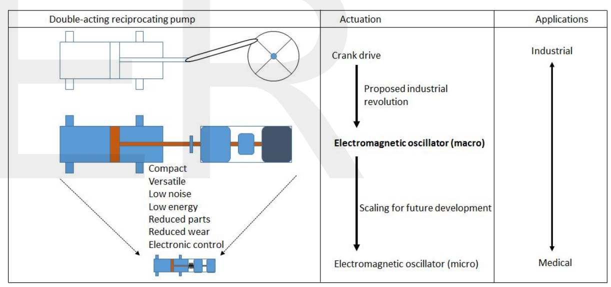

Fig. 1: Purpose of study for industrial development and schemes of advanced research models

However, efforts has been made in the past to develop electromagnetic pumps. In fact many patent works had been produced since late 19th century and research works are still in progress to advance electromagnetic reciprocating pump designs.

1.1 Technical Background

Shiro Takahasi's model of electromagnetic reciprocating pump is a design of a stationary electromagnet adapted to drive a magnetic armature. A pulse current is used to power the stationary electromagnet which attracts the armature thereby moving in the direction of its axis. A return spring is attached to the magnetic armature and reciprocating motion is generated allowing fluid transfer [4]. Kenji Mizuno et al. [5] also developed a similar version of Shiro's model but in their design, are two concentric cylinders. The external cylinder is axially secured to a frame and the internal cylinder is coaxially placed inside the outer cylinder and allowed to move freely with a retractable spring attached forming a working chamber. A magnetic coupling links the outer and inner piston where a reciprocating motion takes place.

The design patent of H.F. Elliot [6] is a different principle from that of Shiro and Kenji. In his patent model, a nonmagnetic material is in form of a cylindrical chamber such that the flat head of the cylinder is a sealed diaphragm. Below the diaphragm is a magnetic solenoid and upper part of the pump are the inlet and outlet ports with each having a check valve. A pulsating unidirectional circuit causes the diaphragm to vibrate creating partial vacuum substantial enough to supply fluid through the inlet port and discharge through the outlet port.

2.0 ELECTROMAGNETIC OSCILLATOR

A bigger electromagnet is produced stationary with fixed polarities while a smaller electromagnet is also produced mounted on a shaft with varying polarities. A switching circuit is designed to alternate the polarities of the smaller electromagnet in fractions of a second. This relatively cause the polarities to vary interchangeably from north to south and vice-versa. Timely, when both electromagnets are in contact with like poles they repel causing the smaller electromagnet to move a translational fixed distance of a stroke in the double-acting reciprocating pump and vice-versa. This movement occurs at a timed interval of oscillation which can be adjusted.

The important factor to be considered in the design of the electromagnets is the force required to overcome friction, static force and all other opposing parameters. The shaft assembled unit is measured by weight and it is expected to move the distance of a stroke. The required force calculation was estimated to 500N.

From Maxwell's pulling equation:

$$F = \frac{B^2 A}{2\mu_0} \qquad (1)$$

According to Ampere's work law or Ampere's circuital law,

$$B = \mu_0 H \qquad (2)$$

Where H, is Field Strength (ampere per meter, A/m)

$$\text{Also, } H = NI/L \qquad (3)$$

By substituting equation (3) into (2), the expression for the flux density B becomes:

$$B = \frac{NI\mu_0}{L} \qquad (4)$$

By substituting equation (4) into equation (1), the force expression can be rewritten as:

$$F = \frac{\mu_0 \, (NI)^2 \, A}{2L^2} \qquad (5)$$

Therefore, the number of turns, N, required by the electromagnets is expressed as;

$$N = \sqrt{\frac{2\,F\,L^2}{I2A\,\mu_o}} \qquad (6)$$

2.1 Circuit Design Consideration

The design of the hydraulic circuit is predicated on certain requirements and assumptions. These includes; The

a) Force required
b) Functional rate of the circuit
c) Environmental conditions
d) Control requirements
e) Economic/cost considerations
f) Duty cycle
g) Life expectancy
h) Maintainability \ reliability
i) Safety

The switching circuit is specially designed to meet the requirement of the electromagnetic operations. The major stages of the switching circuit design are:

2.1.1 Power Input

The power input stage is an *ac* input of 220V/240V channeled into different paths. A path goes to a step-down transformer which transforms the input 220/240V to 12V and powers the oscillating circuit. However, the 12V supply is first rectified before being channeled to the oscillator. The other paths go to rectifiers through which the big electromagnet is powered directly at 220/240V *dc*, and the small electromagnet through the help of two relay coils.

2.1.2 Rectification

A rectifier is an electronic device that converts *ac* input to a *dc* output. It simply changes the sinusoidal nature of an *ac* supply into a straight line *dc* supply [7].

There are three different rectification stages in the circuit as also pointed out above. The first rectification is that through which the oscillator is powered. This rectification section deals only with the voltage required (12V) to initiate a switching action in the relays that control the small

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electromagnet. The second rectification section deals with the voltage at which the small electromagnet is powered (220/240V). This is the voltage that the relays switch. The third rectification stage supplies power to the big electromagnet directly at the same voltage the small electromagnet is powered. Both rectifiers for the big and small electromagnets receive *ac* supply at 220/240V level and converts it to *dc* at same voltage level.

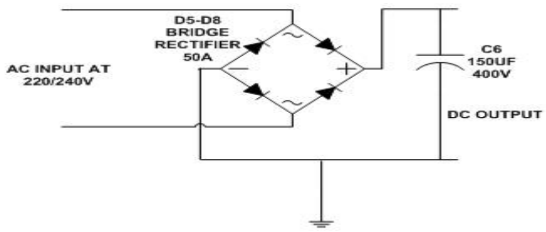

Fig. 2: Circuit diagram showing the rectification phase

In Fig. 2 above, the coupled capacitor works as a filter to minimize the ripple content in the rectifier output. However, the filtered output is the product of the pulsating rectified output and the square root of 2.

2.1.3 Oscillation

An oscillating circuit is that which is used to generate an *ac* signal at a required frequency output. This oscillator is incorporated into the circuit to control the switching time for the connected relay at a regular interval. It should be noted that the oscillator is the heart of the switching required to initiate reciprocation within the electromagnetic unit. An astable multivibrator switch is employed to enable the generation of two pulsating square wave *ac* signal output.

This technique is employed to control the two relays connected to power the small electromagnet. The two outputs from the oscillator are supplied at different but regular time interval and as this is done, the relays are triggered at separate but equal time and causes the relays to switch on and off, thus changing the polarity of the *dc* power supply from the relay at regular time interval.

There are different types of oscillators but the one used in this project is an astable multivibrator.

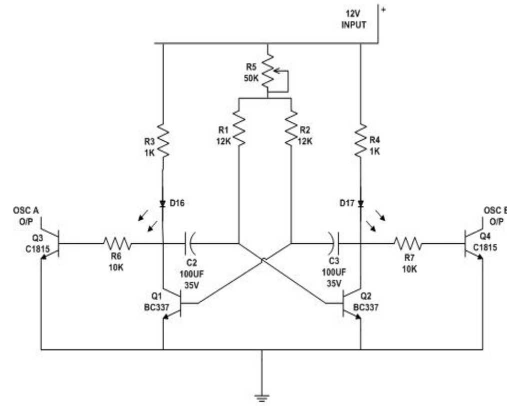

Fig. 3: Switching circuit of the oscillation stage

2.1.4 Switching Time

It can be proved that off-time for Q_1 is $T_1 = 0.69R_1C_1$ and that for Q_2 is $T_2 = 0.69\ R_2C_2$.

Hence, total time-period of the wave is

$$T = T_1 + T_2 \tag{7}$$

$$T= 0.69\ (R_1C_1 + R_2C_2)$$

If $R_1 = R_2 = R$ and $C_1 = C_2 = C$ i.e. the two stages are symmetrical, then

$$T= 0.69\ (RC + RC)$$

$$T= 0.69\ (2RC)$$

$$T = 1.38\ RC \tag{8}$$

From the above expressions the switching time of the switching circuit can be estimated.

$$R_1 = R_2 = R = 12k\Omega \tag{9}$$

From Fig. 3, the minimum time that can be achieved from the switching circuit is 1.656s. The additional resistor of 50kΩ adds to the time and gives a maximum switching time the switching circuit can produce.

The minimum switching time from the circuit is 1.656s and the maximum time is 8.556s. However, the actual time of the practical value has very minimal deviation from the calculated value. This is as a result of the components used not having the actual value as expected.

2.1.5 Relay Switching and Power Output

A relay is an electromechanical switch that switches power supply by the means of a magnetic coil. The section in the relay that initiates the switching requires lesser power input compared to the power required to switch. It has five pins of which two is for the magnetic coil input that

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initiates the movement of the relay gang from one point to another. The three other pins represents the NC (normally closed), NO (normally open) and the COM (common). The switching gang is always at NC when there is no input to the magnetic coil section required to activate the relay. The gang switches to the NO when there is an input sufficient to activate the relay at the magnetic coil section. Both the NO and NC are connected to the COM point but only one of the points can be connected at a time.

The input of the relays that initiate the switching in the circuit is a 12V input supplied from the oscillator. The relay is designed to switch 220/240V dc power supply.

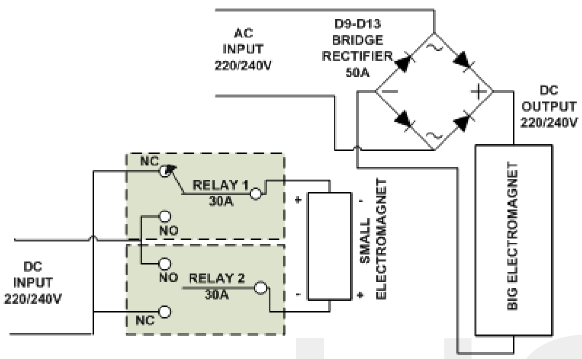

Fig. 4: Circuit for relaying and power output

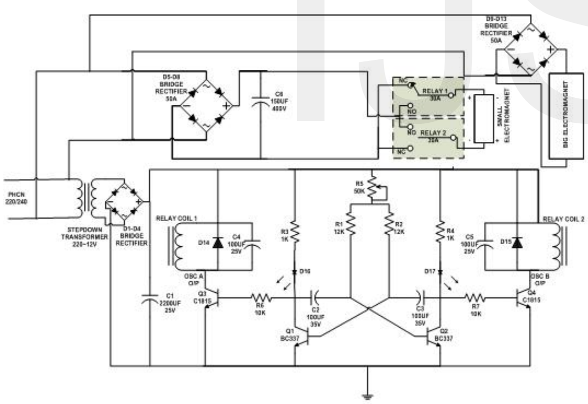

Fig. 5: Switching circuit for controlling the electromagnets

3.0 FABRICATION AND ASSEMBLY

The big electromagnets is wound with 1303 turns of 2mm coil while the smaller electromagnet has 1200 turns of 0.5mm coil. A shaft is extended outwards with a flange fabricated to be coupled to the reciprocating pump. The double-acting reciprocating pump piston assembly shaft is fastened to the shaft of the electromagnets. This directly allows a direct-drive translational motion to and fro in operation. Safety considerations is a teflon-lined plastic cover for the electromagnetic oscillator. Damping mechanisms put in place are felt pads to cushion surface impact of the electromagnets and also to reduce noise. Grease is used to control sliding friction to reduce wear and heat generation due to friction. Teflon dampers are also adopted to reduce shock in the reciprocating pump.

Fig. 6: Fabricated electromagnetic oscillator

Fig. 7: Electromagnetic oscillator coupled to double-acting reciprocating pump

4.0 TEST ANALYSIS AND DISCUSSIONS

The results were derived from series of test run. After the installation of the pump and electromagnetic oscillator, other components installed are;

1. Flow meter is a device used to measure the flow rate of a fluid passing through the system. This helps us read the discharge at the delivery side of the pump.
2. Pressure gauge is used to measure the pressure of fluid flowing in a system. The gauge is used to read the discharge pressure at the delivery side of the pump.

Test running the pump gives us the opportunity to read the initial values starting the pump from maximum displacement in the pump. Using engine oil with fluid density of 888kgm^{-3}, the following results were derived.

Table 1: Discharge readings for first test run

Time (s)	$Q_{engine\ oil}$ ($X10^{-4}$ m^3/s)
10	21
20	40
30	60
40	84
50	105
60	126
70	140
80	167.5
90	198.5
100	210
110	231
120	240.5

It was observed that in the first 120 seconds, there exist variations in discharge of the fluid at every stroke. This is due to the difference in volume of the sides of the reciprocating pump.

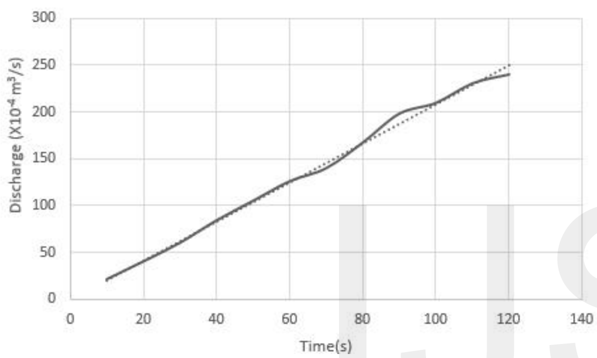

Fig. 8: Graph of discharge with time showing optimum performance line (dotted line)

This has an overall effect on the fluid system, because the flow of fluid in the system varies with the time and stroke. It could reduce the overall efficiency of the flow system and the supply system. There is need to correct this pulsating flow with the aid of applying some mechanical methods. These methods include;

1. Using a flow control valve at the discharge outlet to maintain a constant flow process.
2. The use of air cushion chamber will smooth pulsating flow. Air cushion chamber is usually filled at the suction side of a hydraulic pump to smooth fluctuation and reduce the risk of cavitation on the delivery side.

Computing the values for the second test run, the pressure and displacement characteristics are expressed as shown in fig. 9 and fig. 10 respectively.

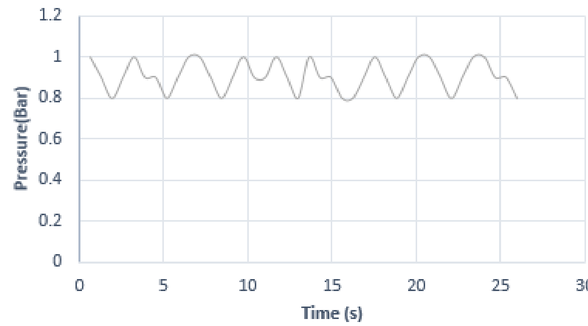

Fig. 9: Pressure curve at discharge in 26s

The displacement characteristics curve in figure 10 indicates that the electromagnet moves at constant displacement over time. This is a significant measure of displacement as the force required to move the piston assembly is achieved indicating that all opposing force especially static friction is overridden. However, pulsating discharge is significant with reciprocating or piston pumps and since a smooth flow is desired, measures are taken into consideration to rectify such undesired problem.

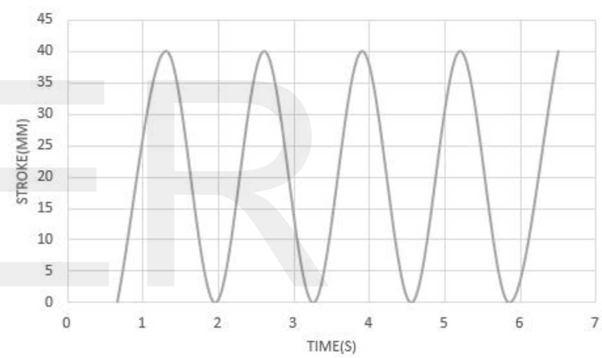

Fig. 10: Measurement of displacement (stroke) at time intervals of approximately 6.5s

4.1 Performance Evaluation

Figure 11 represents the pressure rate increase with time. Thus the pump performance is fitted to the performance graph.

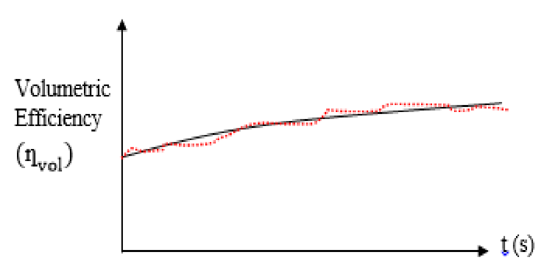

Fig. 11: Performance graph of the electromagnetic reciprocating pump

The diagram in figure 11 shows that the pump has a low performance at the starting point. This is due to static friction that prevents the piston from moving at first. Once this is overcome, the performance increases exponentially but not at a constant rate.

In order to derive the average performance of the reciprocating pump, a mean line is drawn from the starting point along the actual performance graph. It is indicated on the graph in fig. 11 as the thin continuous line.

Pump delivery increases with speed as would be expected but is reduced by slip which is the difference between the swept volume and delivered volume. Therefore volumetric efficiency is defined as

$$\eta_{vol} = \frac{\text{delivered volume}}{\text{swept volume}} \quad (10)$$

$$\therefore \eta_{vol} = \frac{Q}{Q_0} = \frac{Q_0 - Q_1}{Q_0} = 1 - \frac{Q_1}{Q_0} \quad (11)$$

The overall efficiency of the pump is given by;

$$\eta_0 = \frac{\rho Q g H}{P} \quad (12)$$

4.2 Pressure Variation with Fluid Density

The variation of pressure with the use of different fluids of individual densities will enable us determine the limitations of the electromagnetic reciprocating pumps. The table 2 below shows the fluid with their densities and the output mean pressure of the system in two minutes i.e. 120 seconds.

Table 2: Test-run results of pressure with different fluids

Fluid	Density (kg/m^3)	Mean Pressure (bar)
Water	1000	1.23
Soya bean oil	924	1.10
Lubricating oil	900	1.05
Olive oil	880	0.94
Paraffin	800	0.92
Syrup	785	0.89

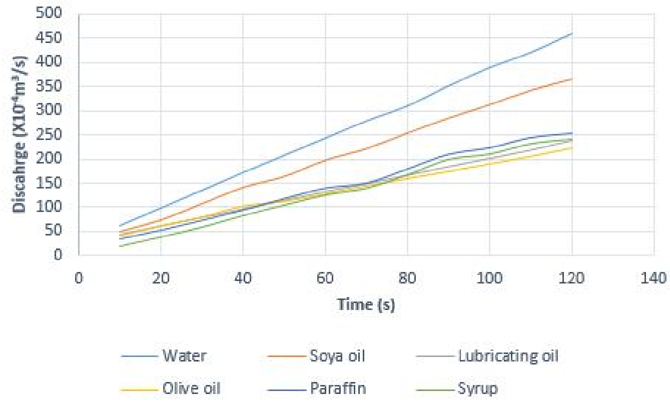

Fig. 12: Analysis of discharge with time for fluids with various densities.

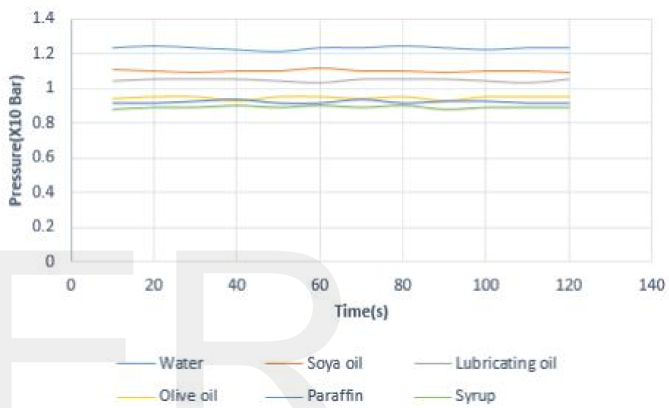

Fig. 13: Analysis of pressure with fluid of different densities

Figure 13 above presents the pressure and effective range of fluid densities workable with the electromagnetic reciprocating pump. Its limitation is viewed from the maximum and minimum values of fluid density the pump can lift. At densities greater than $850kgm^{-3}$, the efficiency of the pump tends to be greater than the functional efficiency and this in turn has significant effect on the pump. Some of the effect are

1. Pressure drop in the system.
2. Abrasive wearing of the pressure seal and the cylinder walls.
3. Side leakage across the pressure seal reducing its discharge.

At fluid densities lower than $800kg/m^{-3}$, the pump tends to experience pressure drop and the pump efficiency also drops. This is due to the increase mass of fluid the power supplied to the pump can carry. Higher densities of fluid in the electromagnetic reciprocating pump could have the following effects.

1 Cavitation- This is the introduction of air bubbles into the cylinder or the whole system which can reduce overall efficiency. This is caused by the inability of the vacuum pressure to effectively draw in the fluid from the source and as thus air bubbles could be trapped in the system.
2 Lower Flow Rate- The flow rate drops due to the viscosity of the fluid which is a function of its density. The resistance to flow and the pressure drop in the connector pipes will result in lower flow rate.

4.3 Ideal Indicator Diagram

The graph between pressure head in the cylinder and stroke length of the piston for one complete cycle of the oscillator under ideal conditions is known as ideal indicator diagram [8].

During suction stroke, the pressure head in the cylinder is constant and equal to suction head (h_s) which is below the atmospheric pressure head (H_{atm}) by a height of h_s. The pressure head during suction stroke is represented by a horizontal line AB which is below the line EF by height h_s.

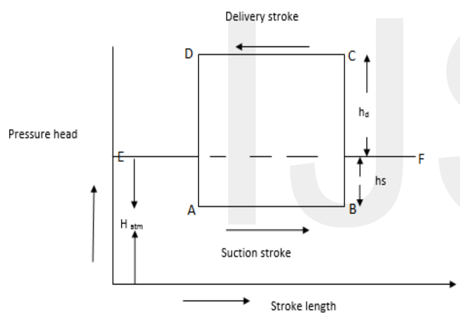

Fig. 14: Ideal indicator diagram for reciprocating pump

4.4 Variation of velocity and acceleration in the suction and delivery pipes due to acceleration of the piston.

When the electromagnetic oscillator starts, the to-and-fro motion, the piston moves forward and backwards in the cylinder. At the extreme left position and right position of the piston in the cylinder, the velocity of the piston is zero. The velocity of the piston is maximum at the center of the cylinder. This means that at the start of a stroke, the velocity of the piston is zero and this velocity becomes maximum at the center of each stroke and again becomes zero at the end of each stroke. Thus the piston will be having retardation. The fluid in the cylinder is in contact with the piston and hence the fluid flowing from the suction pipe or to the delivery pipe will have acceleration at the beginning of each stroke. Therefore velocity of flow of fluid in the suction and delivery pipe will not be uniform.

5.0 CONCLUSIONS

In the wake of revolutionary advancements, the development of an electromagnetic oscillator to actuate a reciprocating pump is feasible. It can however be scaled into a micro pump for future applications. A serious consideration of this method is an area of investment that require further study for optimized pump performance characteristics.

NOMENCLATURE

P = power
H = head
ϱ = Density
Q = delivered volume (m^3/s),
Q_l = loss due to slip
Q_0 = swept volume × speed
H = Field Strength (ampere per meter, A/m)
B = Flux density
N = Number of turns
η_{vol} = Volumetric efficiency
η_0 = Overall efficiency

REFERENCES

[1] J.-H. Z. a. C.-Y. L. Ming-Tsun Ke, "Electromagnetically-Actuated Reciprocating Pump for High-Flow-Rate Microfluidic Applications," *Multidisciplinary Digital Publishing Institute (MDPI),* pp. 13075-13087, 2012.

[2] D. A. a. M. Histand, Introduction to Mechatronics and Measurement Systems, New York: McGraw Hill, 2011.

[3] H. A. a. J. R. M. Haus, " Electromagnetic Fields and," (Massachusetts Institute of Technology: MIT, 01 01 1989. [Online]. Available: http://ocw.mit.edu/resources/res-6-001-electromagnetic-fields-and-energy-spring-2008/chapter-1/01.pdf. [Accessed 26 05 2015].

[4] S. Takahashi, "Electromagnetic reciprocating pump," 12 January 1988. [Online]. Available: https://docs.google.com/viewer?url=patentimages.storage.googleapis.com/pdfs/US4718832.pdf. [Accessed 5 June 2015].

[5] T. O. Y. T. Kenji Mizuno, "Electromagnetic reciprocating pump," 14 April 1992. [Online]. Available: https://docs.google.com/viewer?url=patentimages.storage.googleapis.com/pdfs/US5104299.pdf. [Accessed 5 June 2015].

[6] H. Elliot, "Electromagnetic Reciprocating Fluid Pump," 26 April 1966. [Online]. Available: https://docs.google.com/viewer?url=patentimages.storage.googleapis.com/pdfs/US3381623.pdf. [Accessed 5 June 2015].

[7] R. Sedha, A Textbook of Electronic Circuits, New Delhi: S. Chand and Company, 2012.

[8] D. R. K. Bansal, A Textbook of Fluid Mechanics and Hydraulic Machines, New Delhi: Laxmi Publications Ltd., 2010.