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Original Article

The Effect of Design Parameters on the Discharge of a Transparent Cylinder Single-Acting Reciprocating Pump

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Abstract *- This project presents the Effect of Design Parameters on the Discharge of a Single-acting Reciprocating Pump for use in the Mechanical Engineering laboratory of the Akwa Ibom State University (AKSU). The project provides a portable positive displacement pump for demonstrating the movement of fluids in the laboratory. The component consists of a-transparent piston-cylinder assembly, suction pipe, delivery pipe, suction valve, delivery valve, crank, and connecting rod mechanism powered by an electric motor. During the operation of this apparatus, there will be visual movement of the piston during the suction and delivery stroke per each cycle. The pump piston has a diameter of 0.100 m, a stroke length of 0.305 m, and a designed speed of 20 r.p.m. The suction head and delivery are 0.762 m and 1.585 m, respectively. The practical operations were performed, and data was collected. The reciprocating pump principles were applied for the pressure head analysis during the suction and delivery strokes. The parametric analysis carried out includes the acceleration head during the suction stroke at the beginning of the delivery stroke and the pressure head in the middle of the stroke and at the end of the suction stroke. Analyses were performed, and the results indicate a pump discharge of delivery.0008 m3/s with work done by the pump of 18.40 Nm/sec. Further studies were performed for four different piston diameters, stroke lengths, and speeds. The results were used in the computation analysis for the discharge and work done by the pump.*

Keywords *- Pressure, Suction, Delivery, Single-acting, Reciprocating, Pump.*

1. Introduction

The reciprocating pump is a positive displacement pump that sucks and raises the liquid by displacing it with a piston or plunger, executing the reciprocating motion in a close-fitted cylinder. It consists of the suction section and the delivery section. The pump discharges a fixed fluid volume for each drive stroke through the delivery section. The position of check valves usually determines suction and discharge flow. This pump periodically adds energy to a specific quantity of fluid to a movable mechanical part to supply fluid to the desired point in the system. A force is applied to the movable boundaries of an enclosed fluid volume, which increases the pressure that moves the fluid through valves or ports into the discharge line. It pushes or pulls liquid from one point to another using various mechanical configurations. The reciprocating pump will continue to pump fluid unrestricted if there are pressure differences between the suction and discharge lines. Figure 1 shows a schematic diagram of a reciprocating pump.

In this study, a motor-powered instructional reciprocating pump is designed with a transparent cylinder so that the enclosed piston's movement can be suitable and used for learning and instructional purposes. This pump type is used industrially for agricultural purposes such as irrigation, water supply in communities, gasoline supply, flood control, and marine services.

This project aims to show the parametric effect of the designed cost-effective reciprocating pump with a transparent cylinder casing for instructional and demonstration purposes. This study is limited to fluid mechanics demonstration using liquid (water) as a working fluid. This design practically demonstrates fluid flow principles in fluid mechanics and fluid machinery laboratories in institutions. The concepts can be applied to design a reciprocating pump for industrial purposes.

2. Review of Previous work on Reciprocating Pump

The application of reciprocating pumps in laboratories and industries for fluid flow analysis and simulation of real-life fluid flow scenarios, which are essential, has been performed by different authors. This has given rise to the effective movement of fluid from one point to another, as seen in the fluid flow measurement and analysis in petroleum pipelines, irrigation facilities, automotive industries, wastewater collection systems and treatment plants.

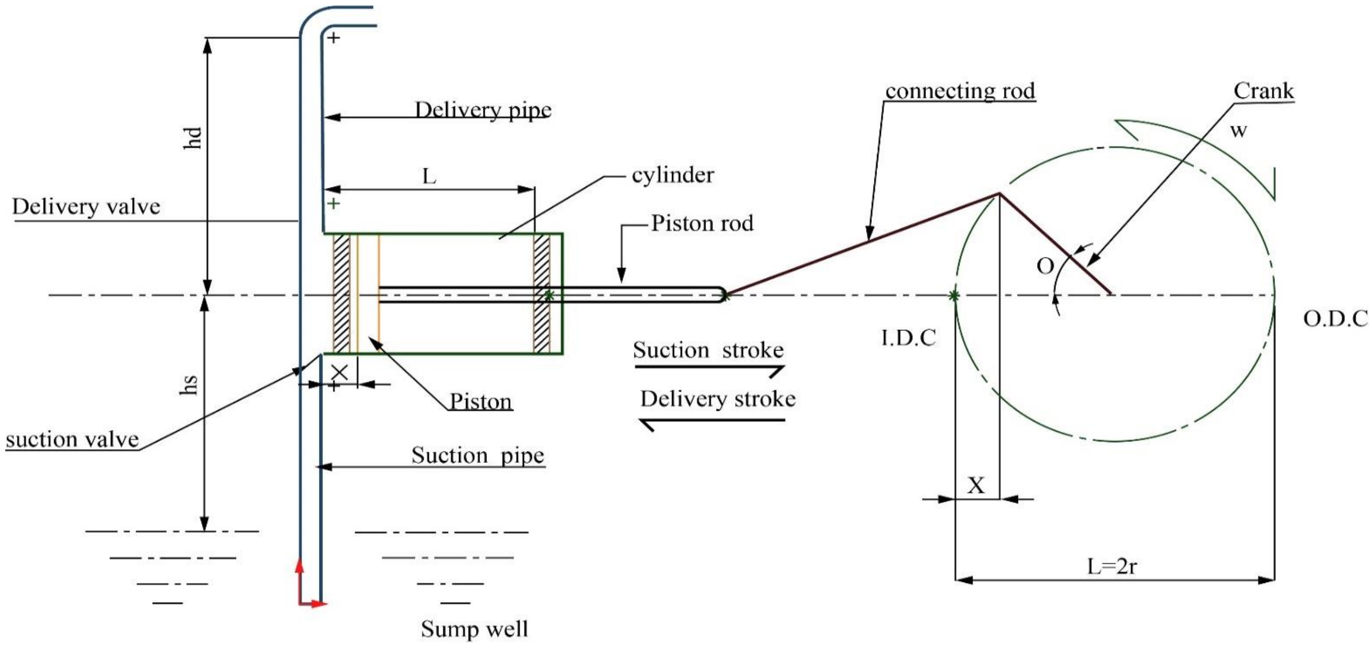


Fig. 1 The component parts of a reciprocating pump [1]

According to [2], a pump is a device that provides energy to a fluid in a fluid system; it assists in increasing the pressure energy or kinetic energy, or both of the fluids by converting the mechanical energy. This section presents a review of the previous work relating to a reciprocating pump which several scholars have extensively discussed. But it is imperative to note that lifting liquid from the suction section to the delivery point is accomplished by the reciprocating movement of the piston within a cylinder aided by the crank system.

According to Performance Analysis of a Single-acting reciprocating pump [1], several authors have also employed the application of reciprocating pump systems along pipelines, aircraft engines and the simulation of pulsatile arterial blood flow and other design parameters in fluid flow measurement and control devices in laboratories, industries, pneumatic pressure systems and different real-life situations. Reciprocating pump is employed in several ways, such as in domestic, research, health sector and industrial purposes. Reciprocating pump is applied in Fluid Mechanics and Hydraulic Machines [2], Dynamic Analysis on Crank-Slider Mechanism of Reciprocating Pump [3], Performance Study on Linear Motor Reciprocating Pump [4], The effect of operating parameters on the wear behaviour of disc poppet valves in reciprocating slurry pumps [5], Failure analysis of a repairable system: the case study of a cam-driven reciprocating pump [6], Solar Based Reciprocating Pump [7], Cavitation in reciprocating pumps [8], Analysis of the Pulsation in Aircraft Deicing System [9], Induced flow reciprocating pumps Part 1 [10], Pressure pulsations in the piping of reciprocating pumps [11], Numerical Modelling of Reciprocating Pumps with Self-Acting Valves [12], Tip Clearance Control Concept in Gas Turbine H.P. Compressors [13], The Effect of Heat Transfer Coefficient Increase on Tip Clearance Control in H.P. Compressors in Gas Turbine Engine [14], Optimum Design Parameters for Reciprocating Pumps Used in Natural Gas Wells [15], Applications of a novel reciprocating positive displacement pump in the simulation of pulsatile arterial blood flow [16], Development of Prototype Pump Using a Vibrating Pipe With a Valve [17], Performance Analysis of a Single-acting Reciprocating Compressor Using Thermodynamic Concepts [18], The Effect of the Design Parameters on Mass Flow Measurement and Control in an Orifice Plate Flow Rig [19], Parametric Effect on the Discharge of Venturimeter Flow Rig [20] and Application of Creativity Tools to Gas Turbine Engine Compressor Clearance Control [21].

It can be seen that renowned scholars have made several attempts to develop reciprocating pumps for various uses. The present work introduces a transparent cylinder casing in the pump which can be used for better explanation and a better visual understanding of the subject matter when discussed in fluid mechanics, fluid machinery laboratories and when used industrially.

3. Methodology

The concept employed in this study includes the application of creativity techniques such as lateral thinking and brainstorming in the conceptual stage for selecting materials based on quality, availability and cost; for details on creativity techniques and their application in problem-solving, the reader is referred to the Application of Creativity Tools to Gas Turbine Engine Compressor by [21] and Application of Creative techniques in Effective Management of a Power Generation Plant by [22]. The principles of a positive displacement pump were also used to analyse the movement of liquid from an area of low pressure to an area of high pressure. The analysis involves the suction and delivery sections of the system.

According to [2], the following expressions were adopted for the design parameters analyses of a single-acting reciprocating pump, where symbols retained their usual nomenclatures.

$$Crank\ radius\ (r) = \frac{L}{2} \quad (3.1)$$

$$Area\ of\ suction, a_s = \frac{\pi D_s{}^2}{4} in\ m^2 \quad (3.2)$$

$$\text{Angular velocity, } w = \frac{2\pi \times N}{60} in (rad/s) \quad (3.3)$$

$$Pressure\ head\ due\ to\ acceleration\ in\ suction\ pipe, h_{as} = \frac{l_s}{g} \times \frac{A}{a_s} w^2 r \cos \Theta \quad (3.4)$$

$$Pressure\ head\ due\ to\ acceleration\ in\ delivery\ pipe, h_{ad} = \frac{l_d}{g} \times \frac{A}{a_d} w^2 r \cos \Theta \quad (3.5)$$

$$Volume\ of\ water\ delivered\ per\ revolution = A \times L \quad (3.6)$$

$$Number\ of\ revolution\ per\ seconds = \frac{N}{60} \quad (3.7)$$

$$Discharge\ of\ pump\ per\ second, Q = \frac{ALN}{60} in\ m^2/sec \quad (3.8)$$

$$Work\ done = wQ(h_s + h_d)\ in\ Nm/sec \quad (3.9)$$

$where\ w\ is\ the\ specific\ weight\ of\ water\ due\ to\ gravity$

4. Results and Discussion

These sections present the results and discussion of the study. The design parameters and their dimensions used in this study are presented in Table 1. These include the diameter of the piston, stroke length, suction head, delivery head, the diameter of pipes, length of the suction pipe, length of delivery pipe, speed of the pump, and atmospheric pressure.

Applying equations (3.1) and (3.2) to obtain the crank radius and the area of the suction pipe;

$$Crank\ radius\ (r) = \frac{L}{2} = \frac{0.305}{2} = 0.153m$$

$$a_s = a_d = \frac{\pi d_s{}^2}{4} = \frac{\pi \times (0.038)^2}{4} = 0.001m^2$$

Then, area of piston is given as;

$$A_{piston} = \frac{\pi D_s{}^2}{4} = \frac{\pi \times (0.001)^2}{4} = 0.008m^2$$

Equations from Section 3 were used, and symbols retained their nomenclatures. They were employed to obtain the angular velocity, the volume of water delivered revolution, the number of revolutions per second, the discharge of the pump per second and the work done by the pump. In the resulting analysis using a crank speed of 20 r.p.m, we have the angular velocity as;

$At\ the\ crank\ speed, N = 20\ r.p.m$

$$w = \frac{2\pi \times 20}{60} = 2.095\ rad/sec$$

$Volume\ of\ water\ sucked\ in\ during\ suction\ stroke = A \times L = 0.008 \times 0.305 = 0.002\ m^3$

$Number\ of\ revolutions\ per\ second = \frac{N}{60} = \frac{20}{60} = 0.333\ rev/sec$

$Discharge\ of\ pump\ per\ second, Q = \frac{ALN}{60} = \frac{0.008 \times 0.305 \times 20}{60} = 0.0008\ m^3/sec$

$Work\ done\ by\ pump\ per\ second, W = wQ(h_s + h_d) = 9810x0.0008(0.762 + 1.585) = 18.387 = 18.40\ Nm/s$

Applying Equations (3.4), the pressure head due to acceleration in the suction pipe is given by $h_{as} = \frac{l_s}{g} \times \frac{A}{a_s} w^2 r \cos \Theta$.

Where h_{as} is the acceleration head during suction stroke, therefore:

At the beginning of the suction stroke, angle $\Theta = 0^0$

$$h_{as} = \frac{L_s}{g} x \frac{A}{a_s} x w^2 r cos\theta = \frac{0.305}{9.81} x \frac{0.008}{0.001} x cos\ 0 = 0.575794\ m\ of\ water$$

Applying Equations (3.5), the pressure head due to acceleration in the delivery pipe is given by $h_{ad} = \frac{l_d}{g} \times \frac{A}{a_d} w^2 r \cos \Theta$.

Where h_{ad} is the acceleration head during delivery stroke, therefore:

At the beginning of the delivery stroke, angle $\Theta = 0^0$

$$h_{ad} = \frac{L_d}{g} x \frac{A}{a_d} x w^2 r cos\theta = \frac{1.829}{9.81} x \frac{0.008}{0.001} x cos\ 0 = 0.864\ m\ of\ water$$

Table 1. Design parameters

S/N	Parameter	Symbol	Quantity (mm)	Quantity (m)	Unit
1	Diameter of piston	D	100	0.1	m
2	Stroke length	L	305	0.305	m
3	Suction head	h_s	762	0.762	m
4	Delivery head	h_d	1585	1.585	m
5	Diameter of pipes	$d_s = d_d$	38	0.038	m
6	Length of the suction pipe	L_s	1219	1.219	m
7	Length of the delivery pipe	L_d	1829	1.829	m
8	Speed of pump	N		20	r.p.m
9	Atmospheric pressure	H atm		10.3	m

4.1. The Effect of Design Parameters on Pump Discharge

In this study, the effects of some design parameters on the pump discharge were evaluated. This includes the stroke length during suction stroke, piston diameter, pump speed, acceleration head during suction stroke and the overall effect of the pump discharge on the work done by the pump was also evaluated to ascertain the performance of the pump.

4.1.1. Effect of Piston Diameter Increase on the Pump Discharge

The piston diameter of the designed pump is 0.100 m. By increasing the piston diameter, in 0.100 m, for four consecutive times to ascertain the effect on pump discharge, the following data were obtained with corresponding pump discharge as shown in Table 2. The graphical presentation of the analysis is presented in Figure 2. The analysis indicates that an increase in the piston diameter gives an increase in the discharge of the pump.

Table 2. Piston diameter against pump discharge

SN	Piston diameter, D (m)	Pump discharge, Q (m^3/s)
1	0.1	0.0008
2	0.15	0.0018
3	0.2	0.0032
4	0.25	0.005
5	0.3	0.0072

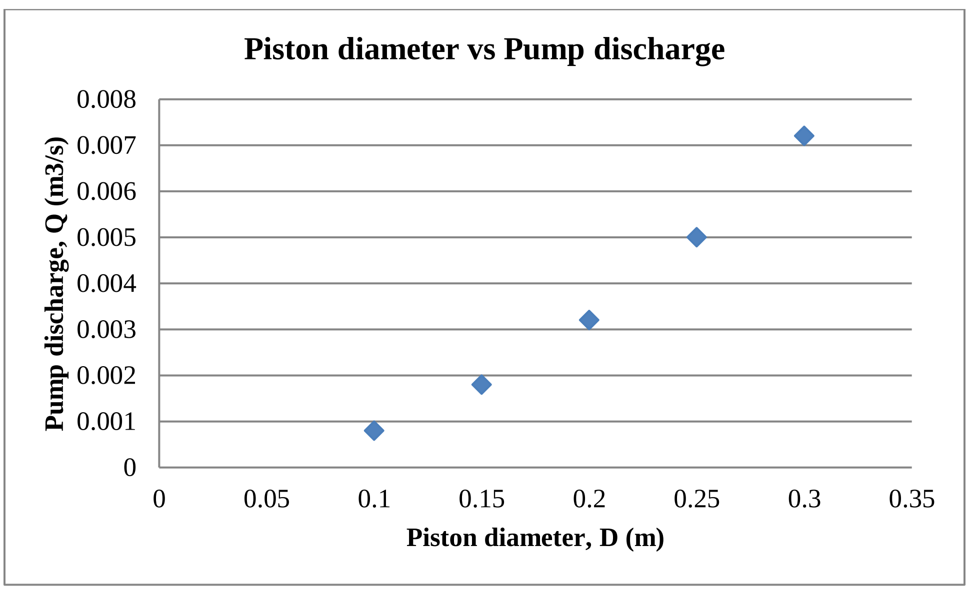


Fig. 2 Piston diameter increase against pump discharge

4.1.2. Effect of Stroke Length Increase on the Pump Discharge

The stroke length of the designed pump during the suction stroke is 0.305 m. By increasing the stroke length, in 0.100 m, for four consecutive times to ascertain the effect on pump discharge, the following data were obtained with corresponding pump discharge, as shown in Table 3. The graphical presentation of the analysis is presented in Figure 3. The analysis indicates that an increase in stroke length gives an increase in the discharge of the pump.

Table 3. Stroke length against pump discharge

S.N.	Stroke length, L (m)	Pump discharge, Q (m^3/s)
1	0.305	0.0008
2	0.405	0.0011
3	0.505	0.0013
4	0.605	0.0016
5	0.705	0.0018

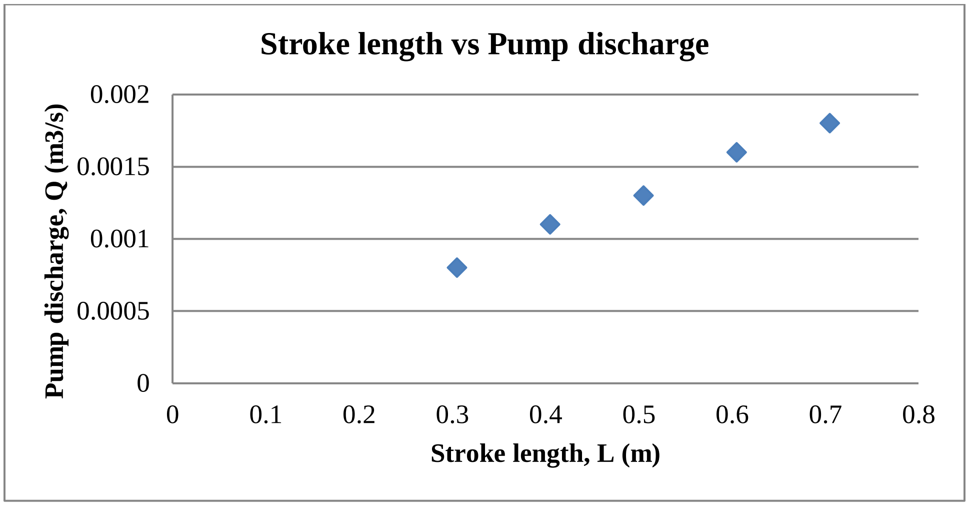


Fig. 3 Stroke length against pump discharge

4.1.3. Effect of Pump Speed Increase on the Pump Discharge

The pump speed of the designed pump is 20 r.p.m. By increasing the pump speed, in 10ths, for four consecutive times to ascertain the effect on pump discharge, the following data were obtained with a corresponding pump discharge increase which is presented in Table 4. The result is graphically presented in Figure 4.

Table 4. Shows an increase in pump speed against pump discharge

SN	Speed, N (r.p.m)	Pump discharge, Q (m^3/s)
1	20	0.0008
2	30	0.0012
3	40	0.0016
4	50	0.002
5	60	0.0024

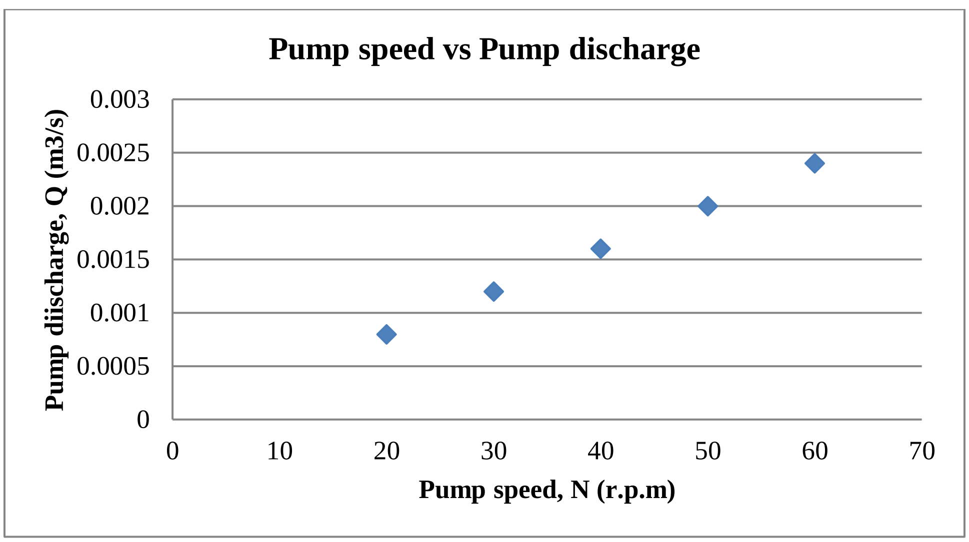


Fig. 4 Pump speed against pump discharge

4.1.4. Effect of Pump Speed Increase on the Pressure Head and Work Done by the Pump

In this analysis, the design pump speed of 20 r.p.m was gradually increased, in 10ths, for four consecutive times to ascertain the effect on the pressure head at the suction pipe, h_{as} in metres of water at the beginning of the suction stroke and the overall work done by pump were computed at each increase. The data were obtained, which is presented in Table 5. The results are graphically presented in Figures 5 and 6, respectively.

Table 5. Pump speed variation with pressure head and work done

SN	Speed, N (r.p.m)	The pressure head at the suction pipe h_{as} (m of water) at the beginning	Work done, W (Nm/s)
1	20	0.5758	18.40
2	30	1.2955	27.58
3	40	2.3032	36.77
4	50	3.5987	46.00
5	60	5.1821	55.16

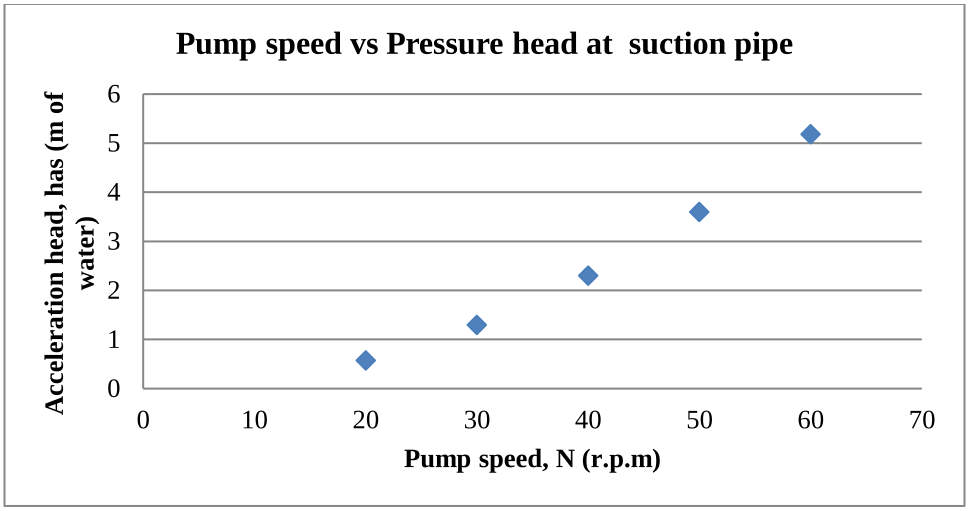


Fig. 5 Pump speed against Pressure head at suction pipe at the beginning of the stroke

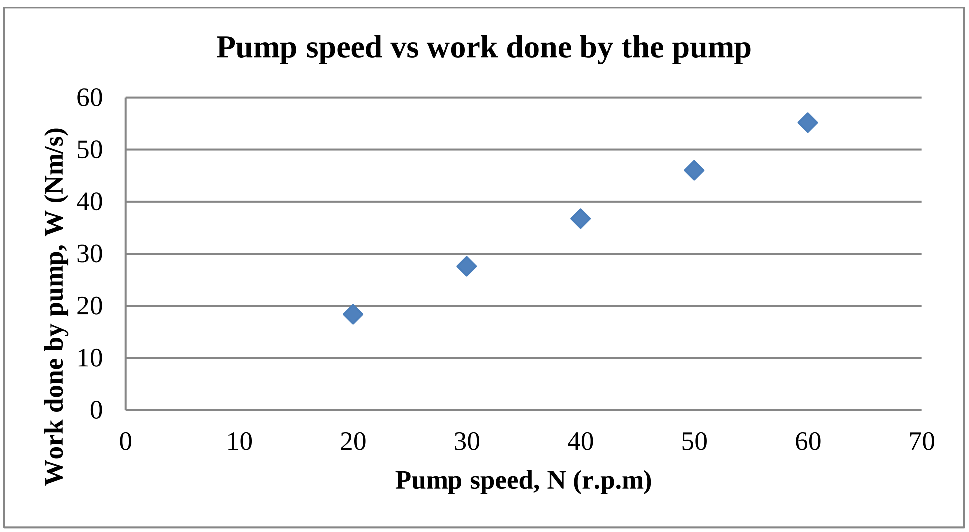


Fig. 6 Pump speed against the work done by the pump

In summary, there is a linear relationship between the pump speeds and the pressure head at the suction pipe at the beginning of the suction stroke, pump discharge and the work done by the reciprocating pump.

4.2. Rajput (2008) Reciprocating Pump Analysis

This section presents a standard computed result from Rajput analysis for the pump's discharge and work done per second by increasing the pump speed in 10^{th}. The results were employed to validate the result of this study. The designed parameters of the Rajput reciprocating pump are as follows: The diameter of the piston is 0.150m, the stroke length is 0.350 m, and the Centre of the pump above the water surface in the sump is 3.5 m and 22 m below the delivery water level. Both suction and delivery pipes have the same diameter of

100 mm, but the suction length is 5 m, the delivery length is 30 m, and the pump speed is 30 r.p.m.

By increasing the speed in 10th for five consecutive times, the following data were computed for the discharge as presented in Table 4.6. The ensuing computation is shown graphically in Figure 4.6. In the analysis, an increase in the speed increases the discharge by the pump. Therefore, there is a linear relationship between the pump speeds and the pump discharge of the reciprocating pump.

Table 6. Rajput discharge per second by a single-acting reciprocating pump

Speed (r.p.m)	Discharge per second by a single-acting reciprocating pump m^3/s)
30	0.003093
40	0.004124
50	0.005155
60	0.006186
70	0.007217

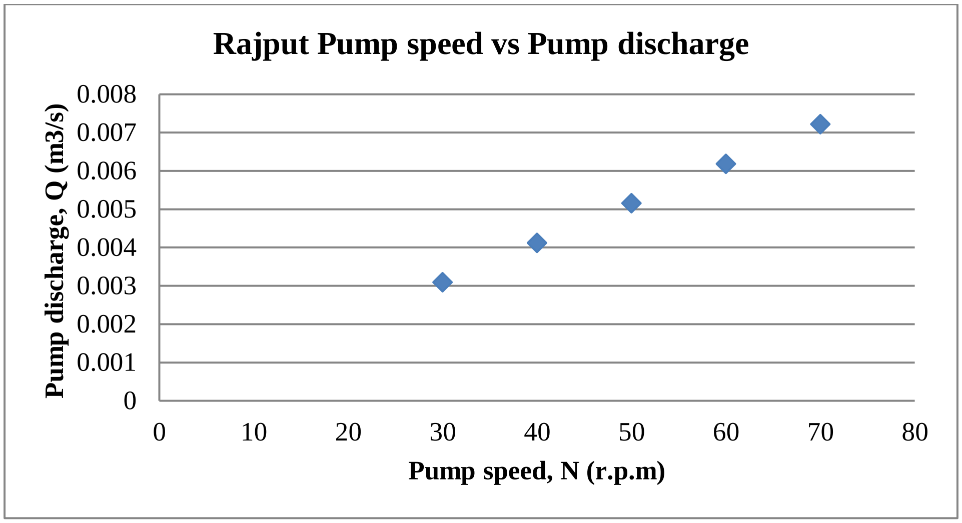


Fig. 7 The relationship between pump speed and pump discharge

4.3. Validation of the Performance Analysis of the EEU Single–Acting Reciprocating Pump Against the Standard Rajput performance Test of a Single-Acting Reciprocating Pump

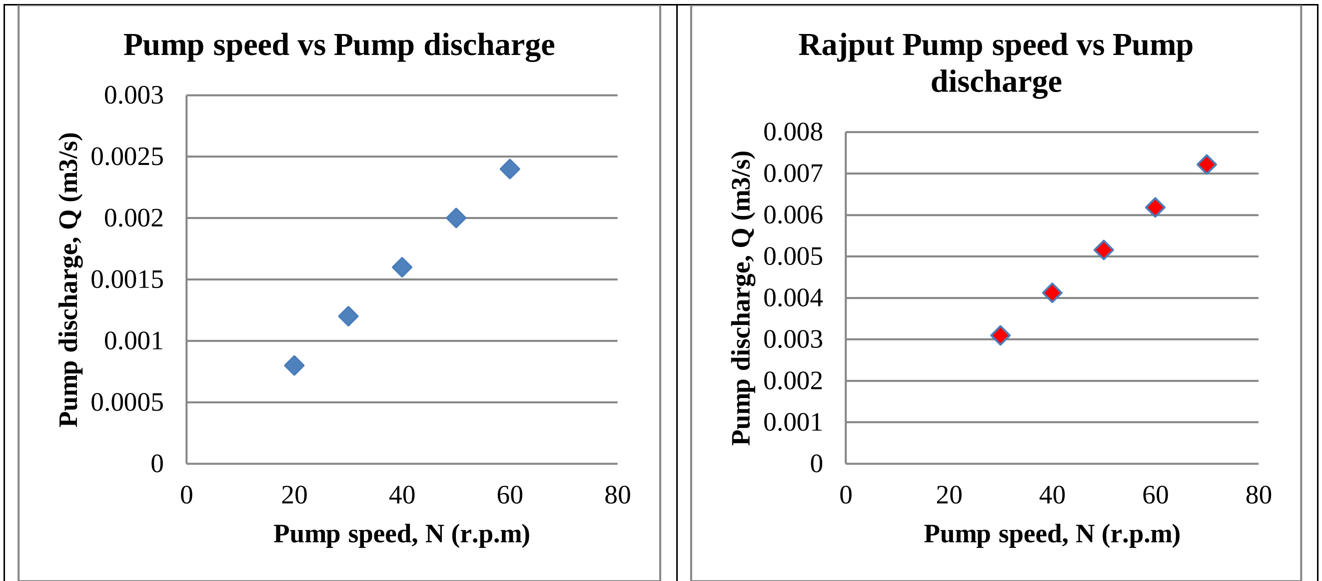
Let EEU data represent the results of this study while RAJPUT represents the results of the Rajput (2008) performance test. The analysis of the EEU reciprocating pump was validated against the standard Rajput (2008) analysis, and they were in good agreement since the trends and profiles were similar. The parameters for the validation involve pump speed and discharge. In each analysis, an increase in the pump speed increases the discharge from the pump, as shown in Table 7. The validation is presented graphically as the EEU discharge profile against Rajput's (2008) discharge profile, shown in Figure 7.

4.3.1. Discussion of the Validation

The results of the analyses for both the EEU reciprocating pump and the Rajput (2008) reciprocating pump show that, as the pump speed increases, there is a corresponding increase in the discharge through the pump. The result confirms the effectiveness of applying fluid flow principles and flow equations in analysing fluid movement in reciprocating pumps. The overall performance validation result shows that the results of the EEU reciprocating pump are in good agreement with the results of the standard Rajput (2008) reciprocating pump analysis. The evidence can be seen in the matching trends and profiles of the pump discharge for both analyses.

Table 7. Shows the EEU reciprocating pump data against the Rajput (2008) data for the reciprocating pump discharge

SN	EEU pump speed (r.p.m)	EEU Reciprocating pump discharge	Rajput pump speed (r.p.m)	Rajput (2008) Reciprocating pump discharge
1	20	0.0008	30	0.003093
2	30	0.0012	40	0.004124
3	40	0.0016	50	0.005155
4	50	0.002	60	0.006186
5	60	0.0024	70	0.007217



(a) EEU pump speed against pump discharge profile	**(b) Rajput (2008) pump speed against pump discharge profile**

Fig. 8 Validation of EEU reciprocating pump discharge profile against Rajput (2008) reciprocating pump discharge profile

5. Conclusion

The effect of design parametric analysis on pump discharge of a single-acting reciprocating transparent pump was performed, and the aim was achieved. The reciprocating pump used in this analysis is a portable device with a transparent cylinder to visually demonstrate the piston movement in the cylinder. It has the capability for easy assembly and disassembly. The project is used to practically demonstrate fluid movement and control in fluid mechanics studies in the mechanical engineering laboratory.

The results indicate that an increase in the piston diameter, stroke length, pump speed, and the pressure head to acceleration in the suction pipe at the beginning of the stroke was in good agreement with the performance of the reciprocating pump in the market, confirming the effectiveness of the concepts of the reciprocating pump employed in this study. The pressure head due to acceleration in the suction pipe at the beginning of the stroke is 0.5758 m of water, while the pressure head due to acceleration in the delivery pipe at the beginning of the stroke is 0.8640 m of water, giving a pump discharge of 0.0008 m3/s and a work done of 18.40 Nm/sec.

The overall performance validation result shows that the results of the EEU reciprocating pump are in good agreement with the results of the standard Rajput (2008) reciprocating pump analysis. The overall performance validation result shows that the results of the EEU reciprocating pump are in good agreement with the results of the standard Rajput (2008) reciprocating pump analysis. The evidence can be seen in the matching trends and profiles of the pump discharge for both analyses.

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