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Research Paper

Performance Analysis of a Single-acting Reciprocating Pump

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Abstract
This study presents the performance analysis of a positive displacement pump known as the reciprocating pump. 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. The project provides a portable positive displacement pump for demonstrating the movement of fluids in the laboratory. The component consists of a cylinder assembly made with a-transparent plastic and a piston, suction pipe, delivery pipe, suction valve, delivery valve, crank and connecting rod mechanism usually powered by an electric motor. This apparatus will demonstrate and allow students to gain a visual understanding of the working principle of the positive displacement pump during the suction and delivery stroke per each cycle of the pumping mechanism. The pump's design and manufacturing were done strictly to international standards to provide a high-precision target for fluid movement. The pump piston has a stroke length of 0.12 m, and the operating designed speed of the pump is 9.2 r.p.m. The ratio of the crank radius was half of the stroke length of the pump plunger. The height of the centre of the cylinder above the liquid surface is 0.5 m, and the height to which the liquid is raised above the centre of the cylinder is 1 m. 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 values generated were used in the computation analysis for the discharge, work done and the power required to drive the pump. The resulting analysis gave the discharge of 0.000145 m^3/s, work done of 2.1268 Nm/sec, and the power required to drive the pump of 2.1268 W. Further studies were performed for four different speeds, and the resulting values were validated against a standard Rajput (2008) reciprocating performance analysis to ascertain the accuracy level of the reciprocating pump. The results were in good agreement with the Rajput (2008) computed values trends. The evidence was seen in the matching trends and profiles of the pump speed against the discharge, pump speed against the work done, and the pump speed against the power required to drive the pump for both analyses, confirming the efficient nature of the reciprocating pump used at Akwa Ibom State University Mechanical Engineering fluid machinery laboratory.
Keywords: *Pressure, Suction, Delivery, Piston, Single-acting, Reciprocating, Pump*

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I. INTRODUCTION

A pump is a device that provides energy to a fluid in a fluid system. An example of a pump is the reciprocating pump. 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. The amount of the liquid pumped and delivered is equivalent to the volume of the fluid displaced by the piston. The pump consists of a liquid end and a drive end. The liquid end consists of a device to displace a fixed fluid volume for each stroke of the drive end. The position of the check valves determined the suction and discharge flow. Like rotary pumps, discharge lines must remain open, and relief valves are used during an operation to prevent pressure from building beyond the system's limitations.

Reciprocating pumps are classified according to how the water comes in contact with the piston, namely single-acting (water is in contact with one side of the piston) and double-acting (water is in contact with both sides of the piston) reciprocating pumps. And according to the number of cylinders, namely single, double, triple, duplex double and quintuplex cylinder pumps. Reciprocating pumps are commonly used in oil field operations, as feeders to boilers, in pneumatic pressure systems and in fluid storage areas where the surface pressure is more significant than atmospheric pressure.

A motor-powered instructional positive displacement pump is designed to have a piston enclosed in a transparent cylinder casing, which will be suitable and used for learning and instructional purposes. Figure 1.1 shows a schematic diagram of a reciprocating pump with the following essential parts: cylinder, piston, suction pipe, delivery pipe, suction valve, delivery valve, crank and connecting rod mechanism usually powered by a steam engine, internal combustion engine or an electric motor.

In this study, the reciprocating pump is powered by an electric motor. For completeness, the operation of the reciprocating pump depends on the crank connection movement, which rotates in a clockwise direction. When the crank rotates, the piston moves backward and forward inside the cylinder, representing the suction and delivery strokes of the operation. The first operation of the reciprocating pump involves the movement of the crank from the inner dead centre (I.D.C) to the outer dead centre (O.D. C), which is known as the suction stroke, where the liquid is sucked from the sump into the piston. The second movement is from the outer dead centre (O.D.C) to inner dead centre (I.D.C), known as the delivery stroke, where the liquid is carried and delivered to the desired point or tank. The continuous movement of the crank in this direction means more liquid is delivered to the desired point or tank.

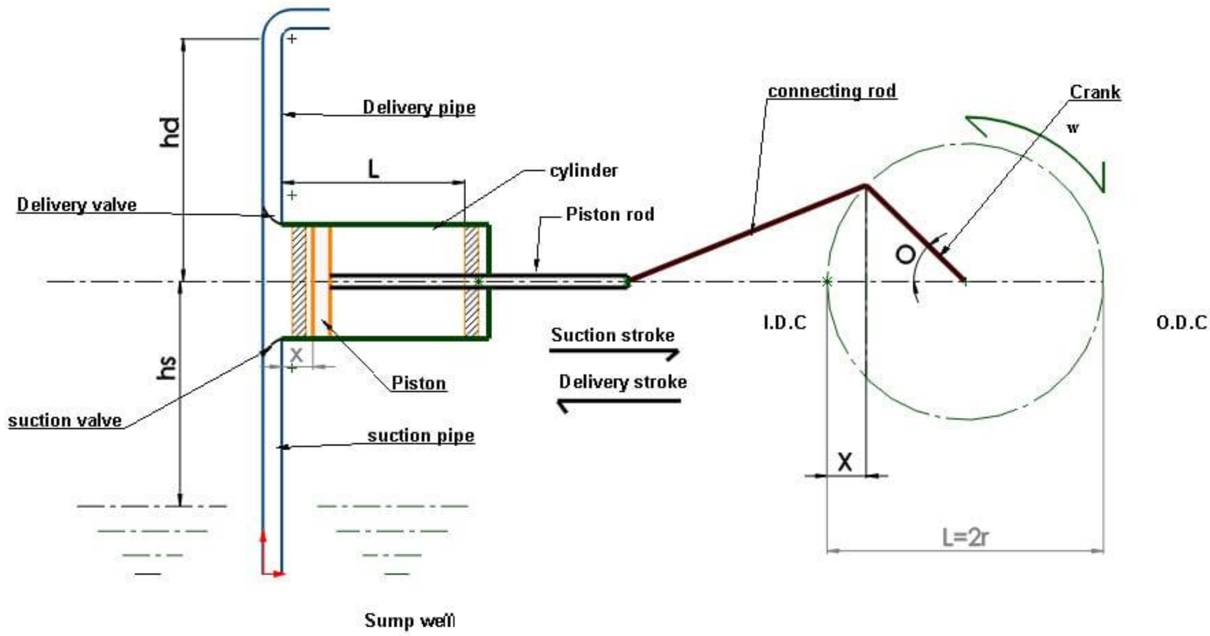


Figure 1.1: The component parts of a reciprocating pump

This study aims to employ fluid flow concepts in analysing the performance of a single–acting reciprocating positive displacement pump designed and manufactured using locally available materials. This design has a transparent cylinder casing for instructional and demonstration purposes. This study is limited to fluid mechanics demonstration using liquid (water) as working fluid. This design is for the practical demonstration of fluid flow principles in fluid mechanics and fluid machinery laboratories. The concepts can be applied to design a pump for industrial purposes.

II. LITERATURE REVIEW

The application of reciprocating pumps in laboratories and industries for fluid flow analyses, and simulation of real-life fluid flow scenarios, which are essential, have been performed by different authors. These have 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, treatment plants, and pneumatic pressure systems.

According to Rajput (2008), a pump is a stratagem that provides energy to a fluid in a fluid system; it assists in increasing the pressure energy or kinetic energy, or both of the liquid by converting it to mechanical energy. Pumps are used for irrigation, water supply, gasoline supply, flood control, and marine services.

They are available in different types according to operating principles, head and discharge, and flow direction. Pumps are classified into two main groups, namely the Rotodynamic pump or Kinetic pump and the Positive-displacement pump, the subject matter in this report. A positive displacement pump, typically a piston and cylinder arrangement, holds a fixed volume of fluid that the piston pushes into a system. The piston then retracts, and the cylinder is refilled. Positive displacement pumps are called so because a fixed amount is displaced, and no fluid returns to its casing or cam ring during the delivery stroke. This amount of water is called a positively displaced amount, which is why it's called a positive displacement pump.

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, the reader is referred to the works by Han and Qing (2011), Yang (2009), Joffe (1988), Dudenhoeffer (1994), Akarte (2022), Sahoo (2006), Wu and Yuan (2012), Burton and Short (1999), Vetter and Friedrich (1987), Johnston (1991), Ekong *et al.* (2012), Ekong *et al.* (2013a), Rodulf *et al.* (2005), Menkara *et al.* (2022), respectively. For further application of reciprocating pumps, other pumps and other flow control and measurement devices in laboratories, industries, pneumatic pressure systems and different real-life situations, the reader is referred to works by Hashimoto (1994), Ekong *et al.* (2020), Ekong, Godwin I. (2020) and Ekong, Godwin I. (2022).

III. METHODOLOGY

The reciprocating pump uses the principles of a positive displacement pump to analyse the movement of liquid from the area of low-pressure head to the area of high-pressure head. The analysis involves the suction and delivery sections of the system.

Another concept was the application of creativity techniques such as lateral thinking and brainstorming in the conceptual stage for selecting materials for good performance. For details on creativity tools and techniques and their application in problem-solving, the reader is referred to the works by Ekong *et al.*, (2013b). Figure 3.1 shows the isometric conceptual model of the reciprocating pump.

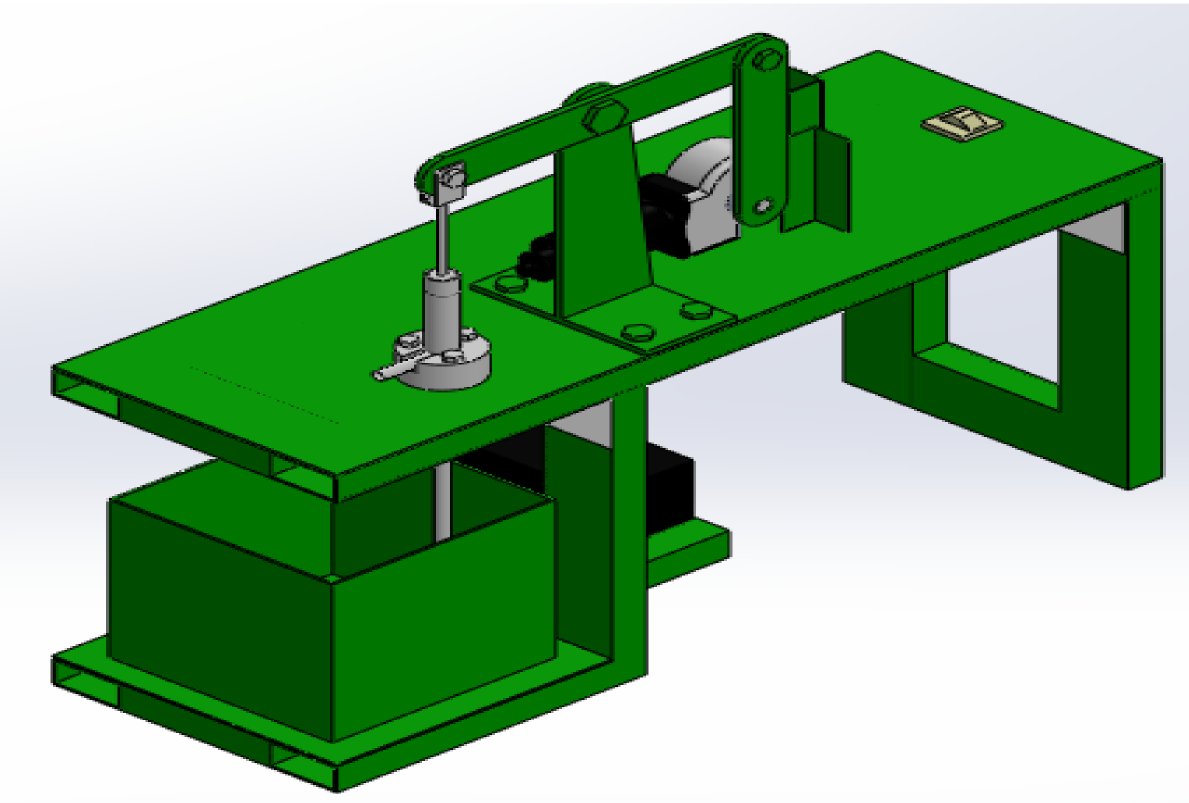


Figure 3.1: The isometric conceptual design model of a reciprocating pump (positive displacement pump)

According to R.K Rajput (2008), the following expressions were adopted for the design, manufacturing and performance analysis of a reciprocating pump.

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

$Cross\ sectional\ area\ of\ piston\ or\ cylinder, a = \frac{\pi D^2}{4} in\ m^2$ 3.2

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

$Volume\ of\ Liquid\ sucked\ in\ during\ suction\ stroke = A \times L$ 3.4

$Number\ of\ revolution\ per\ seconds = \frac{N}{60}$ 3.5

$Discharge\ of\ pump\ per\ second, Q = \frac{ALN}{60} in\ m^2/sec$ 3.6

Using the equation for work done by a single acting reciprocating pump by R.K Rajput (2008)

$Work\ done = \frac{WALN}{60}(h_s + h_d)\ in\ Nm/sec$ 3.7

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

$Power\ required\ to\ drive\ the\ pump = Work\ \ done\ in\ Nm/\sec = \frac{J}{s} = W$ 3.8

IV. RESULTS AND DISCUSSION

4.1 This section presents the results and discussion on the performance of the reciprocating pump. The results were obtained based on both evaluations of the manufactured pump. The input and output data are tabulated for clarity, and graphs were used where necessary to show the dependence of pump speed on other parameters. In this study, the flowing parameters were evaluated:

- The pump discharge
- The work done by the pump
- The power required to drive the pump

Let EE data represent the result from this study that will be used to validate against the standard Rajput (2008) data.

4.1.1 Design analysis

The designed parameters of the reciprocating pump used in this study are:

Diameter of piston = 0.1 m

The area of the piston, a_p is given as:

$$a_p = \frac{\pi {d_p}^2}{4} = \frac{\pi \times (0.1)^2}{4} = 0.007855\ m^2$$

$Stroke\ length\ (L) = 0.12\ m$

The height of the centre of the cylinder above the liquid surface, m, is given as, $h_s = 0.5\ m$

The height to which the liquid is raised above the centre of the cylinder, m, is given as $h_d = 1\ m$

Both suction and delivery pipes have the same diameter = 25mm = 0.025 m

Applying Equation (3.1), the crank radius is given as;

$$Crank\ radius\ (r) = \frac{L}{2} = \frac{0.12}{2} = 0.6\ m$$

For completeness, Equations (3.3), (3.4), (3.5) and (3.6), respectively, were employed to obtain the angular velocity, the volume of water sucked in during the suction stroke per revolution, number of revolutions per second and discharge of pump per second.

In the resulting analysis using a crank speed of 9.2 r.p.pm, we have the angular velocity as;

$At\ the\ crank\ speed, N = 9.2\ r.p.m$

$$w = \frac{2\pi \times 9.2}{60} = 0.9636\ rad/sec$$

$Volume\ of\ water\ sucked\ in\ per\ revolution = A \times L = 0.007855 \times 0.12 =$0.0009426 m3

$Number\ of\ revolutions\ per\ second = \frac{N}{60} = \frac{9.2}{60} = 0.1533\ rev/sec$

$Discharge\ of\ pump\ per\ second, Q = \frac{ALN}{60} = \frac{0.007855 \times 0.12 \times 9.2}{60}$ =0.0001445 m^3/sec

Table 4.1: Discharge per second by a single-acting reciprocating pump

Pump speed (r.p.m)	Discharge per second by a single-acting reciprocating pump (m^3/s)
9.2	0.000145
19.2	0.000302
29.2	0.000459
39.2	0.000616
49.2	0.000773

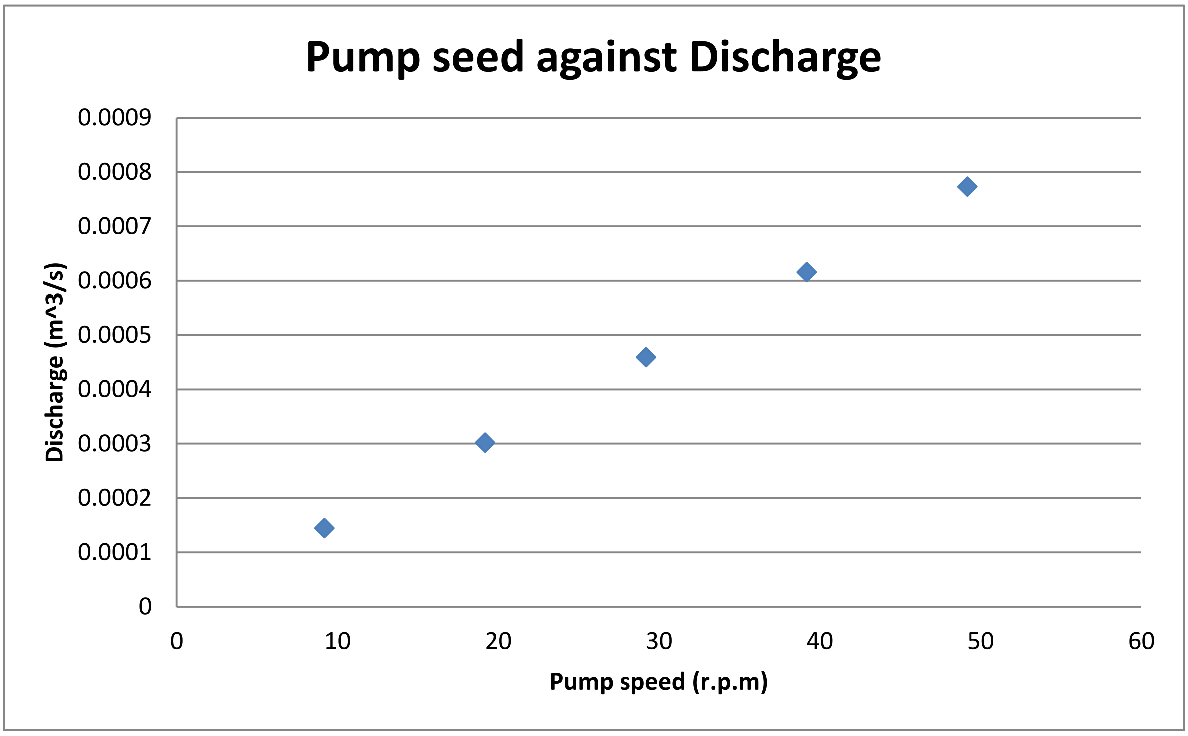


Figure 4.1: A graph of pump speed against discharge

4.1.2 Work done per second by the single acting reciprocating pump

According to R.K Rajput (2008), the following expression is used to determine the actual work done per second in (Nm/s) and recalling Equation 3.7;

At the speed, N = 9.2 r.p.m

$$Work\ done = \frac{WALN}{60}(h_s + h_d)\ in\ Nm/sec$$

$$Work\ done = \frac{9810 \times 0.007855 \times 0.12 \times 9.2}{60}(0.5 + 1.0)$$

$$Work\ done = 2.1268\ Nm/\text{sec}$$

By increasing the speed in 10th for four consecutive times, the following data for work done were computed as presented in Table 4.2.

Table 4.2: Work done per second by a single-acting reciprocating pump

Pump speed (r.p.m)	Work done per second by a single-acting reciprocating pump (Nm/s)
9.2	2.1268
19.2	4.4385
29.2	6.7502
39.2	9.0620
49.2	11.3274

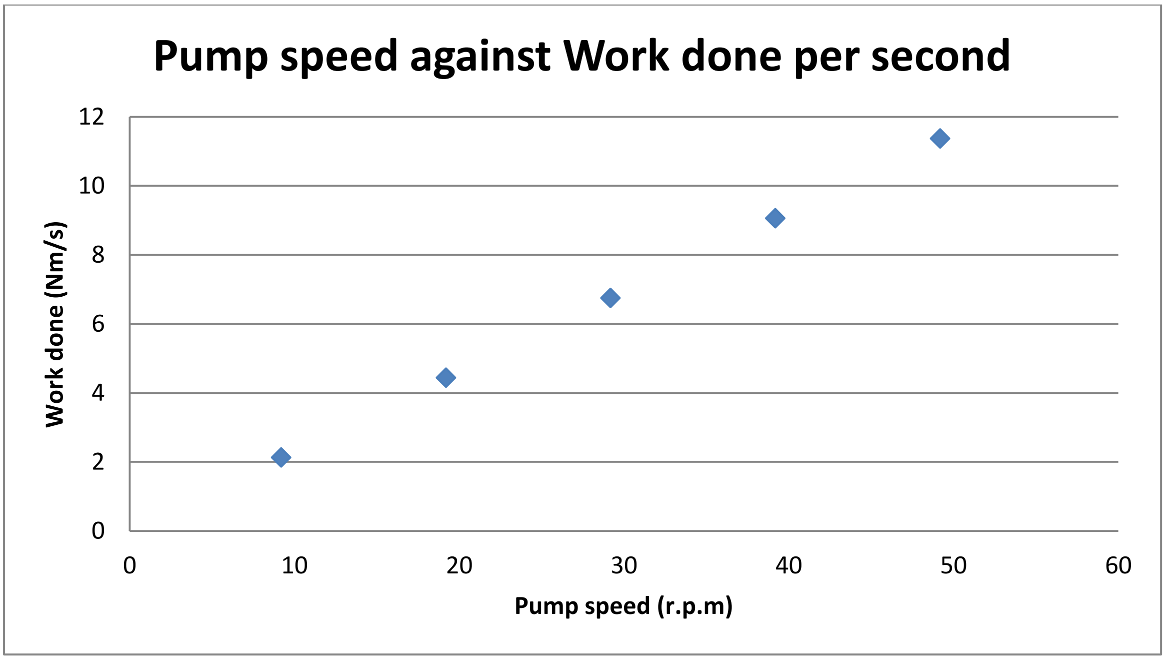


Figure 4.2: A graph of pump speed against work done per second

Work done on a single-acting reciprocating pump, as seen, is affected by the speed of the pump. The work done increases as the speed of the pump increases. These results explain the reason behind the different pressure heads at different speeds. As the speed increases, more work is done in moving the liquid.

4.1.3 Power required to drive the pump

The power required to drive a single-acting reciprocating pump can be obtained by equating the Work done in Newton metres per or Joules per second to Watt as shown in Equation 3.8.
Power required to drive the pump = Work done = 2.1268 Nm/s = 2.1268 J/s = 2.1268 W
Hence, the Power required to drive the pump = 2.1268 W.
By increasing the speed in 10th for four consecutive times, the following data were computed for the power required to drive, as shown in Table 4.3.

Table 4.3: Power required to drive the pump

Speed (r.p.m)	Power required to drive the pump (W)
9.2	2.1268
19.2	4.4385
29.2	6.7502
39.2	9.0620
49.2	11.3274

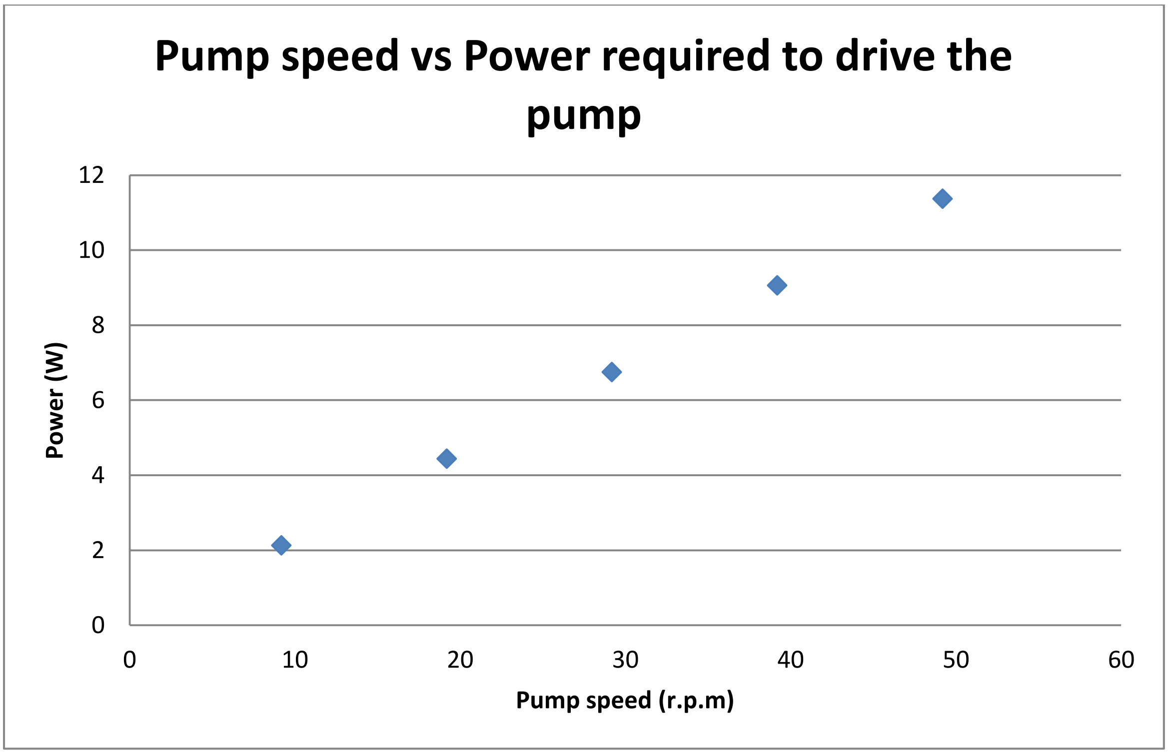


Figure 4.3: A graph of pump speed against the power required to drive the pump

There is a linear relationship between the power required and the work done by the equipment. As more work is done, force requirement increases, influencing the power required to drive the pump. Table 4.3 shows the results on the power requirements of the equipment under different speeds. The effect is further explained with the aid of Figure 4.3. It is seen from the figure that an increase in speed influences the power demands of the equipment.

4.2 Rajput (2008) reciprocating pump analysis

This section presents a standard computed result from Rajput analysis for the discharge, work done per second by the pump and the power required to drive the pump, which will be used to validate the result of this study. The designed parameters and power rating of the Rajput reciprocating pump are as follows: Diameter of piston =150 mm, Stroke length =350 mm, Centre of the pump above the water surface in the sump =3.5 m and 22 m below the delivery water level. Both suction and delivery pipes have the same diameter =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 two consecutive times and decreasing the speed in 10th by two consecutive times, the following data were computed for the discharge, work done, and power required to drive the pump as presented in Tables 4.4, 4.5 and 4.6, respectively. The subsequent computation is shown graphically in Figures 4.4, 4.5 and 4.6. In all the analyses, an increase in the speed increases the discharge, work done, and power required to drive the pump.

Table 4.4: 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)
10	0.001031
20	0.002062
30	0.003093
40	0.004124
50	0.005155

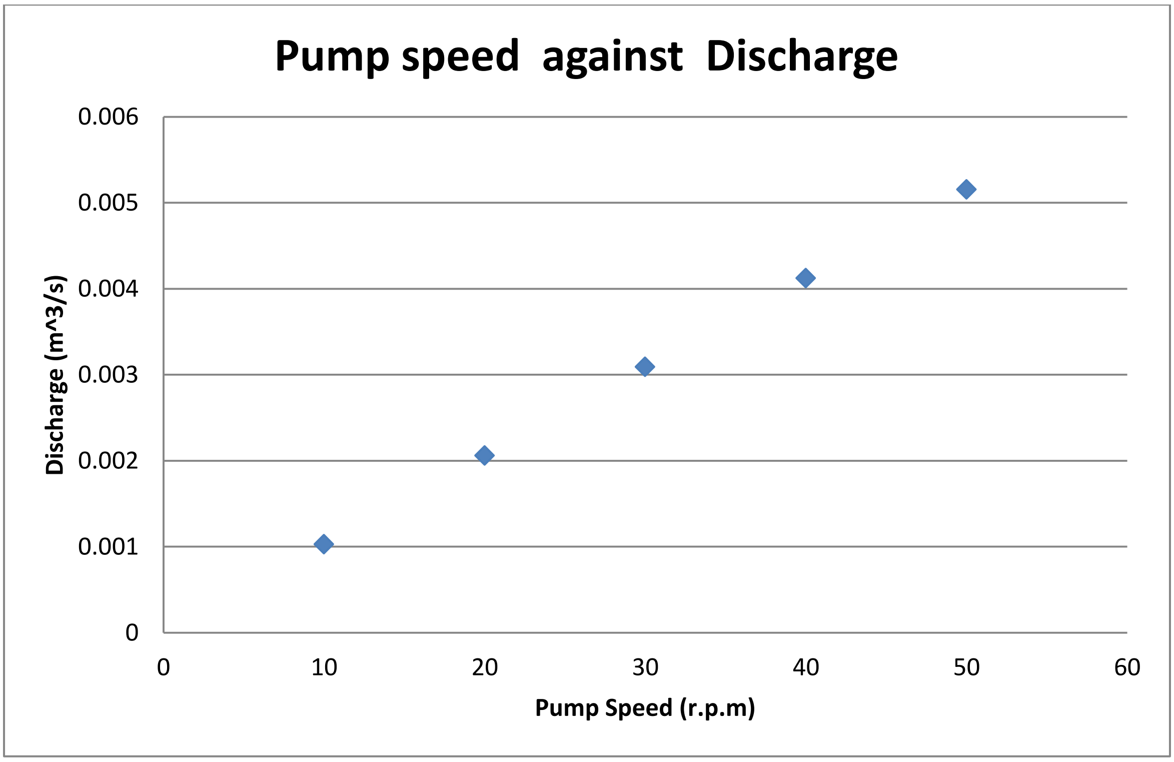


Figure 4.4: The relationship between Pump speed and Discharge

Table 4.5: Rajput work done per second by a single-acting reciprocating pump

Speed (r.p.m)	Work done per second by a single-acting reciprocating pump (Nm/s)
10	257.902
20	515.804
30	773.706
40	1031.608
50	1289.51

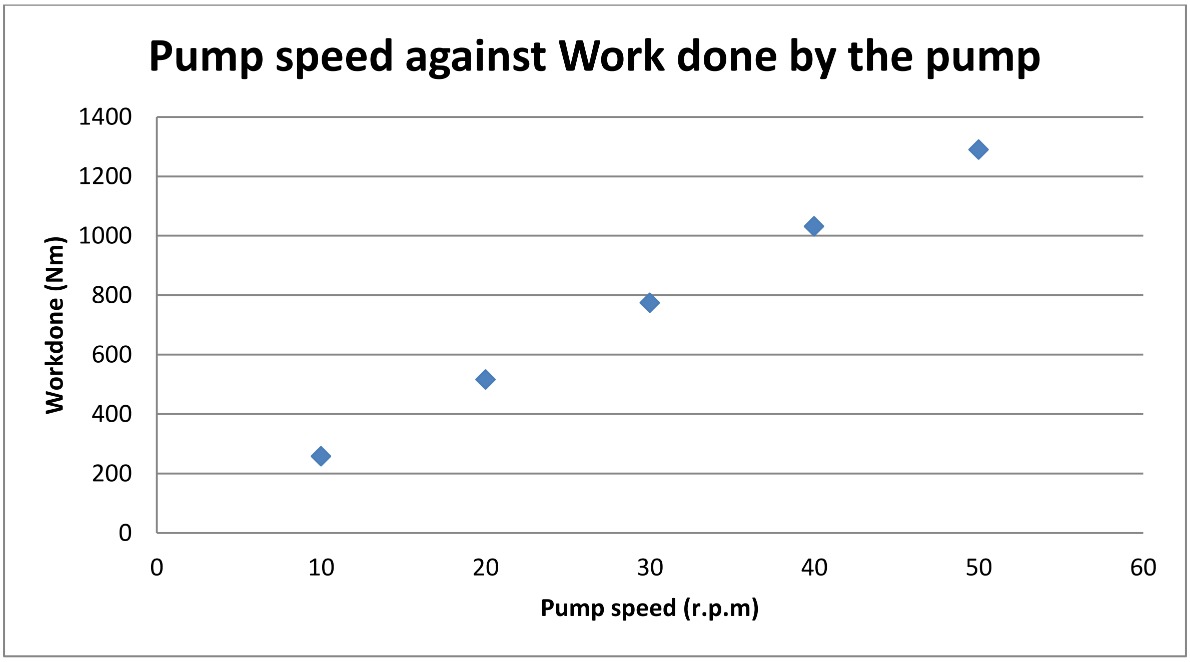


Figure 4.5: The relationship between Pump speed and Work done per second

Table 4.6: Rajput power required to drive a single-acting reciprocating pump

Speed (r.p.m)	Power required to drive a single-acting reciprocating pump (W)
10	257.902
20	515.804
30	773.706
40	1031.608
50	1289.51

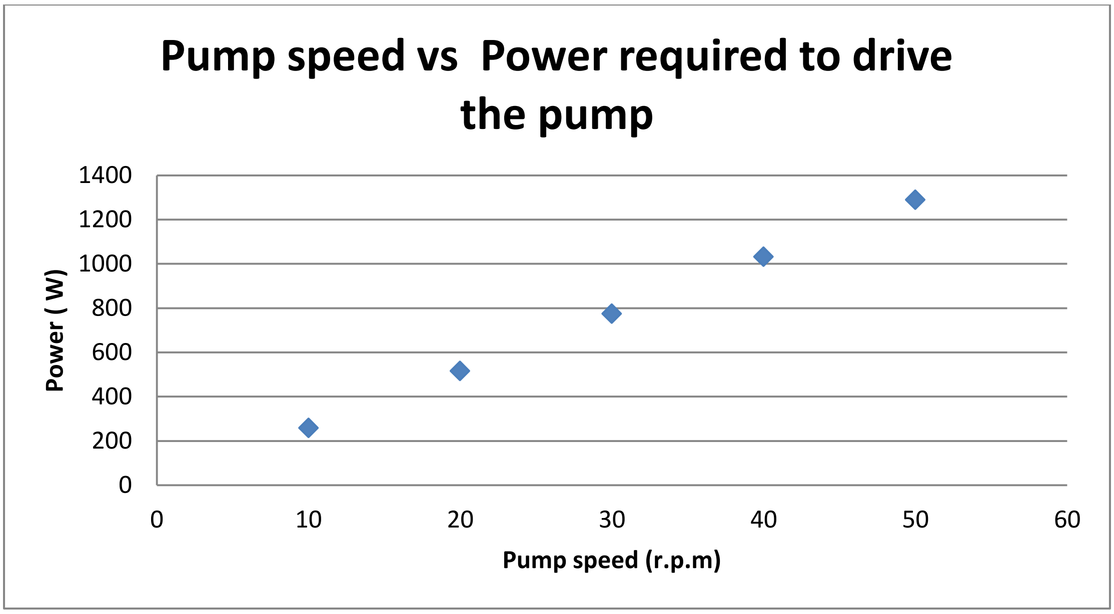


Figure 4.6: The relationship between Pump speed and Power

4.2.1 Discussion of results

The results of the analyses for both the EE 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, an increase in the work done per second with an increase in the power required to drive the pump. The result confirms the effectiveness of applying fluid flow principles and flow equations in analysing fluid movement in reciprocating pumps.

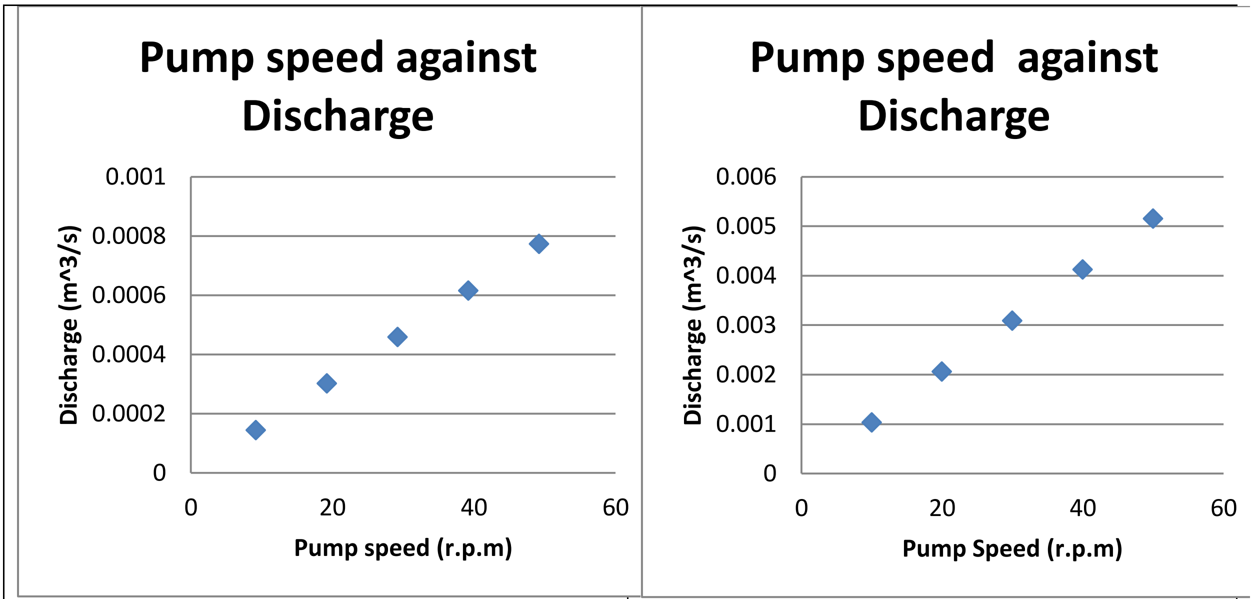
4.3 Validation of the Performance analysis of the EE Single–acting Reciprocating pump against the Standard Rajput Performance test of a Single-acting Reciprocating pump

Let EE data represent the results of this study while RAJPUT represents the results of the Rajput (2008) performance test. The analyses of the EE reciprocating pump were validated against the standard Rajput (2008) analyses, and they were in good agreement since the trends and profiles were the same. The parameters involve pump speed, discharge, work done, and power required to drive the pump. In each analysis, an increase in the pump speed increases the discharge from the pump, the work done per second, and the power required to drive the pump, as shown in Tables 4.7, 4.8 and 4.9, respectively.

The validation is presented graphically as EE discharge profile against Rajput's (2008) discharge profile, shown in Figure 4.7, while the validation of EE work done per second profile analysis against Rajput's (2008) work done per second analysis is presented in Figure 4.8. Figure 4.9 demonstrate the validation of the EE power required to drive the pump profile against the profile of Rajput's (2008) power needed to drive the pump.

Table 4.7: Shows the EE reciprocating pump data against the Rajput (2008) data for the reciprocating pump discharge

SN	EE pump speed (r.p.m)	EE Reciprocating pump discharge	Rajput pump speed (r.p.m)	Rajput (2008) Reciprocating pump discharge
1	9.2	0.000145	10	0.001031
2	19.2	0.000302	20	0.002062
3	29.2	0.000459	30	0.003093
4	39.2	0.000616	40	0.004124
5	49.2	0.000773	50	0.005155

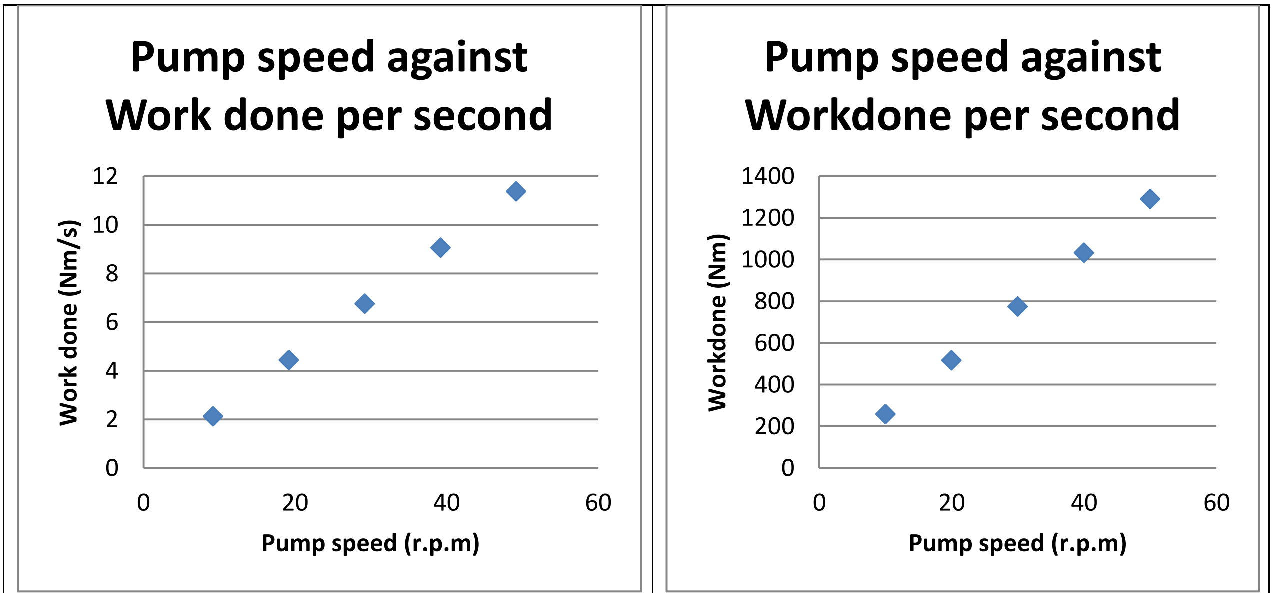


A) EE pump speed against discharge	B) Rajput pump speed against discharge

Figure 4.7: Validation of EE reciprocating pump speed and discharge profile against Rajput (2008) reciprocating pump speed and discharge profiles

Table 4.8: Shows the EE reciprocating pump work done data against the Rajput (2008) reciprocating pump data for the work done

SN	EE pump speed (r.p.m)	EE Reciprocating pump work done	Rajput pump speed (r.p.m)	Raput (2008) Reciprocating pump work done
1	9.2	2.1268	10	257.902
2	19.2	4.4385	20	515.804
3	29.2	6.7502	30	773.706
4	39.2	9.0620	40	1031.608
5	49.2	11.3274	50	1289.51

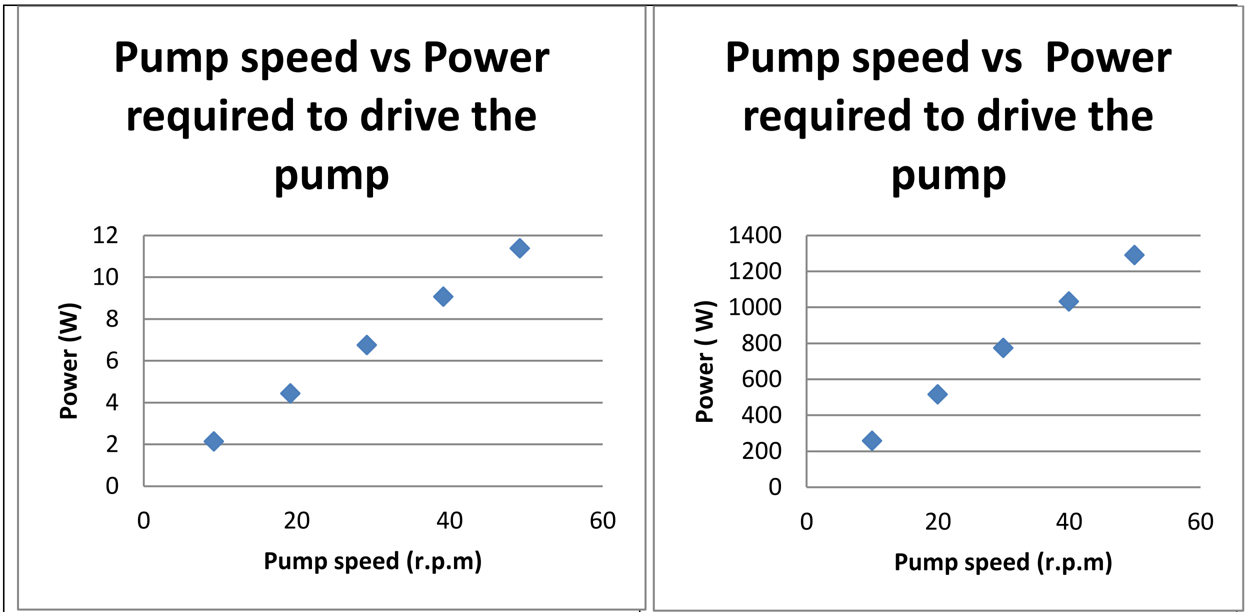


A) EE pump speed against Work done per second	B) Rajput pump speed against Work done per second

Figure 4.8: Validation of EE reciprocating pump speed and work done profile against Rajput (2008) reciprocating pump speed and work done profile

Table 4.9: Shows the EE reciprocating pump power data against the Rajput (2008) power data required to drive the pump

SN	EE pump speed (r.p.m)	EE Reciprocating pump power required to drive the pump	Rajput pump speed (r.p.m)	Raput (2008) Reciprocating pump power required to drive the pump
1	9.2	2.1268	10	257.902
2	19.2	4.4385	20	515.804
3	29.2	6.7502	30	773.706
4	39.2	9.0620	40	1031.608
5	49.2	11.3274	50	1289.51



C) EE pump speed against Power required to drive the pump	D) Rajput pump speed against Power required to drive the pump

Figure 4.9: Validation of EE reciprocating pump speed and power profile against Rajput (2008) reciprocating pump speed and power profile

4.3.1 Discussion of the validation

The overall performance validation result shows that the results of the EE 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 speed against the discharge, pump speed against the work done and the pump speed against the power required to drive the pump for both analyses.

V. CONCLUSION

The reciprocating positive displacement pump was designed, manufactured and tested. The project was completed, and the aim was achieved. The discharge, work done per second and the power required to drive the pump were computed.

The results were analysed and compared with a standard R. K. Rajput performance test of a reciprocating positive displacement pump. The results were in good agreement, confirming the usefulness of the designed concepts of the positive displacement pump in the analysis of the performance of this reciprocating pump. Hence, the results of this reciprocating pump are in good agreement with other existing reciprocating pumps. At a pump speed of 9.2 r.p.m, the resulting analysis gave the discharge of 0.001445 m^3/s, work done of 2.1268 Nm/sec, and the power required to drive the pump of 2.1268 W.

The study practically demonstrates fluid movement and control in fluid mechanics and fluid machinery studies in a mechanical engineering laboratory and can be adopted for industrial purposes. The result of this study can effectively be applied by personnel working in water, automotive, oil and gas industries to control fluid movement and supplies to the desired point. The results show that an increase in the pump speed increases the pump's discharge, the work done by the pump, and the power required to drive the pump.

The overall performance result shows that the results of the EE reciprocating pump are in good agreement with the results of the standard Rajput (2008) reciprocating performance analysis. The evidence can be seen in both results' matching trends and profiles. The fluid flow equipment is used in the Department of Mechanical Engineering of Akwa Ibom State University (AKSU), Nigeria's laboratory, for demonstration and teaching during Fluid Machinery and Applied Fluid Mechanics courses.

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