

# Studies on Hydraulic Pump Characteristics Through Experiment and Simulation in MATLAB Simscape

Muhammad Nizam Kamarudin<sup>1\*</sup>, Sahazati Md Rozali<sup>1</sup>, Mohd Shahrieel Mohd Aras<sup>1</sup>, Mohd Hendra Hairi<sup>1</sup>, Lokman Abdullah<sup>2</sup> and Zairi Ismael Rizman<sup>3</sup>

<sup>1</sup>Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia

<sup>2</sup>Faculty of Industrial and Manufacturing Technology, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia

<sup>3</sup>School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Dungun, Terengganu, Malaysia

\*Corresponding author: [nizamkamarudin@utem.edu.my](mailto:nizamkamarudin@utem.edu.my)

*Submitted 18 March 2024, Revised 13 August 2024, Accepted 03 October 2024, Available online 01 November 2024.*

Copyright © 2024 The Authors.

**Abstract:** Hydraulic pumps are the heart of hydraulic systems that convert electrical energy into mechanical energy. As the behavior of a specific type of hydraulic pump must be identified to cater to the pump's limits and operating range, precise pump selection for particular applications is a must. Hence, this paper presents the research findings on the characteristics of hydraulic pumps, focusing on pump parameters such as pump power, flow rate, and operating pressure. These parameters were evaluated under no-load operating conditions without actuators. The simulation setup is realized through Simscape on the MATLAB platform. The laboratory test rig exploits the advantages of Bosch Rexroth hydraulic pumps and other hydraulic components manufactured by the Rexroth group of companies. The findings from this research find a relationship between pump power, pressure, and flow rate. The simulation and experimental results showed good agreement with a very slight percentage difference, where the factors that contribute to the slight tolerance are thoroughly elaborated.

**Keywords:** Flow rate; Hydraulic power; Hydraulic pump; MATLAB; Simscape.

## 1. INTRODUCTION

The hydraulic system is a branch of technology concerned with the conveyance of pressurized fluids through pipes and hoses. The difference between a hydraulic system and its counterpart, such as a pneumatic, is only the operating pressure. The hydraulic system works in a large pressure range of around 30 bar to 400 bar [1], whereas the pneumatic system requires only an approximate 6 bar working pressure [2]. Compared to pneumatic systems, hydraulic systems offer very good power density due to high operating pressures. Hydraulic systems provide very good path accuracy for the movement characteristic since fluid is hardly compressible as compared to the pressurized air in pneumatic systems. As hydraulic systems deliver a larger force, they play a very important role in industries such as mobile machines and industrial trucks, shipbuilding, the metallurgical and rolling industries, plastic machines, hydraulic presses, steel construction, travel drives, machine tools, and flight simulators.

Figure 1 illustrates the hydraulic systems, that can be categorized into three parts, namely the energy conversion at the input side, control systems, and the energy conversion at the output side. The hydraulic pump is the heart of hydraulic systems that convert mechanical energy into electrical energy. Though the system works under pressure, the pump itself does not produce pressure for the system. The actual purpose of a hydraulic pump is to generate flow rates [3]. The pressure only developed from the restriction on the flow of fluid throughout the system. The restrictions come from hydraulic control systems and circuitries such as flow control valves, pressure relief valves, directional control valves, and check valves. Other sources of restriction are energy converters such as hydraulic cylinders and motors, as well as external exogeneous forces from the loads. Any bending of hoses and other abnormalities in the hydraulic circuit also cause intense pressure on the system.

There are three important parameters to be considered while selecting a hydraulic pump: a displacement volume that is measured in  $\text{cm}^3/\text{rev}$ , a speed range in  $\text{min}^{-1}$ , and a continuous operating pressure in unit bar. Displacement volume is the volume of fluid to be pumped into the system per rotation [4]. Speed range is the speed of a pump driven by an electrical motor via a shaft. The operating pressure is the range of pressure that the pump must work under, depending on the nature of the system, the workplace, and the load. As such, knowledge of pump characteristics is vital in the various applications.

Various studies have been conducted to investigate the hydraulic pump characteristics. For instance, authors in [5]

investigated the hydraulic characteristics of vertical axial flow pump devices using a numerical simulation method. The results therein presented the characteristic curve of the pump's head and discharge rate. The examination of load influence on the flow characteristics of the hydraulic pump was conducted in [6], where the approach was implemented in the laboratory testing. The flow characteristic testing considered the density and the kinematic viscosity of the fluid. The results tabulated the flow efficiency without assessing the pump power. In [7], the characteristic of a centrifugal pump was obtained via a numerical method that exploited the conversion formula and was simulated by a method of characteristics (MOC). The approach requires high mathematical knowledge. The results are bound within the transient without considering a steady run time.

The latest trend of studies focusing on the characteristics of hydraulic pumps seems to have led to numerous investigations into the axial flow pump. In [8], researchers explored the dynamic characteristics of hydraulic pumps based on a modal analysis of axial flow pumps. The approach required parameter identification in normal pumps and pumps with slipper wear faults. The simulation is conducted with a 1440 r/min speed and 4 MPa working pressure. Article [9] reported the agreement between the numerical and model test results of the flow behaviors of the axial-flow pump and the full tubular pump under different flow conditions, hence confirming the accuracy of the numerical results. To observe the transient characteristic of the axial flow pump, more agreement between numerical simulation and experimental study can be found in [10,11,12]. However, the work in [10] was focused on the start-up. While in [11], the approach exploited computational fluid dynamics and later expanded the techniques using acoustic analysis [12]. The methodology supported the investigation of the internal flow behavior and characteristics upon pressure fluctuations, and flow field analysis including static pressure. The article therein explained that noise and vibration may be caused by pressure fluctuations in the hydraulic systems.

Through a literature survey, very few studies on the characteristics of a variable displacement pump have been highlighted. Furthermore, it is interesting to dig more into the flow rate relationship and hydraulic power against operating pressure with less mathematical burden. This paper conducts a simulation study in MATLAB Simscape to investigate the characteristics of hydraulic pumps under no load conditions. The parameters and performances to be analyzed are the pump flow rate, hydraulic energy, and pump displacement. Plus, the extension and retraction times of the hydraulic cylinder are observed and recorded in the results. To verify the simulation, the simulated hydraulic circuit is realized into the actual hydraulic circuit on the Bosch Rexroth Hydraulic test equipment.

The overall structure of the paper takes the form of five sections, including this introductory section. Section 2 discusses hydraulic pumps, including their type, specifications, and operational concept. Section 3 begins by laying out the simulation setup and procedure. Section 4 discusses the realization of the simulated hydraulic circuit on the Bosch Rexroth Hydraulic test equipment. Section 5 concludes the study.

## 2. HYDRAULIC PUMPS

Hydraulic pumps can be categorized into two classes: fixed displacement pumps and variable displacement pumps. The simplest pump, known as a geared pump, is a fixed displacement type where the volume of fluid to be transferred to the system is non-adjustable [13]. Therefore, pressure-compensated configurations are impossible for this type. Vane pumps with a double chamber are available in a fixed displacement configuration, whereas directly operated vane pumps are known to have a variable displacement configuration [14]. Radial piston pumps with internal piston support are fixed displacement pumps, while their counterparts, axial piston pumps with swashplates, are variable displacement pumps [15]. Hydraulic pumps with a variable displacement configuration can be used to facilitate load sensing. Figure 2 shows the schematic symbol for a hydraulic pump. In Figure 2(a), the arrow crossing the circle indicating a variable displacement pump. Alphabet *S* denotes a suction port, and *P* denotes the working port. Adjusting the volume through pilot line allow the excessive fluid to be returned to the tank via the leakage port, *L*. In Figure 2(b), the symbol without the crossing arrow and *L* port represents a fixed displacement pump.

In this study, the experimental circuit is built under the open-loop working principle. The parting between the open loop and the closed loop hydraulic systems is the capacity of the oil consumption where the oil is recycled within the loop. As such, the system requires an auxiliary pump and a charge pump. Open-loop systems are normally used in mobile hydraulics, such as cranes, excavators, tractors, and loaders [16]. On the other hand, open-loop hydraulic systems require a single pump with a larger tank capacity.

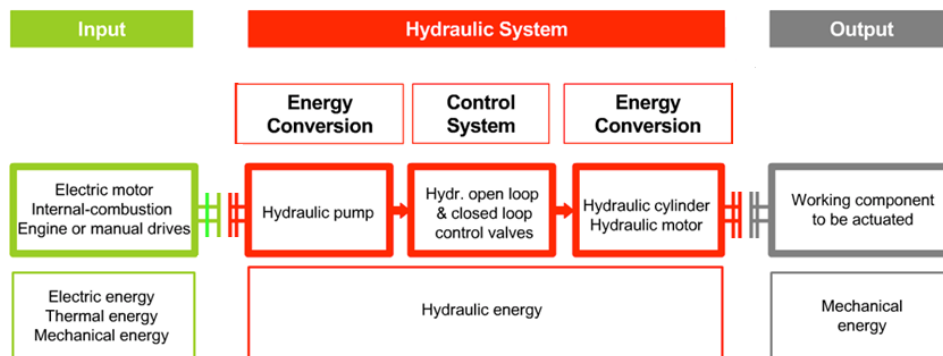


Figure 1. Hydraulic systems.



Figure 2. Schematic symbol for a hydraulic pump: (a) Variable displacement pump, (b) Fixed displacement pump.

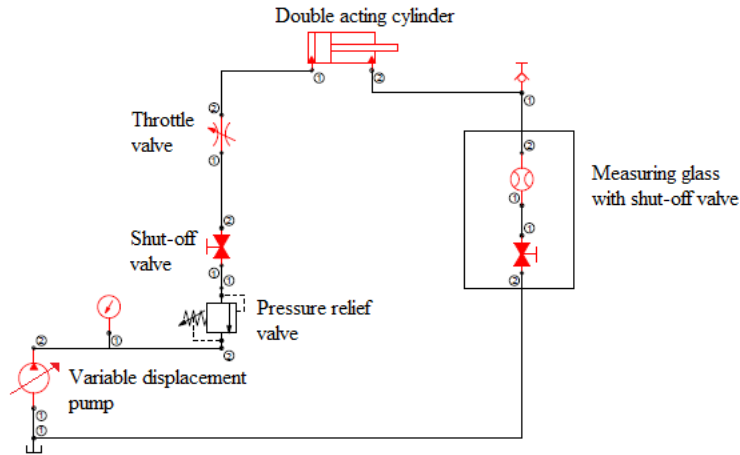


Figure 3. Test circuit without hydraulic cylinder.

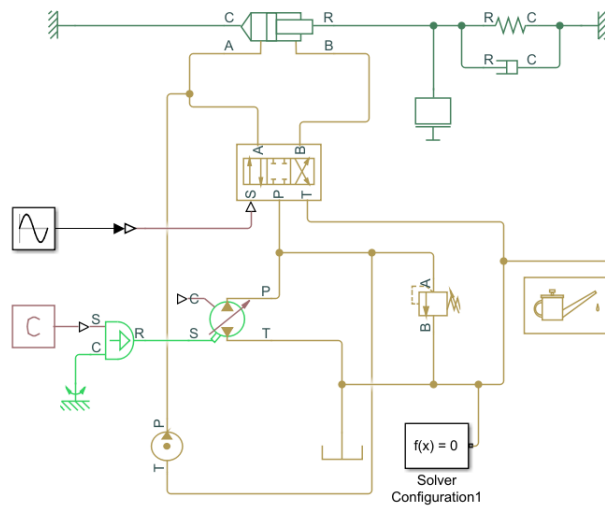


Figure 4. Test circuit with hydraulic cylinder.

### 3. SIMULATION SETUP AND PROCEDURE

It is important to acquire a pressure-flow characteristic curve for the pump, which can be used to determine the relationship between increasing operating pressure and pump losses. To reach this objective, a simulation is conducted in Simscape through MATLAB.

Figure 3 shows the hydraulic circuit that is designed to study the characteristics of a variable displacement pump operating without an actuator (hydraulic cylinder). A pressure relief valve holds the operating pressure  $P_{op}$  for the system. The valve will open as the system pressure,  $P_{sys}$  exceeds or equals  $P_{op}$  in order to maintain the pre-setting  $P_{op}$ . The throttle valve is a flow control valve that regulates the flow rate of the fluid pumped to the system. The pressure in the system can also be adjusted by the throttle valve in conjunction with a pressure relief valve. When the hydraulic cylinder is connected to the system as shown in the circuit in Figure 4, the throttle valve controls the speed and motion of the piston. Note that the measuring glass in the circuit captures the volume of fluid in liters, hence giving the amount of displacement of the pump.

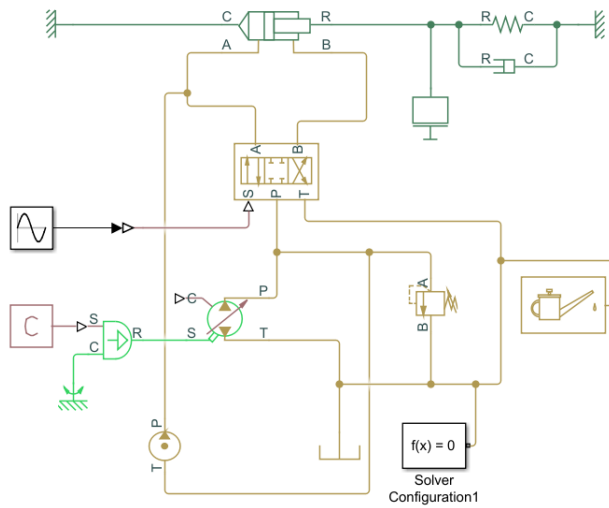


Figure 5. Realization of test circuit in MATLAB Simscape.

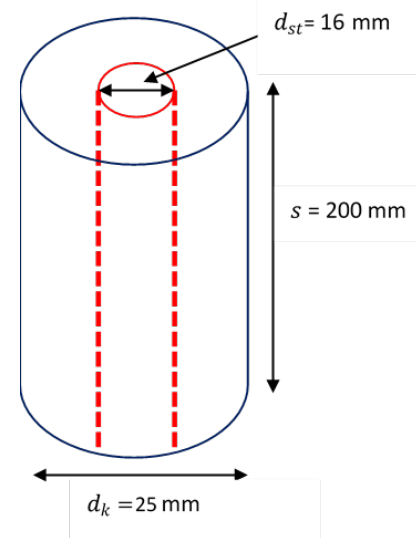


Figure 6. Single-rod double-acting cylinder CD70F25/16-200.

Figure 5 shows the realization of the circuit in MATLAB Simscape. The simulation setup utilizes the actual CD70F25/16-200 single-rod double-acting cylinder manufactured by the Rexroth group of companies. Based on the part number CD70F25/16-200, the piston base diameter is denoted as  $d_k = 25$  mm, piston rod diameter  $d_{st} = 16$  mm, and the piston stroke  $s = 200$  mm. All diameters are depicted in Figure 6. As such, the piston base area can be computed as  $A_K = (\pi/4)d_k^2$ , piston rod area  $A_{st} = (\pi/4)d_{st}^2$ , and the piston ring area  $A_R = A_K - A_{st}$ . The filling volume can therefore be computed as the multiplication of area and piston stroke, denoted as  $A_K s$  and  $A_R s$  for extension and retraction, respectively. With this mathematical proof, no experimental proof is needed to conclude that the retraction time of the single-rod double-acting cylinder is slower than its extension time, as the filling volume during extension is different from the filling volume during retraction.

Figure 7 portrays the simulation procedure to gather simulation data for the pump characteristics. By using the pressure relief valve, the operating pressure,  $P_{op}$  is initially set to 50 bar. The system pressure  $P_{sys}$  is then established at 15 bar via the throttle. This gives different pressures ( $\Delta P = 35$  bar) that allow the flow of fluid according to the flow law [17]. The different pressures allow the fluid to be pumped up to the system and start filling the measuring glass. To observe the characteristics of the pump at a different system pressure, the throttle is adjusted continuously until  $P_{sys}$  reaches  $P_{op}$ . The pump flow rate  $q$ , in  $\ell/\text{min}$  can be computed by using Equation (1), where  $d$  denotes the displacement of the pump in liter.

$$q = 6d \quad (1)$$

The pump power  $\mathcal{P}$ , can be computed by using Equation (2). Note that  $\Delta P$  is the pressure difference between the operating pressure preset by the pressure relief valve and the system pressure preset by the throttle. In this case, throttle mimics the load to restrict the flow of the fluid throughout the system.

$$\mathcal{P} = \frac{\Delta P \times q}{600} * 1000 \quad (2)$$

#### 4. HYDRAULIC CIRCUIT FOR PUMP CHARACTERIZATION

To validate the simulation, a hydraulic experimental test circuit is designed on the Bosch Rexroth WS290 (DS4) workstation with vane pump and flow control (Load-Sensing). The experiment setup is shown in Figure 8. The apparatuses are shown in Table 1.

Table 1. Part list for hydraulic circuit experimental setup.

Hydraulic Components	Quantity	Type	Rexroth material number
Pressure relief valve	1	DBH6G1X/100	R961002520
Throttle valve	1	DV06-1-1X/V	R961002539
Shut-off valve	1	NA	R961002491
Manometer 0-100 bar	1	NA	R961002715
Measuring glass	1	NA	R961009485
Variable displacement pump	1	NA	
Tank	1	NA	
Double acting cylinder	1	CD70F25/16-200	R961009526

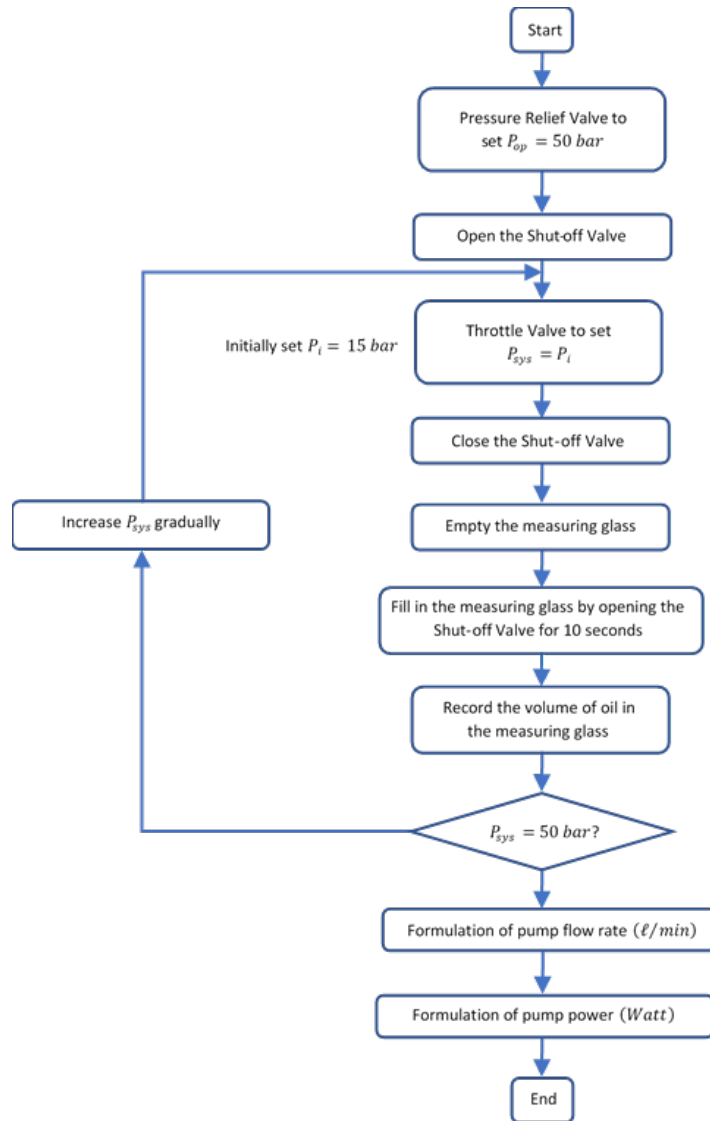


Figure 7. Simulation and experimental procedures.

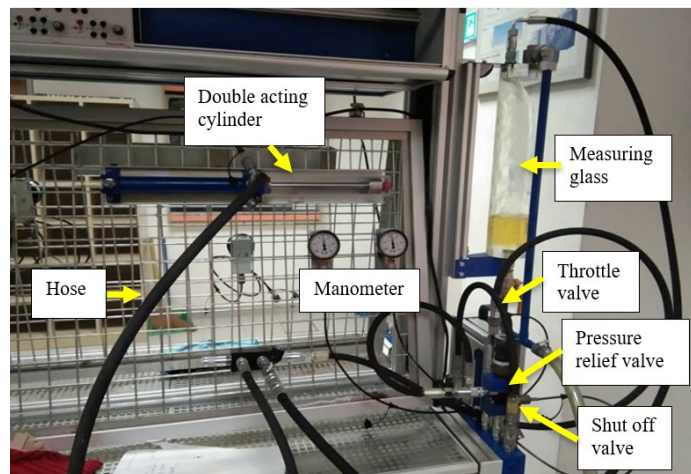


Figure 8. Realization of test circuit on the Bosch Rexroth WS290 (DS4) workstation.

The measuring glass is used to measure the volume of fluid displaced by the pump into the system at various system pressure  $P_{sys}$  while the operating pressure  $P_{op}$  is maintained at 50 bar. Through this procedure, the initial pressure  $P_{sys\text{initial}} = 15 \text{ bar}$  is set in the system via the pressure relief valve and gradually increased until final operating pressure  $P_{sys\text{final}} = 50 \text{ bar}$ . For every  $P_{sys}$ , the pump is allowed to displace the volume for 10 seconds. To obtain the experimental data for the pump characteristics, the similar procedure for the simulation work in Figure 5 is best referred to.

The CD70F25/16-200 double acting cylinder acts as the resistance to the flow to create system pressure, apart from the other choice of regulating the pressure relief valve. The cylinder has a piston diameter of 16 mm, a piston base diameter of 25 mm, a piston ring of 25 mm minus 16 mm that yields a 9 mm diameter, and a full stroke of 200 mm.

## 5. RESULTS AND DISCUSSION

Table 2 and Table 3 tabulate the data observed from the simulation and experiment respectively. The system pressure  $P_{sys}$  is increased from 15 bar to 50 bar by using the throttle valve. This procedure creates the pressure difference between the pump and the system. According to the flow law, the pump generates flow through the pressure difference from the high-pressure side to the low-pressure side. As such, the system will initially operate at a considerably large pressure difference until it reaches a smaller pressure difference with respect to the gradual increases in  $P_{sys}$ .

Table 2. Simulation findings.

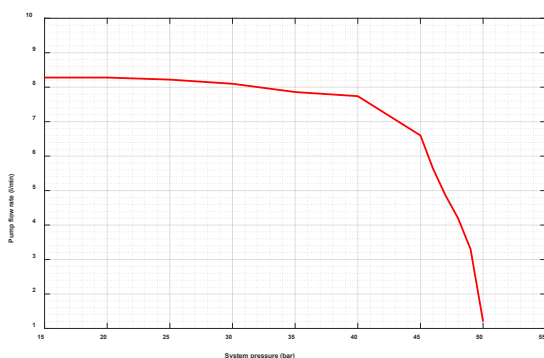
Parameters	Values / data											
System pressure, $P_{sys}$ (bar)	15	20	25	30	35	40	45	46	47	48	49	50
Time (s)	10	10	10	10	10	10	10	10	10	10	10	10
Displacement, $d$ ( $\ell$ )	1.38	1.38	1.37	1.35	1.31	1.29	1.1	0.94	0.81	0.7	0.55	$\approx 0$
Flow Rate, $q$ ( $\ell/\text{min}$ )	8.28	8.28	8.22	8.1	7.86	7.74	6.6	5.64	4.86	4.2	3.3	$\approx 0$
Hydraulic power, $\mathcal{P}$ (W)	207	276	342.5	405	458.5	516	495	432.4	380.7	336	269.5	0

Table 3. Experimental findings

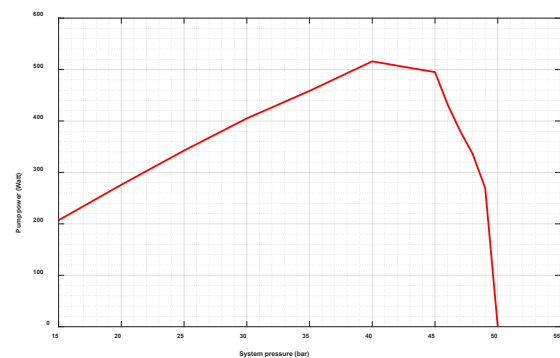
Parameters	Values / data											
System pressure, $P_{sys}$ (bar)	15	20	25	30	35	40	45	46	47	48	49	50
Time (s)	10	10	10	10	10	10	10	10	10	10	10	10
Displacement, $d$ ( $\ell$ )	1.43	1.41	1.39	1.36	1.34	1.31	1.22	0.98	0.85	0.80	0.50	$\approx 0$
Flow Rate, $q$ ( $\ell/\text{min}$ )	8.19	8.21	8.19	7.91	7.81	7.69	6.53	5.63	4.83	3.91	3.22	$\approx 0$
Hydraulic power, $\mathcal{P}$ (W)	204.8	273.7	341.3	395.5	455.6	512.7	489.8	431.6	378.4	312.8	263	0

Figure 9(a) and Figure 9(b) show the pump flowrate and the pump power of a variable displacement pump respectively, as  $P_{sys}$  is varied according to Table 2. Figure 10 clarifies that at considerably large pressure differences, the pump has enough kinetic energy to displace more fluid into the system with very little power consumption. This region is defined as on-stroke time as the pump is able to pump fluid to the system when the system provides less pressure to the pump. As the system pressure increases and nearly reaches the operating pressure, that is  $P_{sys} \approx P_{op}$ , the variable displacement pump will allow more flow to the leakage line. This can be recognized by a light drop-off of the characteristic curve up to about 45 bars. At this point, the pump requires more power to overcome the pressure from the system. After the off-stroke point, the pump enters de-stroke time, which is the time that a variable displacement pump requires to adjust from the maximum flowrate to a flowrate of zero and eventually reach zero-stroke.

Figure 11 shows the comparative behavior of the actual pump with respect to the simulation result. The characteristic curve confirms the findings between the simulation and experimental work with slight percentage of difference as depicted in the comparative histogram in Figure 12. Despite the simulation and experimental results showed good agreement, the slight percentage of difference can be attributed to several scientific factors such as model assumptions and simplifications in the simulation, experimental uncertainties such as pressure drop in the pipeline, parameter sensitivity due to equipment wear and tear that normally leads to a measurement and systematic errors.



(a) Pump flowrate.



(b) Pump power.

Figure 9. Pump flowrate and power characteristic curve.

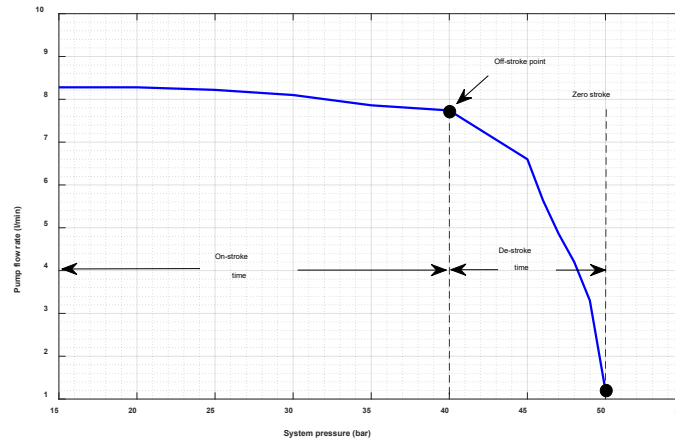
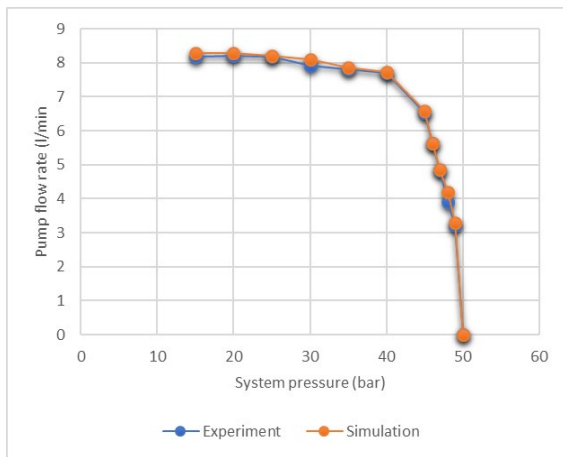
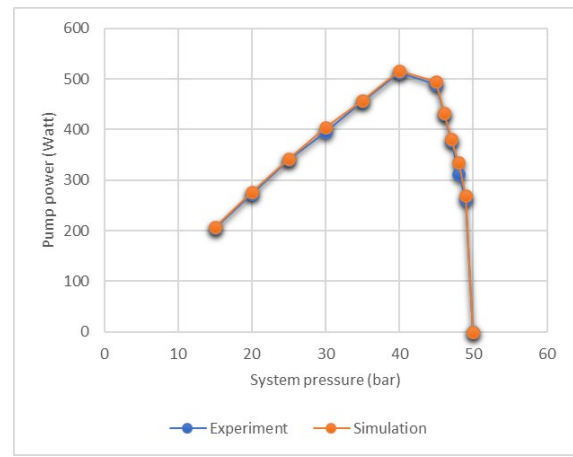


Figure 10. Flow rate characteristic of the pump.

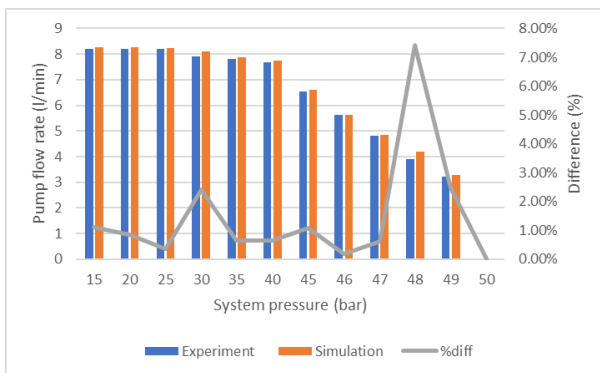


(a) Pump flow rate.

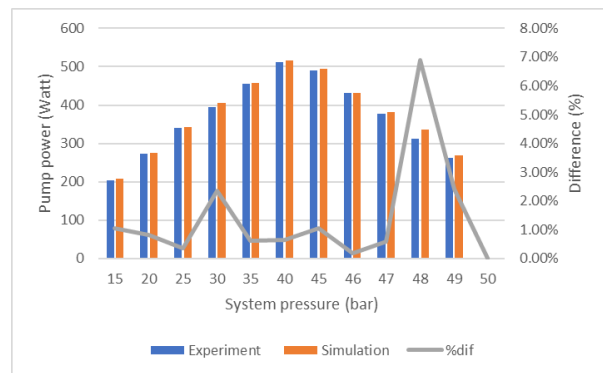


(b) Pump power.

Figure 11. The comparative characteristic curve for simulation and experimental pump circuit.



(a) Pump flow rate.



(b) Pump power.

Figure 12. The characteristic curve with percentage of difference.

A huge difference can be observed at  $P_{sys} = 48$  bars, as the displacement decreases rapidly when the configured maximum value is reached (zero stroke). At this point, the relative error is recorded as high due to the disagreement in response time between simulation and practice. As in practice, the response is attributed to experimental uncertainties such as pressure drop in the pipeline, parameter sensitivity, and equipment wear and tear. While in the simulation, the experiment assumes ideal equipment parameters without uncertainties.

## 6. CONCLUSION

The experimental effort has successfully verified the simulation work in investigating the characteristics of a variable displacement hydraulic pump. As the external forces may produce restrictions to the flow and produce pressure intensification, the experiment and simulation only consider the no-load condition in order to investigate the characteristics of the pump without external perturbation. Both simulation and experimental results showed good agreement with slight percentage of difference due to scientific factors. The result proved the flowrate curve and power curve of the pump upon various system pressures while the operating pressure of the pump is fixed. The pattern gives knowledge on the on-stroke time of the pump, the de-stroke time, and the behavior of the pump power. Whereas, the actuator responses, such as no-load cylinder extension time and retraction time, are proven mathematically without the need for an experimental observation. Upon completion of this work, it is recommended that the approach be applied to a fixed displacement pump in order to distinguish the difference between the two and to observe the operation of a pressure relief valve as the system pressure upticks. To reach this aim, the Bosch Rexroth hydraulic system offers various hydraulic components ranging from a shut-off valve, pressure relief valve, flow control valve, and throttle valve. The observation can also be extended to the characteristics of a pump with energy converters such as hydraulic motors and various types of hydraulic cylinders such as plungers, double-acting, single-acting, double-rod, and single-rod cylinders.

## ACKNOWLEDGEMENT AND FUNDING

This research has been carried out in the Rexroth Training Center at the Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka (UTeM). A special acknowledgement was also addressed to the Bosch Rexroth Drive and Control Academy for the technical support.

## DECLARATION OF CONFLICTING INTERESTS

The authors declare no potential conflicts of interest with respect to the research and publication of this article.

## REFERENCES

- [1] V. Savic, D. Knežević, D. Lovrec, M. Jocanovic and V. Karanovic, Determination of pressure losses in hydraulic pipeline systems by considering temperature and pressure, *Journal of Mechanical Engineering*, 55, 2009, 237-243.
- [2] M. Papoutsidakis, A. Chatzopoulos, D. Papachristos and C. Drosos, Hydraulics and pneumatics: Operational characteristics and control for modern industry applications, *International Journal of Computer Applications*, 178(25), 2019, 31-40.
- [3] R. Keith Mobley, *10 - Troubleshooting Hydraulic Systems*, Book chapter in *Fluid Power Dynamics*, Butterworth-Heinemann, Newnes, 2000, 171-177.
- [4] Y. Song, D. Wang, H. Ren, J. Cai and B. Jing, Research on hydraulic pump displacement control using PI and feed-forward compensation, *Advances in Mechanical Engineering*, 9(12), 2017, 1-8.
- [5] L. Xu, H. Zhang, C. Wang, D. Ji, W. Shi, W. Lu and L. Lu, Hydraulic characteristics of axial flow pump device with different guide vane inlet angles, *Frontiers in Energy Research*, 10, 2022, 1-13.
- [6] J. Kosibaa, Z. Tkáč, J. Jablonický, V. Shcherbak, L. Ganushchak-Yefimenko, M. Paumer, T. Bukoros, G. Čurgaliová and M. Zachar, Experimental testing of the influence of the operating loading on the flow characteristics of hydraulic pump, *Eksplatacja i Niezawodność - Maintenance and Reliability*, 24(3), 2022, 583-589.
- [7] W. Wan and W. Huang, Investigation on complete characteristics and hydraulic transient of centrifugal pump, *Journal of Mechanical Science and Technology*, 25(10), 2011, 2583-2590.
- [8] M. Hao, S. Liu, G. Liu and H. Pan, Research on dynamic characteristics of hydraulic pump slipper with wear based on operational modal analysis, *IEEE 6<sup>th</sup> Information Technology, Networking, Electronic and Automation Control Conference (ITNEC)*, Chongqing, China, 2023, 1098-1103.
- [9] L. Shi, W. Zhang, H. Jiao, F. Tang, L. Wang, D. Sun and W. Shi, Numerical simulation and experimental study on the comparison of the hydraulic characteristics of an axial-flow pump and a full tubular pump, *Renewable Energy*, 153, 2020, 1455-1464.
- [10] S. Fu, Y. Zheng, K. Kan, H. Chen, X. Han, X. Liang and X. Tian, Numerical simulation and experimental study of transient characteristics in an axial flow pump during start-up, *Renewable Energy*, 146, 2020, 1879-1887.
- [11] A. R. Al-Obaidi and A. A. Mohammed, Numerical investigations of transient flow characteristic in axial flow pump and pressure fluctuation analysis based on the CFD technique, *Journal of Engineering Science & Technology Review*, 12(6), 2019, 70-79.
- [12] A. R. Al-Obaidi, Evaluation and investigation of hydraulic performance characteristics in an axial pump based on CFD and acoustic analysis, *Processes*, 12(129), 2024, 1-37.
- [13] R. Keith Mobley, 3 – Hydraulic Pumps (Book chapter), *Fluid Power Dynamics*, Butterworth-Heinemann, Newnes, 2000, 25-46.
- [14] A. Dzhurabekov, J. Rashidov, A. Gazaryan, B. Kholbutaev, S. Mansurova and N. Tashmatov, Improving impeller and water flow section of vane pumps, *IV International Scientific Conference in Construction Mechanics, Hydraulics and Water Resources Engineering (CONMECHYDRO)*, Tashkent, Uzbekistan, 363, 2022, 1-12.
- [15] J. M. Bergada, S. Kumar, D. Ll. Davies and J. Watton, A complete analysis of axial piston pump leakage and output flow ripples, *Applied Mathematical Modelling*, 36(4), 2012, 1731-1751.

- [16] O. Chiavola, E. Frattini, F. Palmieri, A. Fioravanti and P. Marani, On the efficiency of mobile hydraulic power packs operating with new and aged eco-friendly fluids, *Energies*, 16(5681), 2023, 1-16.
- [17] H. Xu, W. Chen and W. Hu, Hydraulic transport flow law of natural gas hydrate pipeline under marine dynamic environment, *Engineering Applications of Computational Fluid Mechanics*, 14, 2020, 507-521.