Momentum Transfer and Mechanical Operations Lab

Pump & Valve Characteristics

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Team: MTMO 2

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Abstract with Graphics

The experiment titled “Pump and Valve Characteristics" aimed to explore the operational principles and performance of centrifugal and peristaltic pumps, along with the characteristics of various valve types including ball, gate, globe, and needle valves.

The primary objective was to understand the working mechanisms of these pumps and valves and to quantify and evaluate their performance. Each valve's unique features and applications are scrutinised, providing practical insights for their use in diverse industrial settings.

In the centrifugal pump (schematics in figure 1) experiment, the flow rate and pressure were measured at different operating points to plot a characteristic curve illustrating the relationship between flow rate and pressure. The results showed a linear relationship between these parameters, aligning with Bernoulli's law.

The peristaltic pump (schematics are shown in figures 2a & 2b) experiment focused on identifying occlusion within the pump and determining its operational range. By adjusting the rotational speed, flow rates were recorded to assess the precision and effectiveness of the pump, particularly its ability to handle delicate fluids without contamination. The

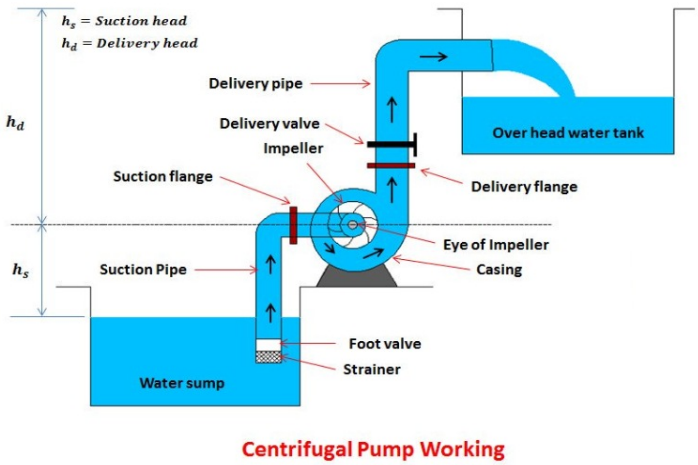
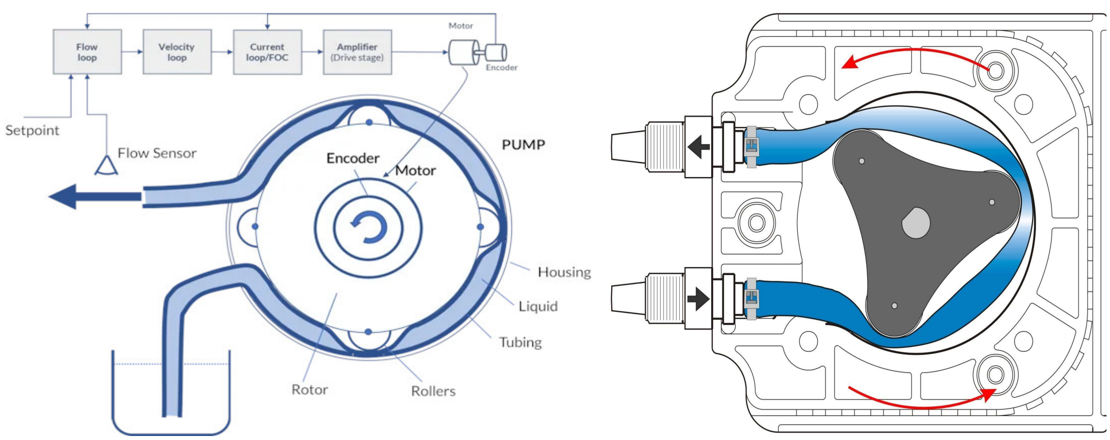


Figure 1: Schematic representation of Centrifugal Pump

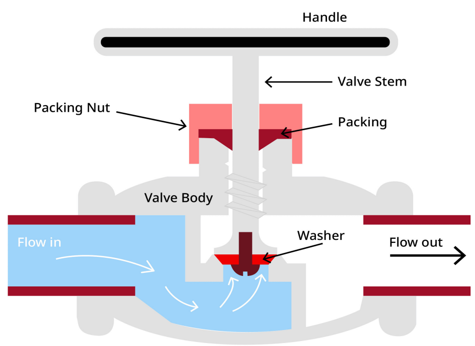
data revealed a slight discrepancy between predicted and actual flow rates, likely due to factors such as occlusion in the tubing or the presence of air bubbles in the fluid.



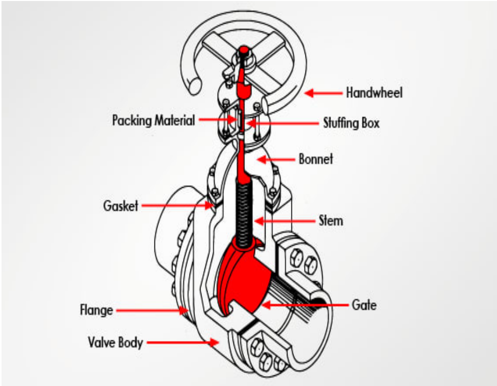
(a) Working of a Peristaltic Pump (b) Internals of Peristaltic Pump

Figure 2: Details of Peristaltic Pump

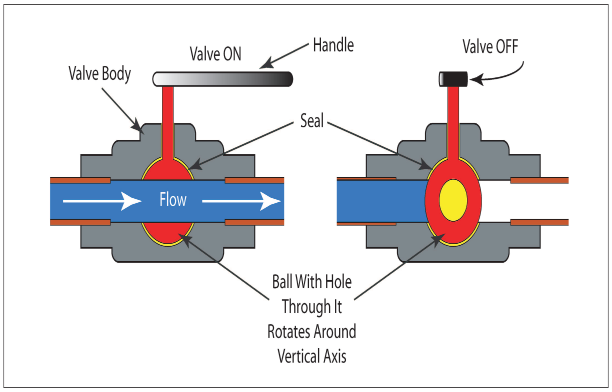
The experiment also included an analysis of various valves (schematically shown in figures 3), examining their flow control characteristics, pressure drop, and operational efficiency. Each valve type exhibited unique flow control properties, affecting the flow patterns and pressure drop across the system. The findings from this experiment provided valuable insights into the performance of different pumps and valves, which are critical in industrial applications involving fluid transport and control.



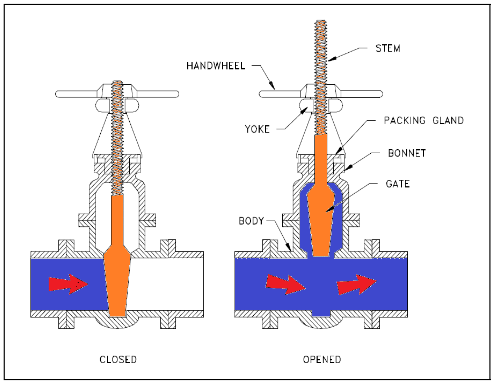
(a) Schematics of Globe Valve



(b) Schematics of Gate Valve



(c) Schematics of Ball Valve



(d) Schematics of Needle Valve

Figure 3: Schematics of Various Valves

A. Pump Characteristics

1 Aim

- Identify the type of pumps and their operating principles.
- Plot the pump characteristic curve for the centrifugal pump.
- Determine Occlusion in the given peristaltic pump and determine the pump's operational range in the current configuration.

2 Background and Motivation

Pumps play a crucial role in various industrial applications, especially in the chemical industry, where the correct selection of pumps directly impacts operational efficiency, maintenance costs, and overall system reliability. Understanding the principles and characteristics of different types of pumps is essential for chemical engineers to make informed decisions regarding fluid handling and particle separation processes. This experiment focuses on two distinct types of pumps: centrifugal pumps and peristaltic pumps, each serving different purposes in industrial applications.

- **Centrifugal Pumps** (shown in figure 4) operate based on the principles of fluid dynamics, specifically centrifugal force. Widely used in water supply systems, HVAC, and industrial processes, they handle large volumes of fluid with minimal maintenance. The working mechanism involves a rotating impeller that creates a pressure difference, propelling fluid from the inlet to the outlet. Understanding the characteristic curve of a centrifugal pump, which represents the relationship between flow rate, head, and efficiency, is crucial for optimizing performance.

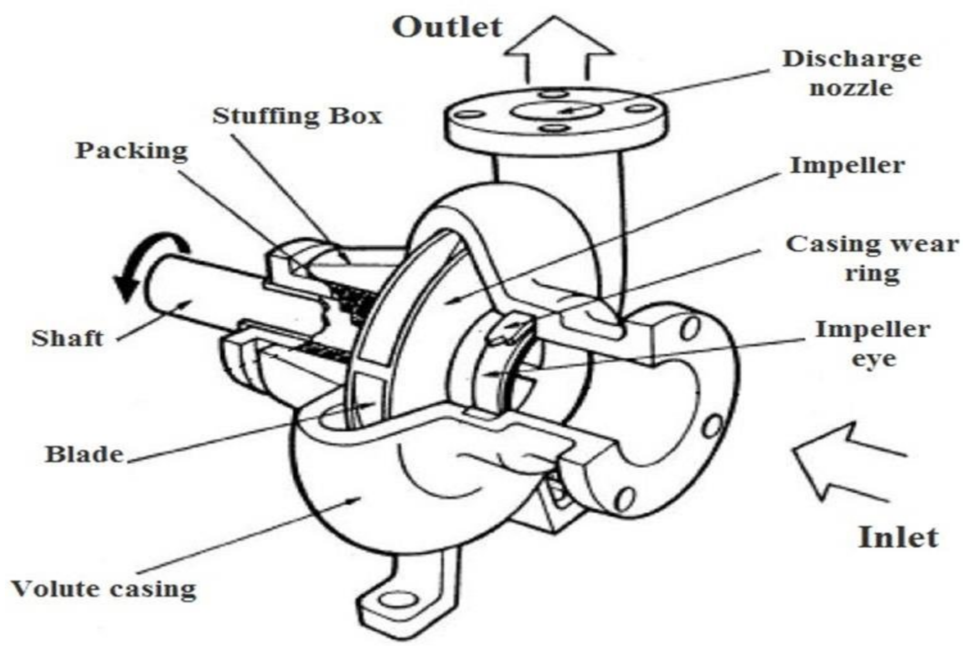


Figure 4: Details of Centrifugal Pump

- **Peristaltic Pumps** (shown in figure 5), on the other hand, belong to the category of positive displacement pumps and are characterized by their ability to handle viscous and sensitive fluids with high precision. These pumps work by compressing a flexible tube with a rotating mechanism, creating discrete chambers that push the fluid forward. Commonly used in medical and laboratory settings, peristaltic pumps minimize contamination and ensure accurate fluid transfer. A key aspect of these pumps is determining the occlusion rate and operational range, which directly affects flow rate and precision.

Figure 5: Peristaltic Pump

3 Materials and Methods

3.1 Apparatus & Materials Required

1. **Centrifugal Pump Experiment** – Centrifugal pump, Water reservoir, Pressure gauge, Flow meter.

2. **Peristaltic Pump Experiment** – Peristaltic pump head, Tubing, Fluid reservoirs, Pressure sensors, Measuring cylinder, Stopwatch.

3.2 Experimental Setup Description

The experimental setups are shown in figure, (shown in figures 6 & 7) which are the two sub-parts of the pump-characteristics experiment.

3.2.1 Centrifugal Pump Experiment

- The centrifugal pump setup typically involves a closed-circuit system that includes a centrifugal pump driven by an electric motor, a water tank, connecting pipes, and various measuring instruments.

- The setup is designed to measure the flow rate and pressure at different operating points to plot the characteristic curve of the pump.

- The pump is mounted on a base-plate with the inlet and outlet submerged in the water reservoir.

- The outlet is split into two sections: one directed to the pool and the other connected to a volume flow rate measuring device.
- This setup allows for the collection of data that can be used to construct characteristic curves, such as Flow rate vs. pressure, which is crucial for understanding the pump's performance under various conditions.

Figure 6: The Complete set-up for Centrifugal Pump with Water Reservoir

3.2.2 Peristaltic Pump Experiment

- The peristaltic pump setup involves a peristaltic pump head, tubing, beakers with water (fluid reservoirs), flow measurement devices, and pressure sensors.
- The setup is designed to assess the occlusion within the pump and determine its operational range. The pump head is securely mounted, and tubing is connected to both inlet and outlet ports.
- The flow rate is adjusted by varying the pump's rotational speed, which affects the peristaltic action on the tubing. Pressure sensors are installed at the pump inlet and outlet for monitoring pressure within the tubing.

- This setup allows for the recording of flow rates, pressure differentials, and pump speed at different operational points, which helps in verifying the pump's flow rate accuracy and assessing its performance.

Figure 7: The Complete set-up for Peristaltic

3.3 Procedure

3.3.1 Centrifugal Pump Experiment

- Install the centrifugal pump securely on a base-plate, ensuring that both the inlet and outlet are fully submerged in the water reservoir. The outlet of the pump should be bifurcated, with one pathway directed toward the pool and the other connected to a device for measuring the volumetric flow rate.

- Document the flow rates across a range of pressures, continuing until the flow meter attains its maximum capacity.

- Utilize the recorded data to develop characteristic curves, including the flow rate and pressure correlation.

3.3.2 Peristaltic Pump Experiment

- Securely fasten the pump head and attach tubing to both the inlet and outlet ports.
- Control the flow rate by adjusting the pump's rotational speed, which directly influences the peristaltic action on the tubing.
- Install pressure sensors at both the inlet and outlet of the pump to monitor the pressure within the tubing.
- Record flow rates, pressure differentials, and pump speed under various operational conditions.
- Verify the accuracy of the pump's flow rate by comparing the recorded values with the expected results, based on pump speed and tubing characteristics.

4 Observation Tables

The tabulations include the observed data from the sub-experiments that include the pumps and are tabulated in both the following tables (tables 1 & 2):

$\dot{V}$ (L/hr)	ΔP (psi)
2500	0.0
2600	0.0
2690	0.0
2790	1.4
2919	1.5
3039	1.6
3276	1.8
3396	1.9
3513	2.0
3626	2.2
3752	2.3

$\dot{V}$ (L/hr)	ΔP (psi)
3877	2.4
4000	2.5
4128	2.7
4240	2.8
4355	2.8
4472	3.0
4609	3.1
4762	3.5
4835	3.6
4840	3.6
4850	3.6

Table 1: Tabulation for Centrifugal Pump

$\dot{V}$ (mL/min)	V (mL)	T (s)
50.0	46	60.73
100.0	98	60.82
150.0	140	60.80
200.0	190	60.61
300.0	287	60.68
400.0	392	60.84

Table 2: Tabulation for Peristaltic Pump

5 Results & Calculations

5.1 Centrifugal Pump

In this analysis, we studied the impact of the Pressure Drop (Δp) created by the Centrifugal Pump on the Volumetric Flow Rate ($\dot{V}$) of the system. The results are provided in the plot below (figure 8):

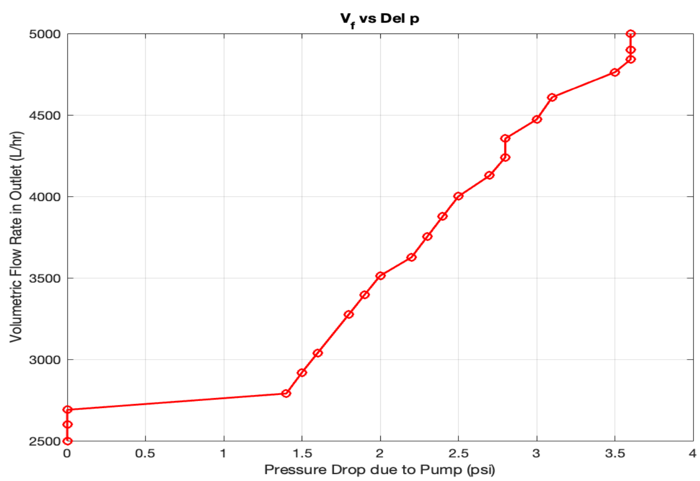


Figure 8: Characteristic Curve of Centrifugal Pump

5.2 Peristaltic Pump

In the case of Peristaltic Pump, we studied the Volumetric Flow Rate ($\dot{V}$) shown in the settings, and the error which occurs when we actually measure it. The results are as follows (figures 9 & 10):

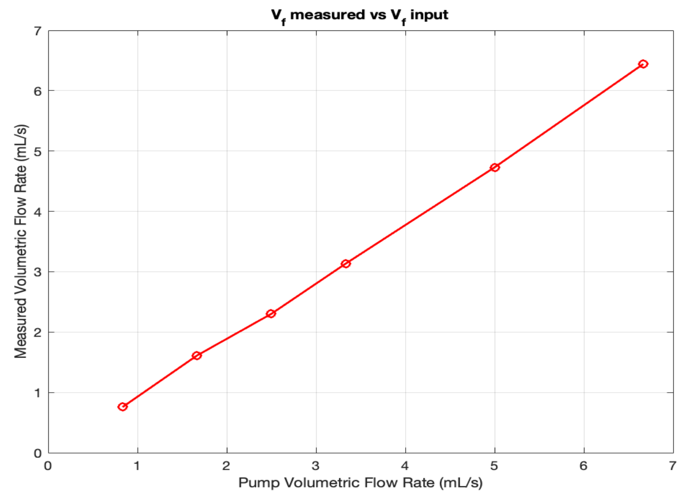


Figure 9: Volumetric Flow Rate in Peristaltic Pump

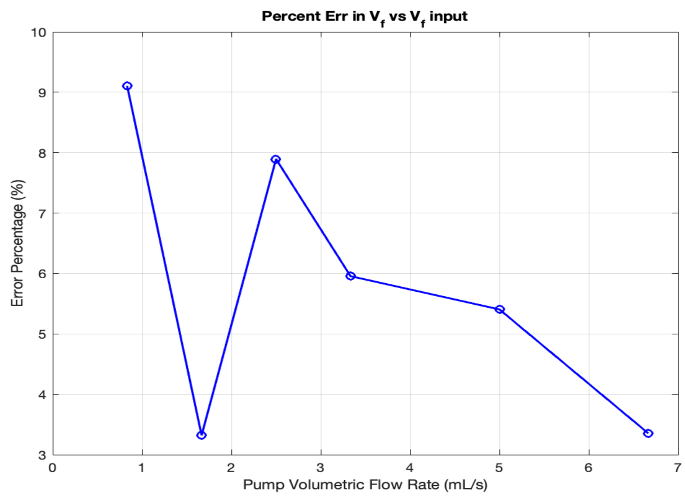


Figure 10: Error in measurements given by Peristaltic Pump

5.2.1 Occlusion

The term 'Occlusion' is refers to the measurement of the amount of squeeze applied on the tubing by the roller inside a Peristaltic Pump. The formula to calculate this value is given below :

$$y = \frac{2t - g}{2t} \times 100\% \tag{1}$$

Here, t = wall thickness of the tubing, and g = minimum gap between roller and housing.

6 Conclusions and Remarks

6.1 Centrifugal Pump

- There is a general trend in the characteristic curve of this pump, which shows that an increase in Volumetric Flow Rate ($\dot{V}$) causes an increase in Pressure Drop (Δp) in a linear relation.
- The Pressure Drop $\Delta p = 0$ for all $\dot{V} < 2700\ L/hr$. This is because for lower Volumetric Flow Rates, the water flow is not strong enough, and there is air present in the pipes.
- It is also observed that for very high Volumetric Flow Rates ($\dot{V} > 4850\ L/hr$), the value of Pressure Drop Δp remains constant.

6.2 Peristaltic Pump

- It is observed that the measured Volumetric Flow Rate ($\dot{V}$) is always slightly lower than the Volumetric Flow Rate shown by the RH-P1005 pump.
- The rotation speed of the roller present inside the machine increases as the Volumetric Flow Rate ($\dot{V}$) increases.
- It is also noted that according to literature data, the value of Occlusion is usually in the range of 10% to 20%.

7 Error Analysis

Least Count of stopwatch $\equiv \Delta t = 0.01$ sec
Least Count of Volume beaker (small) $\equiv \Delta V_p = 1$ mL
Least Count of Volume beaker (large) $\equiv \Delta V = 2$ mL
Least Count in Pressure Drop Readings = 0.1 psi

7.1 Sources of Error

- **Centrifugal pump:**
  - Parallax error.
  - The pump with a faulty flow meter/pressure gauge can produce incorrect readings.

- Friction between the fluid and pipe walls can cause pressure loss along the pipeline. Pipes sizing bends and rough surfaces can exacerbate this issue, reducing the flow rate and efficiency.
- Corrosion of pipe material can lead to reduced flow area, leaks, and structural weakness, impacting efficiency and safety. The imperfect linear graph shows that.
- we have systematic errors, and any one or all of them could be responsible for the same.

- **Peristaltic pump:**
  - Fluctuations or imprecise management of pump speed within the experiment resulted in inaccuracies in flow rates.
  - Occurrence of error while taking the readings of flow rates due to inaccurate motor speed control.
  - There might be partial or complete occlusion in a tube, which results in inaccurate flow rate measurements.
  - The air bubbles in the fluid can impact tube compression and introduce variations in flow rates.
  - The error increases with an increase in flow rate, indicating that the pump cannot measure the flow rate accurately as it rises.

B. Valve characteristics

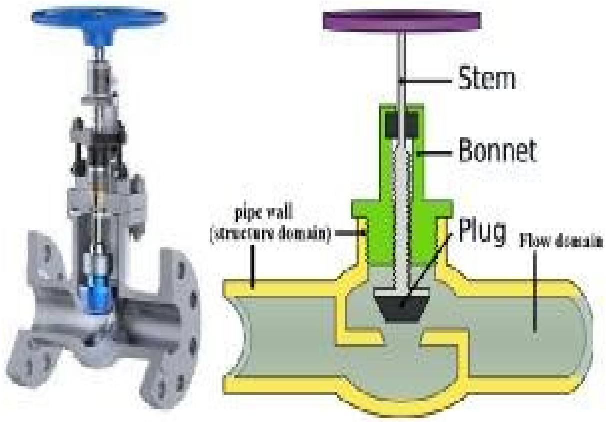
1 Aim

- Identify the types of valves and their applications. Determine the valve opening range and plot percentage flow versus percentage of valve opening.
- Determine the pressure drop across these valves and establish the relationship between volume flow and pressure drop for each valve type.
- Obtain a master plot of percentage volume flow, pressure drop and percentage valve opening comparing the various valves tested. Comment on the findings.

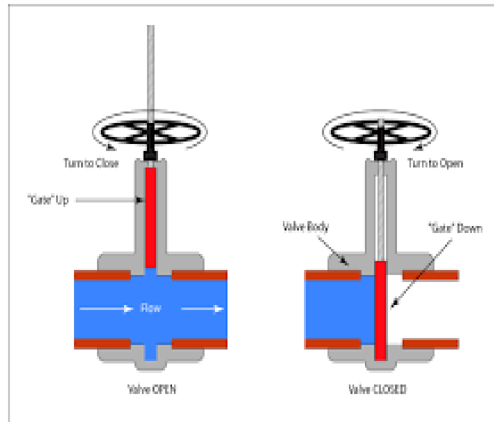
2 Background and Motivation

Valves are integral components in piping systems, serving as essential tools for regulating and controlling the flow of fluids. In chemical industries, where precision in fluid handling is critical, the correct selection and understanding of valve types are vital for maintaining operational efficiency, safety, and cost-effectiveness. Each valve type exhibits unique characteristics and performance behaviors, influencing flow control, pressure management, and system reliability. The study of valve characteristics, including Ball, Globe, Gate, and Needle valves, helps engineers optimize processes that depend on accurate fluid regulation.

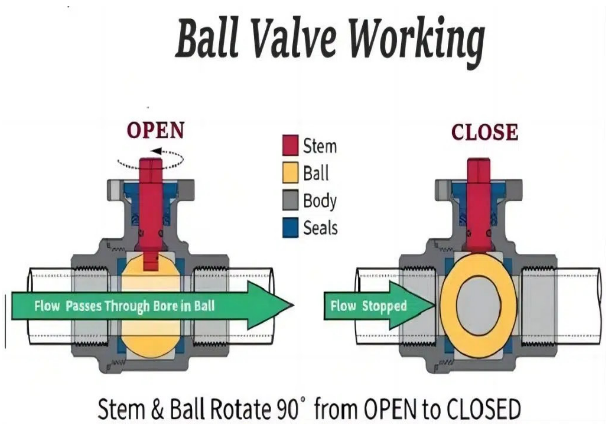
- **Ball Valves** (figure 11c) are known for their simplicity and quick operation. They use a rotating ball with a bore to control the flow of fluid. Ball valves are often chosen for applications requiring complete shutoff and fast response times. Their design allows for minimal pressure drop when fully open, making them suitable for high-flow applications. However, due to the on-off nature of their operation, they may not provide fine flow control, making them less ideal for throttling applications.
- **Globe Valves** (figure 11a), on the other hand, are designed for precise flow control. Their internal mechanism consists of a movable disk and a stationary ring seat, providing a linear relationship between the valve position and flow rate. Globe valves are often used in applications where flow regulation is needed, as they allow for fine adjustments. However, they typically generate a higher pressure drop compared to other valve types, which can impact overall system performance.
- **Gate Valves** (figure 11b) are typically employed in applications requiring minimal pressure loss and where valves are either fully open or fully closed. They operate using a gate that moves perpendicular to the flow, offering a low-resistance path when open. While gate valves are ideal for applications requiring minimal pressure



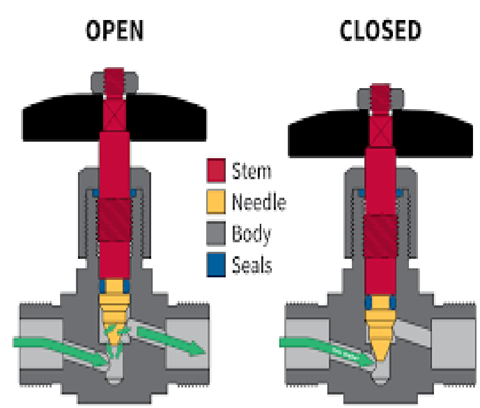
(a) Globe Valve



(b) of Gate Valve



(c) Ball Valve



(d) Needle Valve

Figure 11: Various Valves

drop and full-flow capabilities, they are not suited for precise flow regulation due to their non-linear flow characteristics when partially open.

- **Needle Valves** (figure 11d) offer the highest level of precision in flow control. Their design incorporates a slender, needle-like plunger that fits into a conical seat, allowing for fine-tuned adjustments of flow. Needle valves are commonly used in low-flow, high-precision applications such as laboratory experiments and instrument calibration. Their capability to regulate small flow rates with accuracy makes them indispensable in applications requiring exact control, though they may also contribute to a higher pressure drop.

3 Materials and Methods

3.1 Apparatus & Materials Required

Gate valve, Ball valve, Globe valve, Needle valve, Bucket/Measuring jug.

3.2 Experimental Setup Description

The experimental setup is shown in figure 12, which are the four sub-parts of the experiment as a whole.

Figure 12: Experimental Set up for the Valves Experiment

- The setup for testing valve characteristics typically involves a system that includes various types of valves (ball, gate, globe, and needle valves), a fluid source, and measuring instruments.
- The valves are connected in series or parallel with the fluid source, and the flow rate and pressure drop across each valve are measured at different valve openings.
- This setup allows for the examination of the flow control capabilities, pressure drop, and operational efficiency of each valve type.
- Each valve's unique flow control properties are analysed to understand how they influence the flow patterns and pressure drop across the system.

3.3 Procedure

- Begin by selecting one valve from the set of four available options.
- Install the chosen valve, ensuring a secure, leak-proof connection for fluid flow at the inlet. Attach pressure gauges to both the inlet and outlet of the valve.
- Fully open the valve and record the number of turns required to transition from a fully closed to a fully open position.
- Measure the pressure at various valve openings, including fully open, 25% closed, 50% closed, and 75% closed.
- Document the pressure drop at each valve position, and measure the time required to fill a 10-liter beaker with water.
- Utilize the recorded data to calculate the volumetric flow rate.
- Construct a graph illustrating the relationship between valve opening percentage, volumetric flow rate, and pressure drop.

4 Observation Tables

The tabulations include the observed data from the sub-experiments that include the valves and are tabulated in both the following tables (tables 3a, 3b, 4a & 4b):

Rotations	% Open	ΔP (psi)	V (mL)	T (sec)
4.5	100	10.2	1020	29.28
3.5	77.78	8.8	1060	26.40
2.25	50	8.8	1060	28.66
1.0	22.22	8.8	1020	34.19

(a) Tabulation for Needle Valve (max rotation = 4.5)

Rotations	% Open	ΔP (psi)	V (mL)	T (sec)
3.5	100	9.2	10	20.25
2.5	71.43	9.2	10	21.43
1.5	42.86	9.2	10	24.61
0.5	14.29	11.7	10	35.70

(b) Tabulation for Globe Valve (max rotation = 3.5)

Table 3: Tabulation for Needle & Globe Valves

Rotations	% Open	ΔP (psi)	V (mL)	T (sec)
2	25	11.5	10.0	13.17
4	50	6.0	10.0	5.47
6	75	1.9	9.1	4.44
8	100	0.9	10.0	4.46

(a) Tabulation for Gate Valve (max rotation = 8)

Rotations	% Open	ΔP (psi)	V (mL)	T (sec)
22.5°	25	11.2	10.0	27.92
45.0°	50	7.9	10.0	10.06
67.5°	75	2.6	10.0	4.88
90.0°	100	0.0	9.1	3.66

(b) Tabulation for Ball Valve (max rotation = 90°)

Table 4: Tabulation for Gate & Ball Valves

5 Results

In the case of Valves, the Volumetric Flow Rates ($\dot{V}$) were measured with different percentages of Valves opened ($Open\%$). The results are as follows (figure 13) :

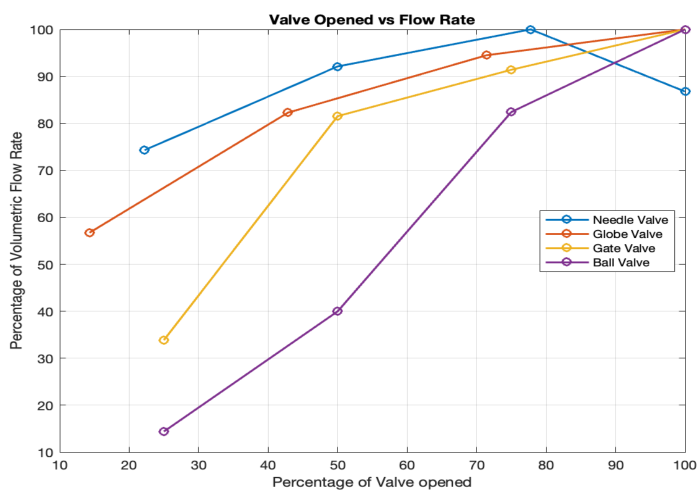


Figure 13: Volumetric Flow Rates with different Percentages of Valve Opened

Next, we take a look at the characteristic curves of the four different valves in our experiment. The Pressure Drop (Δp) was measured with different Volumetric Flow Rates ($(\dot{V})$), and the results are plotted below (figures 14, 15, 16, 17) :

Finally, we make a master plot in MATLAB which takes into consideration all three variables ($Open\%$, $\dot{V}$ and Δp) at the same time. It is recommended to render this plot in real-time using the MATLAB codes provided in our reference GitHub repository, as the

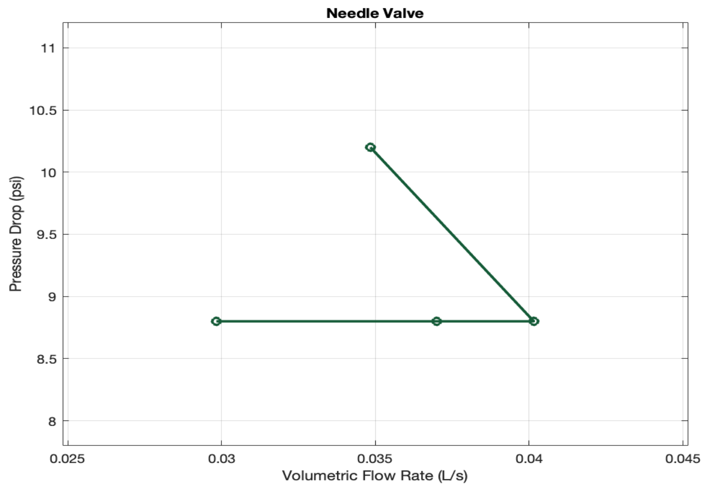


Figure 14: Characteristic Curve of Needle Valve

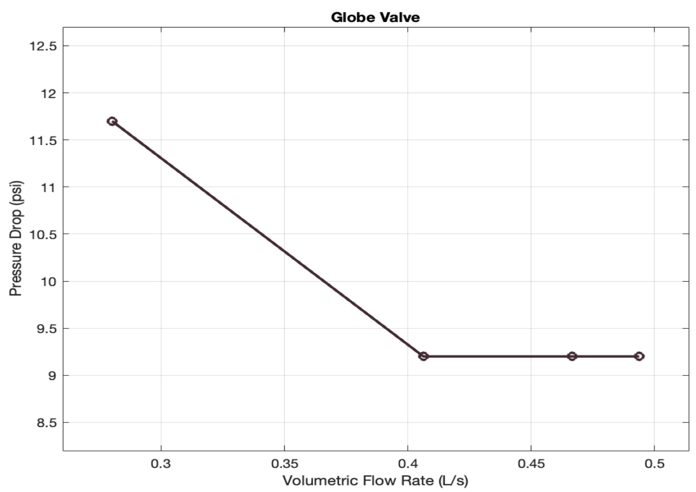


Figure 15: Characteristic Curve of Globe Valve

plot is a 3D plot.
For reference, an image of the plot is provided below as figure 18 :

6 Conclusions and Remarks

- Firstly, it is observed that opening any Valve causes an increase in the Volumetric Flow Rate. It is also seen that the relation between $Open\%$ and $\dot{V}$ is linear.

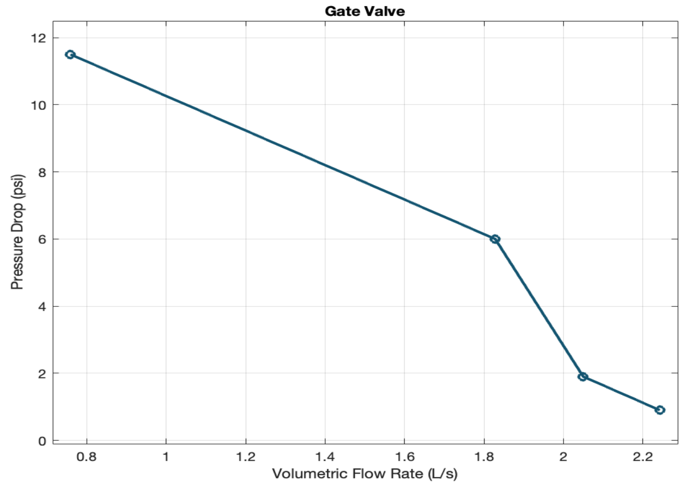


Figure 16: Characteristic Curve of Gate Valve

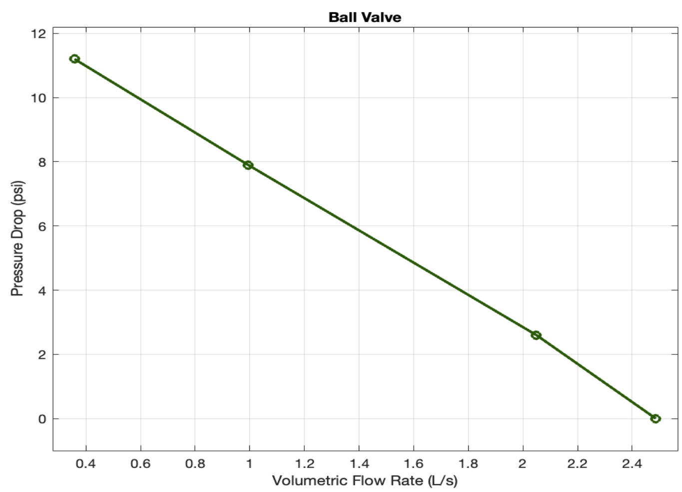


Figure 17: Characteristic Curve of Ball Valve

- In the case of Needle and Globe Valves, the characteristic curve shows that the Pressure Drop (Δp) remains almost constant irrespective of the change in Volumetric Flow Rates ($\dot{V}$).
- However, in the case of Gate and Ball Valves, we see a linear relation where an increase in Volumetric Flow Rate ($\dot{V}$) causes a decrease in Pressure Drop (Δp).

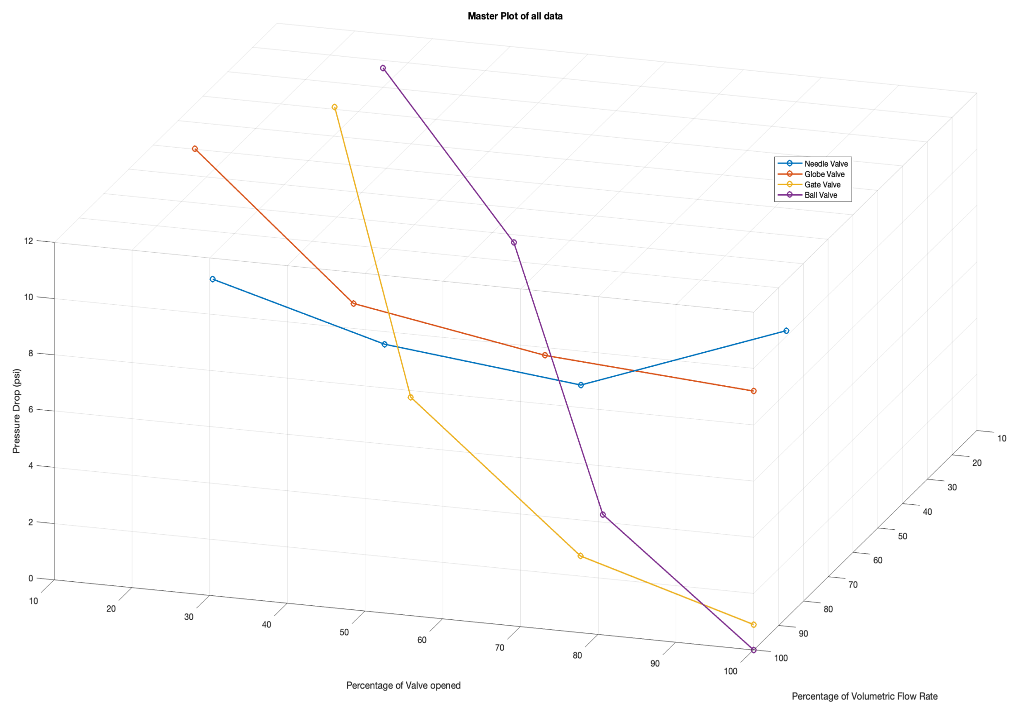


Figure 18: Master Plot of all Valve Measurements

7 Error Analysis

Least Count of stopwatch $\equiv \Delta t = 0.01$ sec
Least Count of Volume beaker (small) $\equiv \Delta V_p = 20$ mL
Least Count of Volume beaker (large) $\equiv \Delta V = 0.1$ L
Least Count in Pressure Drop measurements $= 0.1$ psi

7.1 Sources of Error

The following are the sources of errors that may affect the accuracy of the pressure drop and flow rate calculations around the valves (globe, gate, needle, and ball):

- Possible fluctuations in the readings due to environmental factors, such as temperature changes or vibrations.
- Manufacturing defects or wear and tear in the valves might cause irregularities in the valve's flow characteristics, affecting the pressure drop and flow rate. Incomplete sealing of the valve could cause unexpected pressure losses or leaks.

- Improper placement of the flow meter (too close to bends, valves, or other fittings) can lead to inaccurate flow measurements due to flow disturbances or non-uniform flow profiles.
- Air bubbles in the piping system could cause erratic pressure readings and affect flow rate measurements.
- Friction losses from the piping system, fittings, and connections before and after the valves could introduce additional pressure losses that are difficult to quantify.
- In mechanical systems, valves can exhibit hysteresis (lag in response when the valve is being opened or closed), potentially leading to inaccurate flow control and pressure drop measurements.

8 Precautions

- Verify that all pumps, valves, and sensors are installed correctly, ensuring secure and leak-free connections to avoid erroneous readings or equipment damage.
- Ensure that the fluid systems are free from air bubbles, as entrained air can cause fluctuations in pressure and flow readings, affecting the accuracy of the characteristic curve for the centrifugal pump.
- When testing valve opening and closing, adjust valve positions gradually to avoid sudden pressure surges that could damage the system or skew data.
- Ensure that the peristaltic pump operates within its recommended range to prevent overheating or excessive wear on the tubing, which could lead to inaccurate occlusion measurements.
- Continuously monitor pressure changes during the experiment, particularly when determining pressure drops across valves, to avoid exceeding the safe operating limits of the system.

Thought Question / Open-Ended

Q. Is it possible to measure the pressure change across the centrifugal pump at a flow-rate of 10 LPM using the given setup. Explain your answer with reasons. If yes, then what will be the range of pressure change? If no, give reasons for the same and how can you modify the setup to perform the same measurement?

A. No, we cannot measure the Pressure Change across the Centrifugal pump at a flow rate of 10 L/min.

The reason behind this is that the observed range of the given pump was from about 2700 L/hr to 4850 L/hr, which is about 45 L/min to 80.83 L/min. For any volumetric flow rate below 45 L/min, the equipment simply showed a value of $\Delta p = 0.0 \ psi$.

We can conclude two facts from this :

- The diameter of the pipe is large enough that for any volumetric flow rate below 45 L/min, air gets mixed in with water, making it impossible for the equipment to properly calculate Pressure Change. As such, it is recommended to decrease the pipe diameter.
- The Least Count of the Pressure Change measurement is 0.1 psi is too big. We would not be able to measure the value at 10 L/min. As such, it is recommended to change the Least Count to 0.001 psi or lower.

We can solve this issue by making the two above mentioned changes in the experiment setup.

For now, we can estimate the value of Pressure Drop by performing Linear Regression on the Data taken from this experiment.

$$At \ 10 \ L/min \ : \ \Delta p = -0.9447 \ psi \tag{2}$$

This value is NOT useful at all, because the range of our Linear regression was between 45 L/min and 80.83 L/min. However, we can tell that the value of Δp will be much smaller then the value we got at 45 L/min.

Acknowledgements

We as a group contributed our respective parts into completing the above report on Pump and Valve Characteristics.

In terms of specifications, Lakkireddy Vishnu Vardhan Reddy helped with “Abstract" & “Apparatus & Materials" parts of the report. Atharva Sunilkumar Ghodke contributed in “Procedure", “Experimental Setup Description" & “Precaution" parts. Anomol Upadhyay delivered the content for “Aim (Objective)", “Background & Motivation" parts for both the subparts of the report and rest of all the parts are done, written, calculated & organized by Deepanjhan Das (general editor) & Aayush Bhakna (proof reader).

Regarding AI transcript for the open-ended thought question asked, we didn't use ChatGpt for our thought question. It was more confusing and so we, after discussing the scenario and after reading some related papers, we wrote as per our understanding. Therefore no such transcript is provided in the **Appendix** section.

And at last but not the least, we specially thank the respective TA for this experiment Mr. Saurabh bhaiya for his kind help and to let us have a thorough understanding of the whole process and the concept. We thank all the course instructors for their effective control and high co-operation as per the need.

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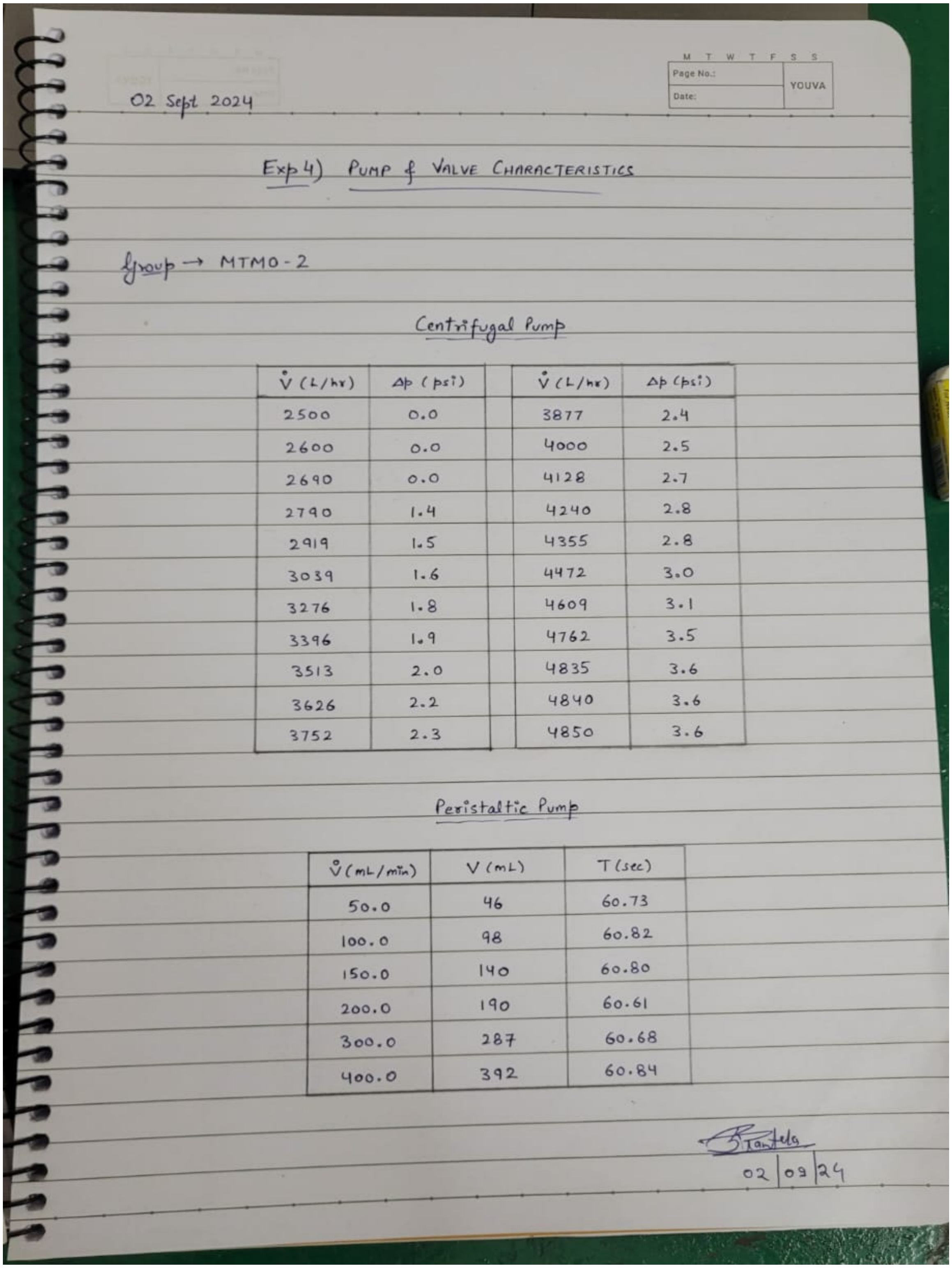
- Fluid Mechanics 4th Ed. by Frank M. White.
- Centrifugal Pumps - Chapter 5, 6, Pump Handbook by Igor J. Karassik, Joseph P. Messina, Paul Cooper, and Charles C. Heald.
- Peristaltic Pumps - Section 12.17 Portable Transfer of Hazardous Liquids, Pump Handbook by Igor J. Karassik, Joseph P. Messina, Paul Cooper, and Charles C. Heald.
- Globe Valve - Section-3.1.1, 10.1.2, Gate Valve - Section-10.1.1, Ball Valve - Section-10.1.10, Control Valve Handbook 6th Ed. Emerson Fisher.
- Needle Valve - Section 29.21 Steam Turbines, Speed Control Systems, Perry's Chemical Engineers' Handbook" edited by Robert H. Perry and Don W. Green.

Appendix

Lab Data: All the experimental observations with each of the pump & valves of the main experiment that was performed and tabulated during the laboratory session are included in order in the following (in figures 19, 20, 21).

Reference to all the contents: The official GitHub repository which contains all the related data and coded scripts for calculations is also provided below: https://github.com/deep183Das/CH3510_MTMO_Lab_Group_2/tree/main/Experiment_4. One can easily refer to all the related lab resources from this GitHub repository from where screenshots of few instances are shown in the above figures, in in this report.



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Exp 4) PUMP & VALVE CHARACTERISTICS

Group → MTMO-2

Centrifugal Pump

$\dot{V}$ (L/hr)	Δp (psi)	$\dot{V}$ (L/hr)	Δp (psi)
2500	0.0	3877	2.4
2600	0.0	4000	2.5
2690	0.0	4128	2.7
2790	1.4	4240	2.8
2919	1.5	4355	2.8
3039	1.6	4472	3.0
3276	1.8	4609	3.1
3396	1.9	4762	3.5
3513	2.0	4835	3.6
3626	2.2	4840	3.6
3752	2.3	4850	3.6

Peristaltic Pump

$\dot{V}$ (mL/min)	V (mL)	T (sec)
50.0	46	60.73
100.0	98	60.82
150.0	140	60.80
200.0	190	60.61
300.0	287	60.68
400.0	392	60.84

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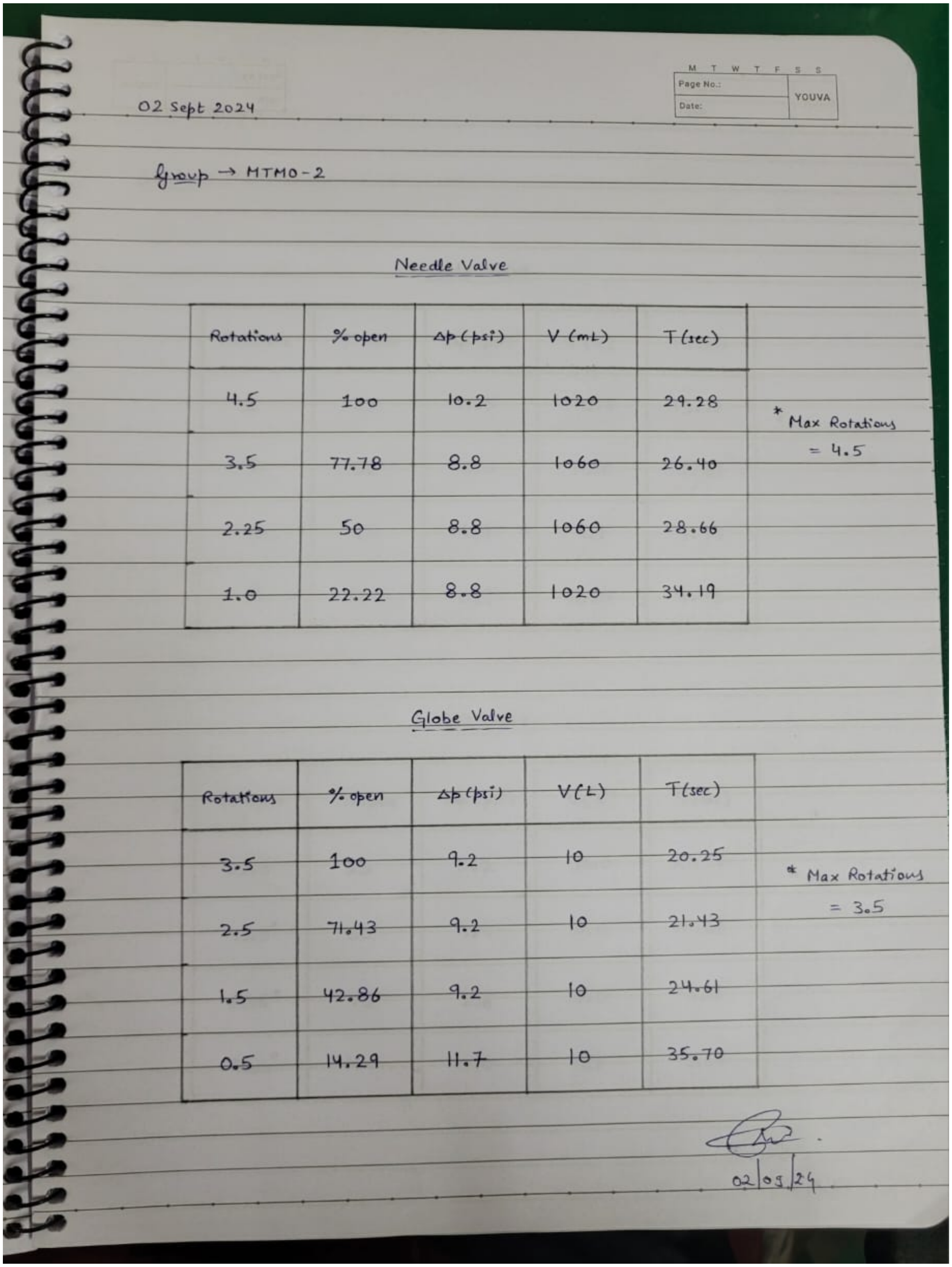
Figure 19: Data for Centrifugal & Peristaltic Pumps



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Group → MTMO-2

Needle Valve

Rotations	% open	Δp (psi)	V (mL)	T (sec)
4.5	100	10.2	1020	29.28
3.5	77.78	8.8	1060	26.40
2.25	50	8.8	1060	28.66
1.0	22.22	8.8	1020	34.19

* Max Rotations = 4.5

Globe Valve

Rotations	% open	Δp (psi)	V (L)	T (sec)
3.5	100	9.2	10	20.25
2.5	71.43	9.2	10	21.43
1.5	42.86	9.2	10	24.61
0.5	14.29	11.7	10	35.70

* Max Rotations = 3.5

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Figure 20: Data for Needle & Globe Valves

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Group → MTMO-2

Gate Valve

Rotations	% open	Δp (psi)	V (L)	T (sec)
2	25	11.5	10.0	13.17
4	50	6.0	10.0	5.47
6	75	1.9	9.1	4.44
8	100	0.9	10.0	4.46

* Max rotations = 8.0

Ball Valve

Rotation	% open	Δp (psi)	V (L)	T (sec)
22.5°	25	11.2	10.0	27.92
45.0°	50	7.9	10.0	10.06
67.5°	75	2.6	10.0	4.88
90.0°	100	0.0	9.1	3.66

* Max rotation = 90°

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Figure 21: Data for Gate & Ball Valves