Elements & Evaluation of a Centrifugal Pump

2. **Abstract**

In this experiment, the assessment is made on a 100 W centrifugal pump through disassembly and analysis of the performance of the pump. These include: the structural breakdown of the pump with a view of identifying its components; performance tests aimed at generating the pump curves for different operating conditions. The theory behind the experiment focuses on mechanical energy balance to predict the pump head as well as system loss in a piping configuration. Experimental activities include pumping the pump at the three power settings (I, II, III), taking pressure and flow rates and controlling a throttling valve in order to get a wide range of data. Graphs and plots of the pump performance curves were developed from these results and the discrepancy between the experimentally determined system head and theoretical prediction was established. From the experiment, students benefited with practical learning of real conditions affecting centrifugal pump and system head loss

3. **Aim**

- Exploded view of centrifugal pump to analyse its construction and its working.
- Compare the performance of a 100W centrifugal pump by obtaining the performance curves under various flow rates conditions.
- Check the theoretical calculations of system head and compare the same with the experimental findings.

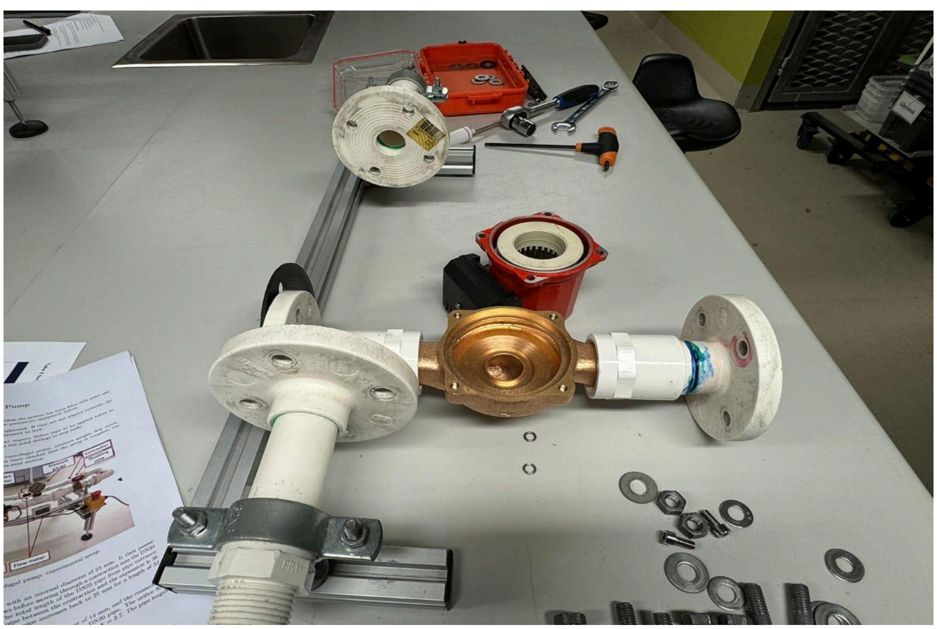
- The above research question points at the relationship that exists between pressure, flow rate and head loss in the system.

4. Questions

(a) Sketch of the System

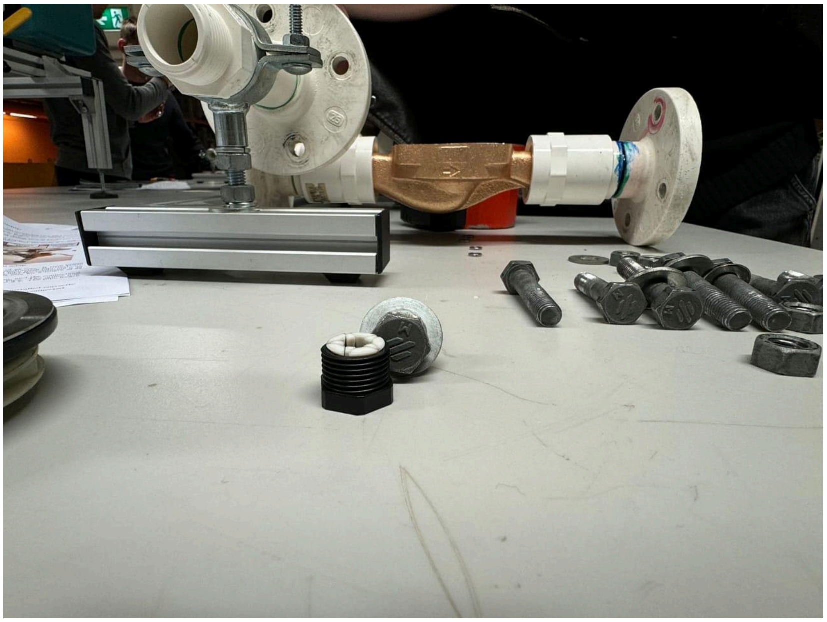
The system consists of several key components, including a water reservoir, a centrifugal pump, pressure gauges, a flow meter, and various pipe sections with different diameters. Below are the system elements and their respective specifications:

- Water Reservoir: Supplies water to the system.
- DN25 PVC Pipe (Diameter = 25 mm): Length = 108 cm, connects the water reservoir to the centrifugal pump and includes the inlet section.



- Centrifugal Pump: Positioned between the DN25 and DN20 pipes, providing energy to drive the water through the system.

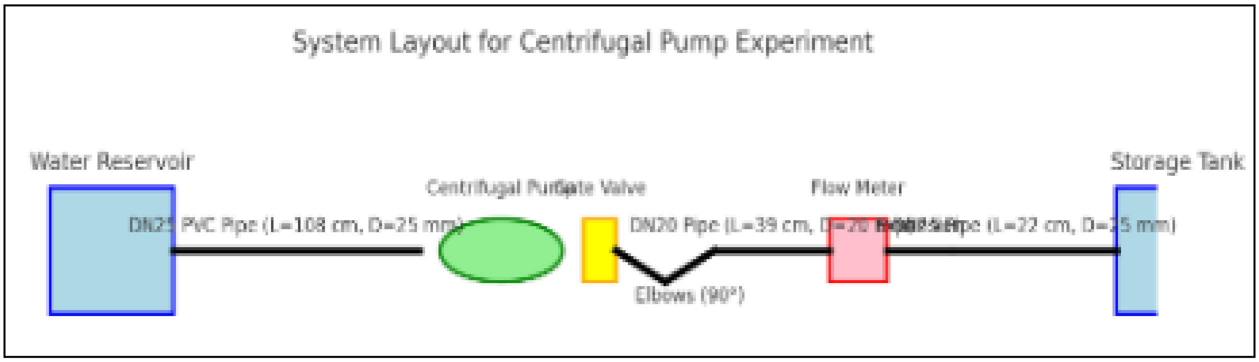
- Gate Valve: Installed downstream of the pump to regulate flow and control pressure in the system.
- Elbows (90° bends): Two elbows are present, which contribute to minor losses in the system.
- Contraction to DN20 PVC Pipe (Diameter = 20 mm): Length = 39 cm, follows the pump and the gate valve.

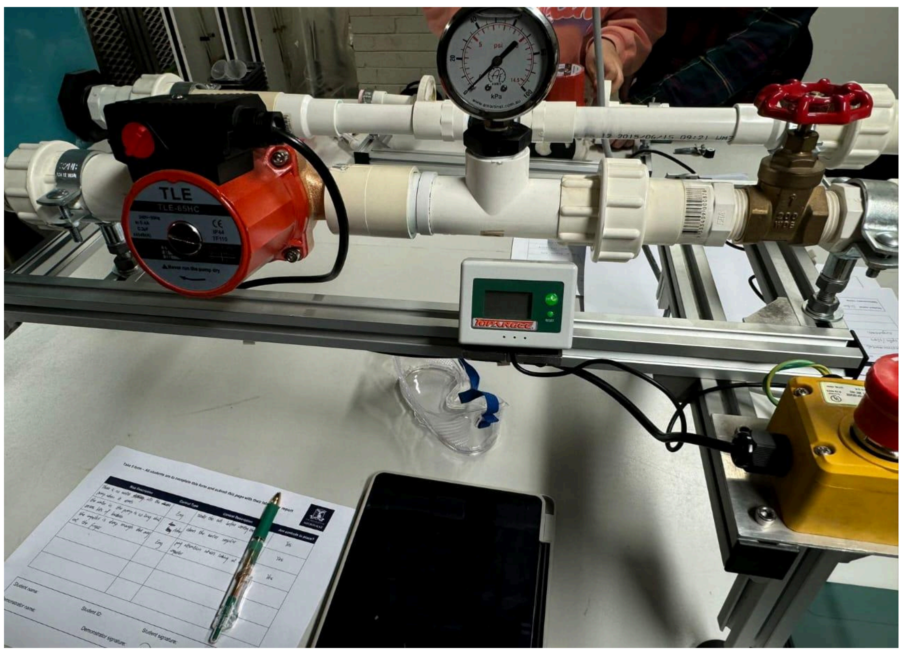


- Flow Meter (Internal Diameter = 14 mm): Positioned in the DN20 pipe, responsible for measuring the flow rate. It acts as a contraction and expansion point, contributing to additional pressure losses (K = 2.7).
- Expansion to DN25 PVC Pipe: After the flow meter, the pipe diameter increases back to 25 mm for a length of 22 cm before water exits into the storage tank.

Minor losses are considered at the following points:

- Pipe fittings (elbows and contraction/expansion sections).
- Flow meter (considered as having resistance due to contraction and expansion).





(b) What is priming a pump? Why is it important before initial startup?

Priming refers to the process of filling the pump and its suction line with liquid before starting the pump (Wang et al., 2019). This is done to ensure that no air pockets remain in the system, which could prevent the pump from creating the necessary vacuum for proper operation.

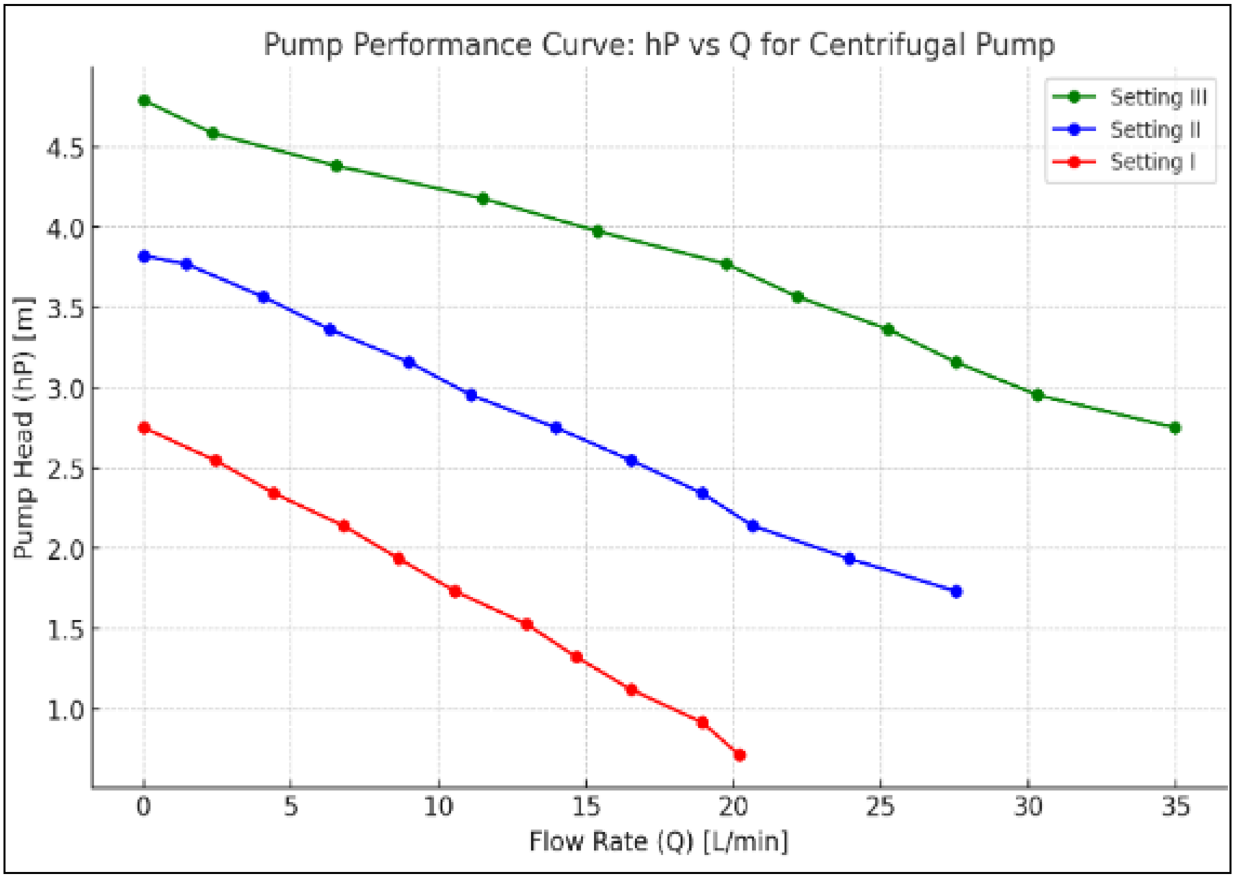
Importance of priming before initial startup

- Centrifugal pumps rely on the movement of liquid to generate the required pressure to pump fluid through the system (Mohammadi et al., 2023). If air is present in the pump, the impeller will spin without moving the liquid, leading to a condition known as air binding.

- Running the pump dry without priming can cause damage to internal components, particularly the impeller and seals, as they are designed to be lubricated and cooled by the liquid.

- Priming ensures that the pump functions efficiently and maintains its performance throughout the operation, preventing operational failures such as cavitation, which occurs when vapor bubbles form and collapse, potentially causing significant damage (Qian et al., 2024).

(c) Pump performance curve



The plot above illustrates the experimental data for each pump setting (I, II, and III) showing the relationship between the pump head (hP) in meters and the flow rate (Q) in L/min for the centrifugal pump. As the flow rate increases, the pump head decreases for all three settings, with Setting III showing the highest pump head at any given flow rate, followed by Settings II and I. This behavior is typical of centrifugal pumps, where higher flow rates result in lower head due to increased fluid velocity and corresponding losses.

(d) Pump curves for the 3 pump settings

The experimental data for the centrifugal pump at three different settings (I, II, and III) was used to fit a non-linear model of the form:

$hP = a + bQ^{c}$

Where:

- hP is the pump head (in meters).
- Q is the flow rate (in L/min).
- a, b, and c are constants derived from the curve fitting process.

The purpose of this model is to generate a best-fit equation for each pump setting that describes how the pump head decreases as the flow rate increases.

Results of Curve Fitting

1. Setting III (Highest Pump Speed):

   $hP = 4.73 - 0.0315Q^{1.17}$

   - a = 4.73: This indicates the initial pump head when the flow rate Q=0. It represents the maximum head the pump can generate at this setting.
   - b = -0.0315: This parameter controls the rate at which the head decreases with increasing flow rate. A negative value shows that as the flow rate increases, the pump head drops.

- c = 1.17: This exponent represents the non-linear relationship between flow rate and head. The value being greater than 1 indicates a slightly accelerated decline in head as flow rate increases.

2. Setting II (Medium Pump Speed)

   $hP = 3.86 - 0.0816Q^{0.99}$

   - a = 3.86: The initial pump head is lower than in Setting III, reflecting the slower pump speed.
   - b = -0.0816: A larger negative value indicates a more rapid decline in head compared to Setting III as flow rate increases.
   - c = 0.99: The exponent is close to 1, indicating an almost linear relationship between the flow rate and the head loss.

3. Setting I (Lowest Pump Speed)

   $hP = 2.75 - 0.0796Q^{1.07}$

   - a = 2.75: This is the lowest initial pump head, as expected, given the lowest pump speed setting.
   - b = -0.0796: Similar to Setting II, the head decreases at a significant rate with increasing flow.
   - c = 1.07: The exponent indicates a slightly non-linear relationship between flow rate and head loss, but it is close to linear.

Interpretation

- At Setting III, the pump generates the highest initial head, but the decrease in head as the flow rate increases is more gradual, making it suitable for higher flow rates with relatively stable pressure (Li, X et al., 2020).
- At Setting II, the pump still generates a good amount of head, but it declines more quickly than in Setting III.
- At Setting I, the pump operates with the lowest initial head, and its performance drops off more quickly with increasing flow, indicating it's optimized for lower flow rates (Wu et al., 2022).

(e) What a throttling valve is used for, and consequences of having a throttling valve installed prior to the pump inlet

Purpose of a Throttling Valve

A throttling valve is a crucial device employed for measuring the flow rate as well as pressure in the pumping systems (Hu et al., 2021). Depending of the valve position the amount of resistance in the system increases or decreases, in this way the level of flow changes which influences the flow of the liquid within the pipes. The main purposes of using a throttling valve are:

- Flow Regulation: It provides potential control on the flow rate and so, with the help of a valve the individuals control more or less fluid flow to maintain the required process conditions.
- Pressure Control: The valve by creating the resistance in the system can be used in varying the pressure in the piping downstream of the pump.
- System Protection: Throttling valves help to reduce the flow rate and thus prevent overloading of the pump which is critical in ensuring that the pump operates in its design conditions (Golwalkar and Kumar, 2022).

The use of a throttling valve is often situated on the discharge side of the pump powered so that the pump is capable of delivering full head and flow, but the downstream post pumping flow rate and pressure can be controlled.

Implications of Placing a Throttling Valve Before the Pump Inlet

When the throttling valve is installed prior to the inlet of the pump, it may lead to several undesirable outcomes on the pump performance and efficiency. Key implications include:

1. Flow Restriction

If the valve is placed upstream of the pump then it controls the flow of the liquid that is entering the draw of the pump. This in turn can decrease the demands of incoming fluid flow and develop high pressure drop in the suction line. As with all centrifugal pumps, the inlet flow affects the pump’s performance, so any interference may be detrimental to the pump.

2. Reduction in Suction Pressure

In case of operating the control dam before the pump, it limits the flow which results in a decrease in the pressure of the pump inlet. Reduced suction pressure may cause the pump to be unable to pull enough liquid quantities required to deliver the flow rate and head, thus compromising the performance of the system.

Exploitation using the Perspective of Net Positive Suction Head

NPSH is a concept one needs to consider to comprehend why having throttling valve upstream of the pump inlet is unadvisable. NPSH is another significant parameter in operation of the pump; its function is linked to avoidance of cavitation in the pump and efficiency of the pump.

There are two important aspects of NPSH:

- NPSH Available (NPSHA): This means the pressure at the suction port of the pump, should be higher or equal to the pressure exerted by the vapour that is above the liquid. NPSHA is defined by system specifics and natural conditions including the heigh of the source and barometric pressure.
- NPSH Required (NPSHR): This is the least pressure that must be maintained at the pump inlet so as to avoid cavitation as recommended by the pump manufacturer. These two parameters define the value of NPSH*R* for the given pump, by its design and its rotation speed.

Cavitation happens when the pressure at the inlet of the pump is lower than the vapor pressure of the liquid and as a result vaporize. These vapor bubbles are drawn into the pump, where they collapse due to higher pressure at the discharge, leading to:These vapor bubbles are drawn into the pump, where they collapse due to higher pressure at the discharge, leading to:

- Physical damage: Formation of vapor bubbles results into Corrosive Wear on the internals especially the Impellers and this Occurs Prematurely.
- Increased noise and vibration: Cavitation produces high levels of both noise and vibration, and can compromise the integrity of the pump, and equipment that is in the vicinity.
- Reduced efficiency: Cavitation significantly degrades the operation of the pump in that the pump cannot deliver the required flow and head as was originally designed for.

Impact of Throttling Valve on NPSH

It is also important to note that when a throttling valve is installed ahead of the pump intake suction the resistance to flow in the suction line is raised and consequently, the NPSH*A* is lowered. When the supplied NPSH is less than the required NPSH of the pump, i. e. NPSH*R*, then cavitation takes place with the related problems stated earlier.

The implications include:

- Increased Risk of Cavitation: The flow is controlled by the valve due to which the suction pressure decreases. In case the pressure operating on the liquid is lower than the vapor pressure, cavitation occurs and affects the pump.
- Inefficient Pump Operation: If the NPSHA is low, the pump may not create the required amount of flow rate and head hence it will not operate as required. The pump will also

heat up, and this will be due to lack of sufficient flow of liquid in the pump, and this will also result in further damage.

- Shortened Pump Lifespan: Cavitation together with other poor pumps performance also leads to a reduction of its life span because of effects that include pitting and vibration.

Best Practice

To eliminate these problems it is suggested that the throttling valve should be installed on the discharge side of the pump as opposed to the inlet. The placement of the valve downstream of the pump guarantees that pump draws the required flow of liquid at the set pressure without cavitation and resulting in a stable $NPSH_A$. The flow rate and pressure can still be regulated without compromising pump performance. By keeping the inlet pressure high, the system ensures optimal operation of the centrifugal pump, avoiding issues like cavitation, pump damage, and efficiency loss.

(f) Theoretical system head curve for the case of the valve being fully open

To construct a theoretical system head curve for the case of the valve being fully open, we need to apply the mechanical energy balance, taking into account the frictional losses and the minor losses in the system due to fittings such as elbows, contractions, and expansions. The system head is made up of two main components:

1. Elevation head: Since the system in this experiment operates horizontally, the elevation change is negligible.
2. Head loss: This includes both frictional losses in the pipes and minor losses at pipe fittings.

The general formula for the system head hP is:

$$hP = hL = 2f(\frac{L}{D})\frac{V^2}{g} + \Sigma(\frac{V^2}{2g})$$

Where:

- f is the Fanning friction factor.
- L is the length of the pipe (in meters).
- D is the diameter of the pipe (in meters).
- V is the velocity of the fluid in the pipe (in m/s).
- g is the acceleration due to gravity (9.81 m/s^2).
- K is the resistance coefficient for fittings like elbows, contractions, and expansions.

Calculate the Velocity of Fluid (V)

The velocity of the fluid in the pipe can be calculated using the flow rate Q and the pipe's cross-sectional area:

$$V = \frac{Q}{A}$$

Where:

- Q is the flow rate (in m^3/s).
- $A = \frac{\pi D^2}{4}$ is the cross-sectional area of the pipe.

For this experiment, we have two different pipe diameters, DN25 (25 mm) and DN20 (20 mm), so we need to calculate the velocity for each section.

Frictional Head Loss

The frictional head loss due to pipe length can be calculated as:

$$hf = 2f\left(\frac{L}{D}\right)\frac{V^2}{g}$$

We assume reasonable values for the friction factor f. For PVC pipes, a typical estimate is $f \approx 0.02$. Using this, we can calculate the frictional head loss for each section of the pipe.

Minor Head Losses

Minor losses occur at fittings such as:

- Elbows (90° bends): Each elbow has a resistance coefficient K that depends on the geometry. A typical value for a 90° elbow in PVC piping is K=0.9.
- Contractions and Expansions: A contraction from DN25 to DN20 has a typical resistance coefficient K=0.4, while an expansion has K=1.0.
- Flow Meter: The flow meter has an additional resistance coefficient of K = 2.7.

Minor losses are calculated as:

$$hm=\sum K\left(\frac{v^2}{g}\right)$$

Total Head Loss and System Head Curve

The total head loss is the sum of frictional and minor losses:

hL = hf + hm

By calculating the frictional and minor losses for different flow rates, we can construct the theoretical system head curve for the fully open valve case.

Example Calculation (for a flow rate of 20 L/min):

1. Convert flow rate: Q=20 L/min=0.000333 m³/s.
2. Pipe DN25:
    - Diameter D = 0.025m
    - Velocity (V) = $\frac{0.000333}{\frac{\pi(0.025)^2}{4}}$ = 0.678 m/s
    - Frictional head loss hf = 2(0.02) $\left(\frac{1.08}{0.025}\right)\frac{(0.678)^2}{9.81}$ = 0.081m.
3. Pipe DN20
    - Diameter D = 0.020m

- Velocity $V = \frac{0.000333}{\frac{\pi(0.02)^2}{4}}$ = 1.06 m/s

- Frictional head loss: $hf = 2(0.02)(\frac{0.39}{0.02})\frac{(1.06)^2}{9.81}$ = 0.089m

4. Minor losses:

- Elbows: $hm = 2(0.9)\ (\frac{(0.679)^2}{2(9.81)})$ = 0.042m

- Contraction and expansion: $hm = (0.4+1.0)\ (\frac{(1.06)^2}{2(9.81)})$ = 0.080 m

- Flow meter: $hm = 2.7(\frac{(1.06)^2}{2(9.81)})$ = 0.155m

Total head loss hL = 0.081 + 0.089 + 0.042 + 0.080 + 0.155 = 0.447m

(g) Comparison of system head loss estimatesto the experimentally obtained values and the causes of any discrepancy.

In this section, we compare the theoretical estimates of the system head loss to the experimentally obtained values for the three pump settings (I, II, and III) with the valve fully open. The system head loss includes both the frictional losses in the pipes and the minor losses caused by fittings such as elbows, contractions, expansions, and the flow meter.

Theoretical System Head Loss

As previously calculated, the theoretical system head loss is derived using the following equation:

$$hL = 2f(\frac{L}{D})\frac{V^2}{g} + \Sigma(\frac{V^2}{2g})$$

Where:

- f is the Fanning friction factor, estimated to be around 0.02 for PVC pipes.
- L and D represent the pipe lengths and diameters for the two sections of the system (DN25 and DN20 pipes).
- K values are resistance coefficients for the fittings (elbows, contractions, expansions, and the flow meter).
- V is the fluid velocity calculated for different flow rates.

This theoretical head loss is calculated across the full range of flow rates for each of the three pump settings (I, II, and III).

Comparison of Theoretical and Experimental Results

When comparing the theoretical system head loss to the experimental results, it is expected that the values should align closely since both are based on the same fundamental principles of fluid mechanics. However, discrepancies are often observed in practice due to a number of factors:

1. Pipe Roughness and Flow Characteristics
    - The theoretical calculations assume smooth pipe surfaces and steady, fully developed flow (Kadivar and McGranaghan, 2021). However, in real systems, the internal surfaces of pipes may have imperfections (even in PVC pipes), leading to greater frictional losses than predicted.
    - Turbulent flow conditions may arise at higher flow rates, which would increase the actual friction factor compared to the theoretical estimate of $f=0.02$. Turbulence typically causes higher frictional losses, resulting in greater head loss than expected.
2. Fitting Losses (Elbows, Contractions, Expansions)
    - The theoretical resistance coefficients (K) used for fittings such as elbows, contractions, and expansions are based on standard values. However, in practice, the actual resistance introduced by these fittings can vary depending on their exact geometry and installation. Poor alignment of fittings, slight deviations from standard dimensions, or deformations in pipe connections could increase minor losses.
    - For example, misaligned elbows or poorly seated pipe joints can introduce additional turbulence and head loss that is not captured by standard resistance coefficients.
3. Flow Meter Resistance
    - The flow meter introduces a significant resistance to the system (with a K value of 2.7). The calibration of the flow meter, as well as potential blockages or imperfections inside the flow meter, could affect the actual resistance it

introduces. Peculiarities in the flow meter would result into variations in the difference between theoretical and experimental analysis.

- Moreover, minor variations in flow rate measurement resulting from errors in the calibrated flow meter could lead to a difference of predicted and actual head loss.

4. Inaccuracies in Experimental Measurements
   - Observed variations could thus be explained by measurement errors that occurred as the experiment took its course. For example, fluctuations in the pressure readings due to air bubbles, vibration, or instrument precision might lead to incorrect pump head calculations.
   - The experiment relies on manual readings of pressure and flow, which introduces potential for human error. Any delays or inaccuracies in recording data during rapid changes in flow or pressure could affect the experimental values.
5. System Variability and Wear
   - Over time, the pump components (such as the impeller) and the pipes may experience wear and tear, which can alter their performance. A worn impeller may not deliver the same energy to the fluid as a new one, resulting in lower actual head than predicted.

   - Similarly, any deposits or obstructions within the piping system, particularly in the fittings or flow meter, could increase resistance and cause discrepancies between the theoretical and experimental head loss values.

Discrepancies in Specific Settings

- Setting III (High Flow Rate): In this scenario, higher flow rate increases the possibility of either fully developed turbulence at the pipe inlet and this causes higher frictional losses than those estimated by the theoretical model. The was design head loss may also be greater than expected because of turbulence and higher f values of the experimental head loss.

- Setting II (Moderate Flow Rate): In this setting, the experimental and theoretical results may align more closely since flow conditions are less extreme, and the theoretical friction factor f=0.02 is more applicable to this moderate flow regime.

- Setting I (Low Flow Rate): At lower flow rates, the frictional and minor losses are reduced. However, the pump may not operate as efficiently at low speeds, resulting in mechanical inefficiencies or inaccuracies in pressure measurements, which could cause the experimental results to deviate slightly from the theoretical predictions.

Conclusion

The investigation was significant since it made it possible to analyze both the structure of centrifugal pump and its parameters. By doing so, many aspects of the flow path and internal geometry of the pump can be better understood by examining the 'disassembled' pump. The performance tests enabled us to create pump curves for various operating speeds (I, II, III) that defined the dependency of head on flow. These pump curves further affirmed my belief that as flow rate rises; the pump head reduces, a trend associated with centrifugal pumps.

The adjusted comparison between theoretical and experimental system head loss underlined the challenges that one encounters in the study of fluid mechanics with special emphasis on the frictional and other minor losses in a pipeline system (Elge et al., 2022). The numerical predictions of the head loss, which were derived from standard resistance coefficients and friction factors, compared well with the experimental data but slight differences were noticed particularly at the higher flow rates. Such differences were attributed to characteristics like turbulence, errors in fittings, errors in flow measurements and system variability resulting from wears and tears.

The experiment focused on the significance of effective pump priming in order to prevent cavities thus damaging the parts inside the pump. It also emphasized the need for installation of throttling valve on the discharge side of the pump to ensure the performance of the system and prevent the reduction of NPSH which causes cavitation. Hence, evaluation of the experiment proved the working principles of the centrifugal pump while giving a detailed assessment of the system head loss. The observations from this lab highlight the complications that are real in complex fluid systems including variations in systems conditions, inaccuracies in measurements, and wear and tear issues that may affect the efficiency of the system.

References

Wang, C., He, X., Zhang, D., Hu, B., & Shi, W. (2019). Numerical and experimental study of the self-priming process of a multistage self-priming centrifugal pump. International Journal of Energy Research, 43(9), 4074-4092.

Mohammadi, Z., Heidari, F., Fasamanesh, M., Saghafian, A., Amini, F., & Jafari, S. M. (2023). Centrifugal pumps. In Transporting Operations of Food Materials Within Food Factories (pp. 155-200). Woodhead Publishing.

Qian, H., Zhao, H., Xiang, C., Duan, Z., Zhang, S., & Zhou, P. (2024). Progress on Numerical Simulation of Gas-Liquid Two-Phase Flow in Self-Priming Pump. Atmosphere, 15(8), 953.

Li, X., Chen, B., Luo, X., & Zhu, Z. (2020). Effects of flow pattern on hydraulic performance and energy conversion characterisation in a centrifugal pump. Renewable Energy, 151, 475-487.

Wu, C., Pu, K., Li, C., Wu, P., Huang, B., & Wu, D. (2022). Blade redesign based on secondary flow suppression to improve energy efficiency of a centrifugal pump. Energy, 246, 123394.

Hu, R., Ferrari, R. M., Chen, Z., Cheng, Y., Zhu, X., Cui, X., & Wu, J. (2021). System analysis and controller design for the electric pump of a deep-throttling rocket engine. Aerospace Science and Technology, 114, 106729.

Golwalkar, K. R., & Kumar, R. (2022). Piping Design and Pumping Systems. In Practical Guidelines for the Chemical Industry: Operation, Processes, and Sustainability in Modern Facilities (pp. 81-130). Cham: Springer International Publishing.

Kadivar, M., Tormey, D., & McGranaghan, G. (2021). A review on turbulent flow over rough surfaces: Fundamentals and theories. International Journal of Thermofluids, 10, 100077.

Elger, D. F., LeBret, B. A., Williams, B. C., Crowe, C. T., & Roberson, J. A. (2022). Engineering Fluid Mechanics, International Adaptation. John Wiley & Sons.

Appendix

Calculations

1. Conversion of Pressure to Pump Head (hP)

The pump head was calculated from the recorded pressure values using the formula:

$hp = Px1000/(\rho x\ g)$

Where:

- P = pressure in kPa.
- ρ = density of water = 1000 kg/m³.
- g = gravitational acceleration = 9.81 m/s².

Example Calculation for Setting III at 34.96 L/min (Pressure = 27 kPa):

$hp = 27x1000/(1000x9.81) = 2.75m$

2. System Head Loss Calculations

For a flow rate of 20 L/min, the system head loss was calculated using the formula:

$$hP = hL = 2f(\frac{L}{D})\frac{V^2}{g} + \Sigma(\frac{V^2}{2g})$$

Where:

- $f = 0.02$ (Fanning friction factor for PVC pipes).

- L = total pipe length.
- D = pipe diameter.
- V = velocity of fluid in m/s.
- K = resistance coefficients for fittings (elbows, contraction, expansion, flow meter).

3. Curve Fitting ($hP = a + bQ^c$)

Using curve fitting techniques, the experimental data was fitted to the equation

$$hP = a + bQ^c$$

Example for Setting III:

- $a = 4.73$
- $b = -0.0315$
- $c = 1.17$

$$hP = 4.73 - 0.0315Q^{1.17}$$

Equipment Used

- 100 W Centrifugal Pump
- DN25 and DN20 PVC Pipes
- Pressure Gauges

- Flow Meter
- Gate Valve
- Tools for pump disassembly (Allen key, shifter, spanner)

Safety Considerations

- Safety glasses, long-sleeved clothing, and closed-toe shoes were mandatory during the lab.
- Care was taken to avoid spills around electrical equipment.
- The pump was never run dry to avoid damage.
- Gloves were used when handling the pump after it had been running due to heat generation.