Elements and Evaluation of a Centrifugal Pump

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Abstract

This experiment is to investigate how the pressure changes at different flow rates through a centrifugal pump by using the flow meters and pressure gauges as well as the throttling valve and the pump, which provides three different speed settings for the experiment.

The pump head is measured using the meters and gauges and is plotted against the flow rate, the pump curves are constructed using MATLAB. The throttling valve's purpose is discussed in terms of Net Positive Suction Head (NPSH) and the consequences of improper application are emphasized.

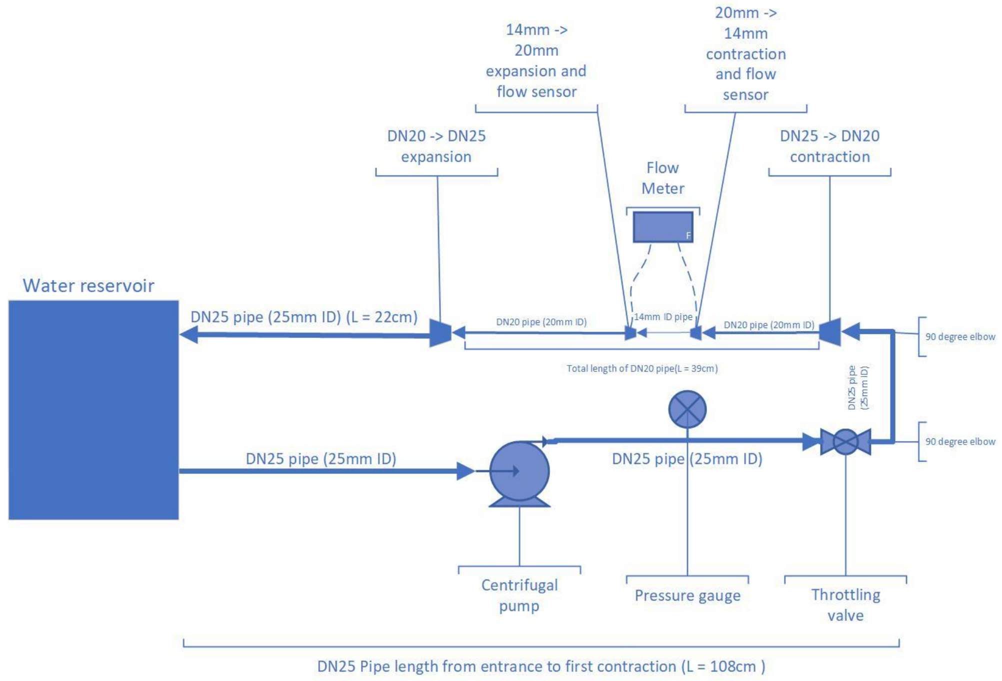
The theoretical system head is calculated and plotted against the flow rate, this curve is compared with the experimental system head curve to outline any differences.

Aims

The aims of the experiment are to investigate the structure of a centrifugal pump by dismantling its and taking key measurements, construct a curve illustrating the relationship between pump head and flow rate at different settings, and create and determine the disparities between the theoretical system head and experimental system head due to fictional and minor losses.

Questions

Question 1 - Schematic Diagram and Experimental setup



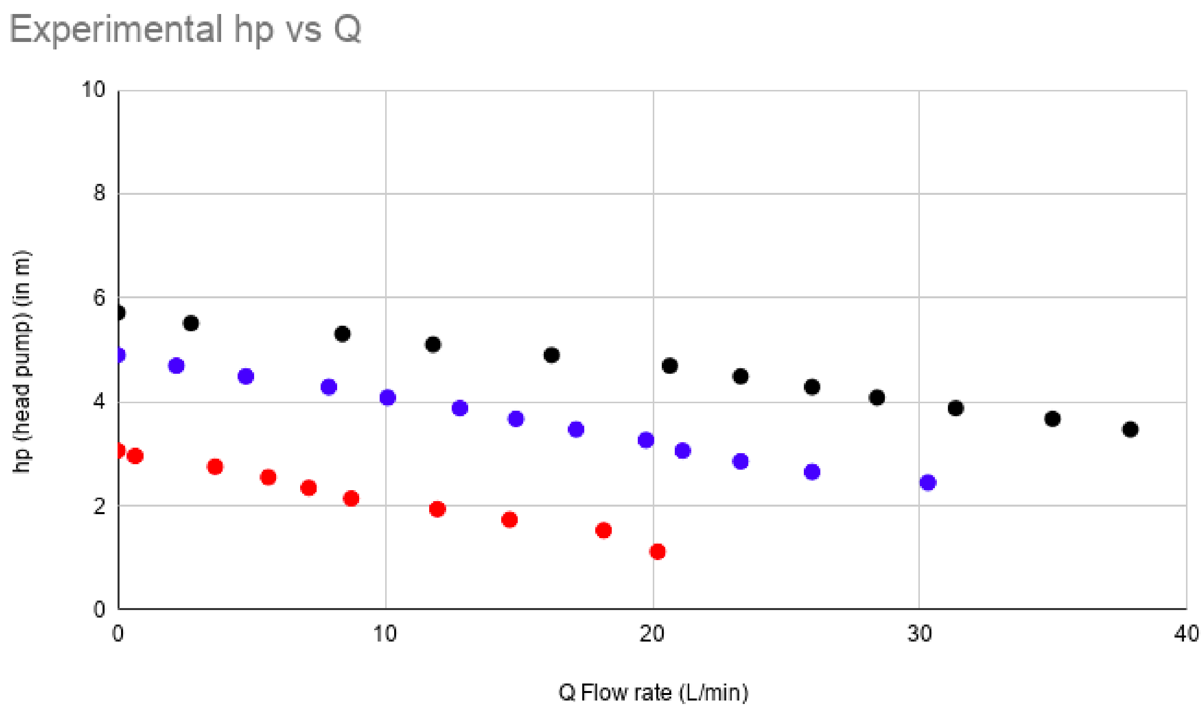
Question 2 - What is priming a pump? Why is it important before initial start-up?

Priming a pump is the act of introducing water into the pump before it is run. It is important because if a centrifugal pump runs with air input it can result in the pump not producing the appropriate head and suction pressure due to differences in the properties of air and water, and thus it may not work.

Additionally, it may cause overheating if run for an extended period of time and damage the pump due to less heat displacement by air.

Question 3 - plotting pump head vs Q for each pump setting

See Appendix D: Tabulated Results and Sample Calculation for 3. Plot of the head pump versus Q for the tabulated data.



Where the Red dots, Blue dots and Black dots are Settings 1, 2 and 3 respectively.

Question 4 - constructing pump curves for each pump setting and finding equations of best fit

The pump head equation takes the form $h_p = a + bQ^c$ where hp is the fitted pump head in meters. Where we define a as our intercept, b is the gradient (or the slope) and c is the power of the flow rate. They are arbitrary constants we are trying to solve for, and Q is the flow rate in L/min. We can easily read of the values for a as we take from the intercept for each fitting from the experimental data. When the head pump is at maximum when the flow rate is at 0 L/min.

To find b and c our unknown parameters, we require to deal by trial and error to find the empirical values to fit each model setting from the experimental results from Question 3.

Table 1. Values for a,b and c for each setting.

Parameter	Setting 1	Setting 2	Setting 3
a	3.063894737	4.901838689	5.718811804
b	-0.107	-0.071	-0.0238
c	0.939	1.027	1.217

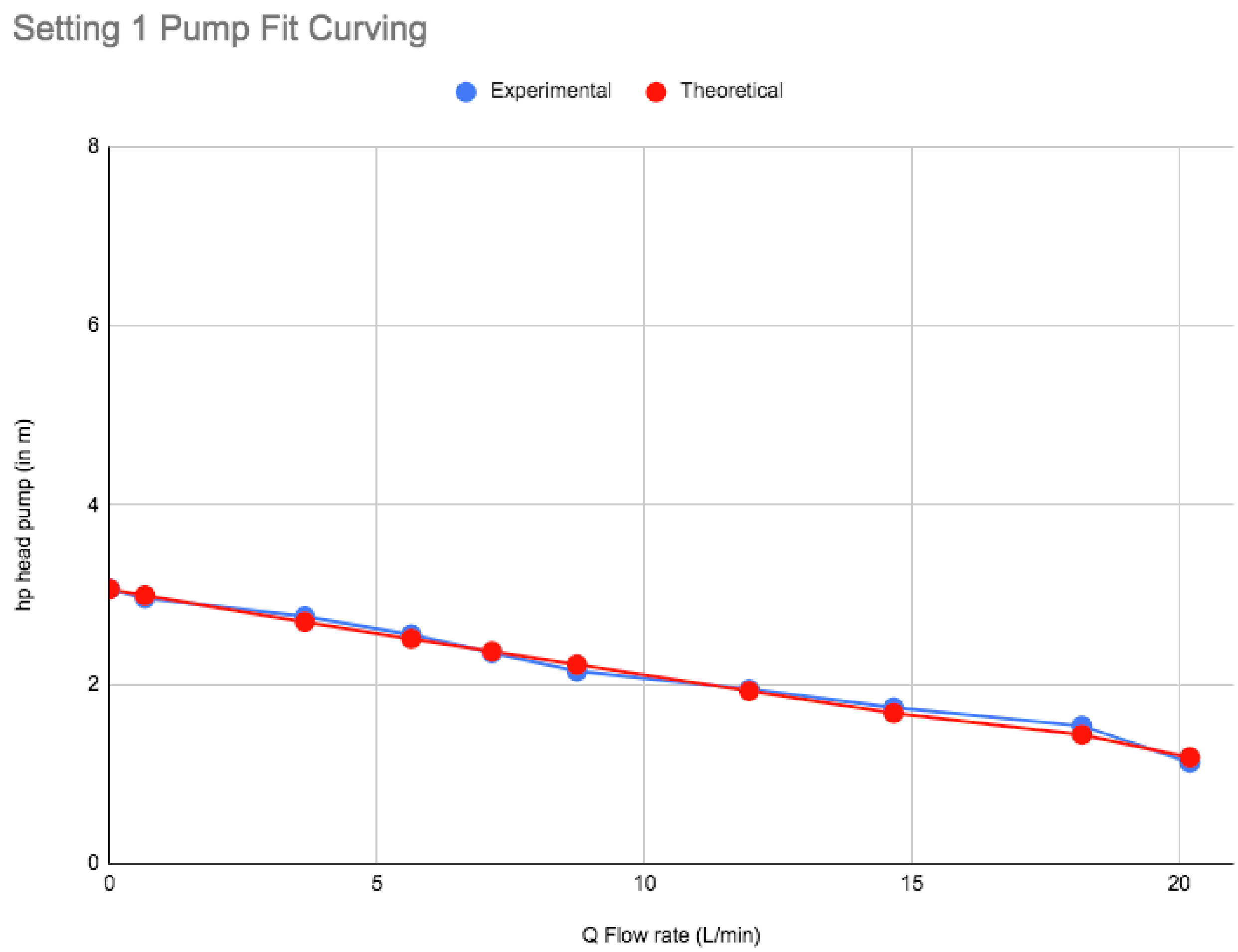


Figure 3.

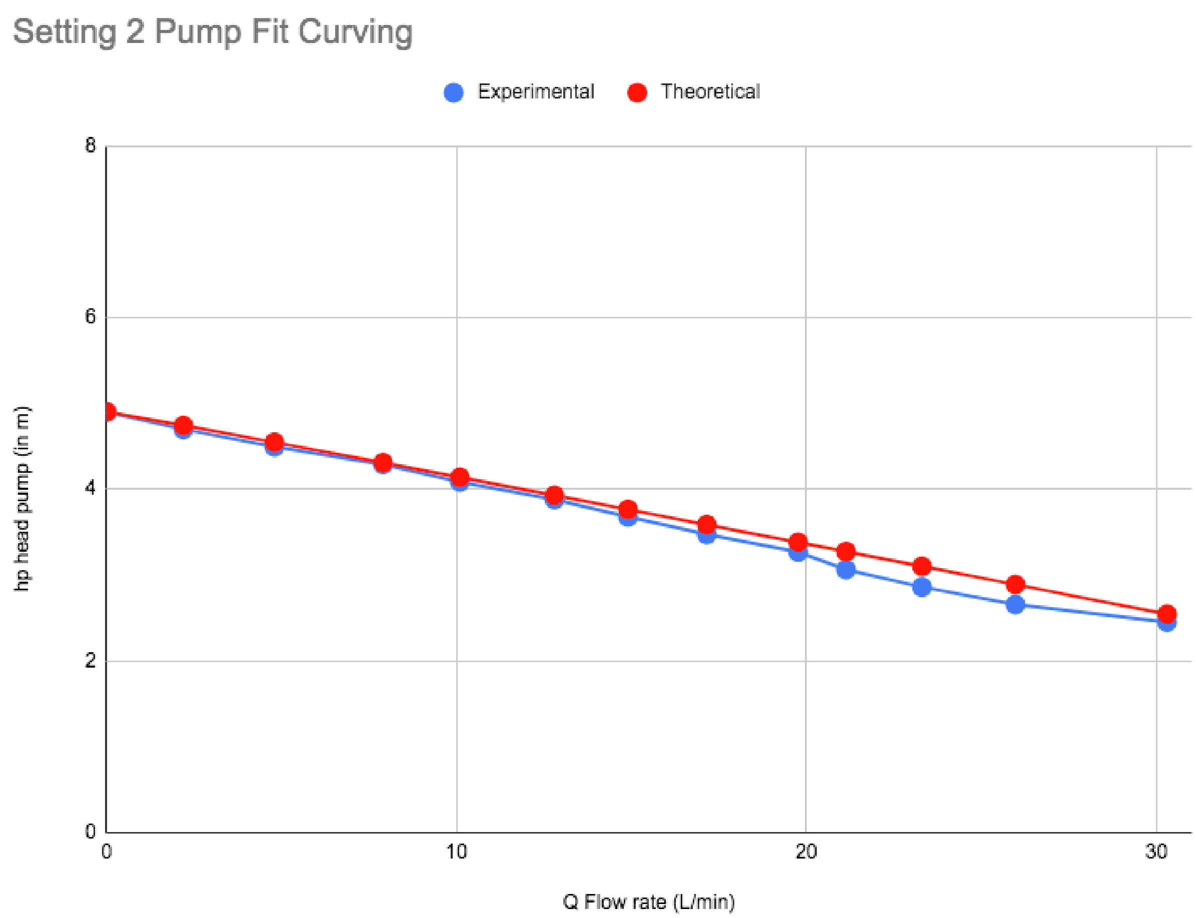
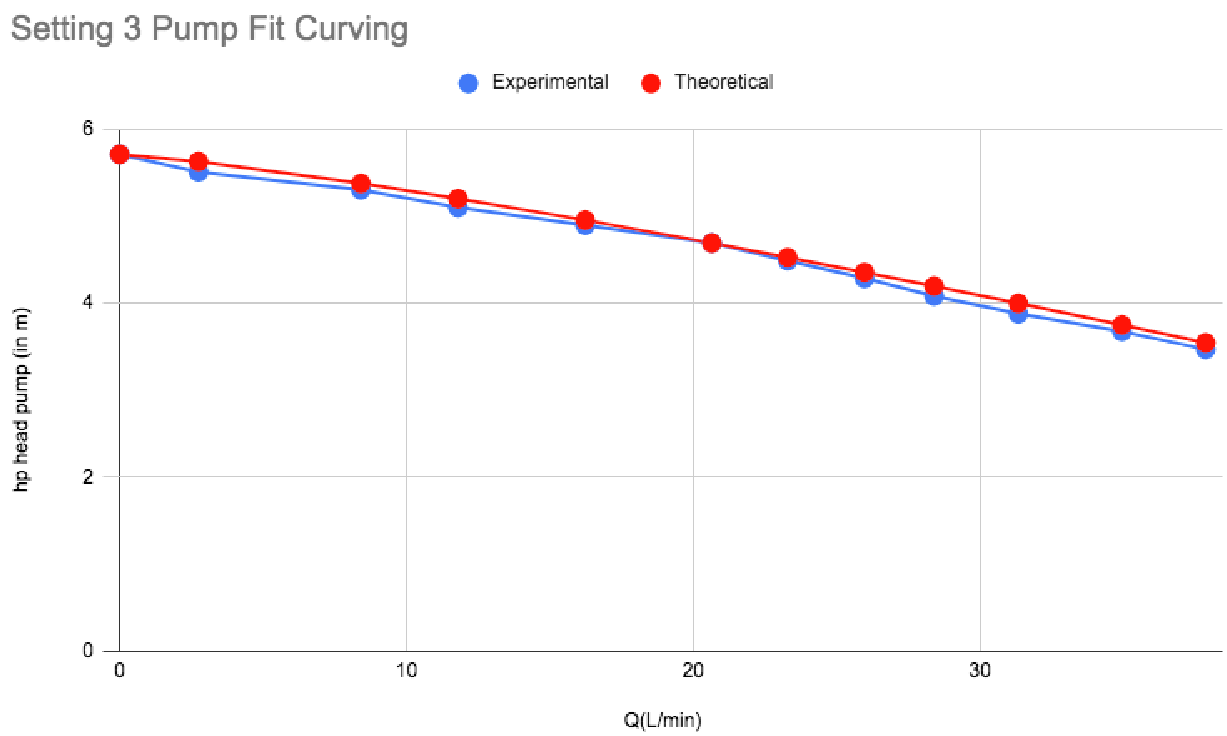

Setting 2 Pump Fit Curving
Experimental
Theoretical
8
6
4
2
0
0
10
20
30
hp head pump (in m)
Q Flow rate (L/min)

Figure 4.



Setting 3 Pump Fit Curving
Experimental
Theoretical
6
4
2
0
hp head pump (in m)
0
10
20
30
Q(L/min)

Figure 5.

Using the results from MATLAB we are able to create the pump curves with the parameters with Table 1. Fitted Curve parameters Values for each setting (see Appendix E). This is the theoretical plot for the head pump (in m) vs. the Q Flow rate (in L/min).

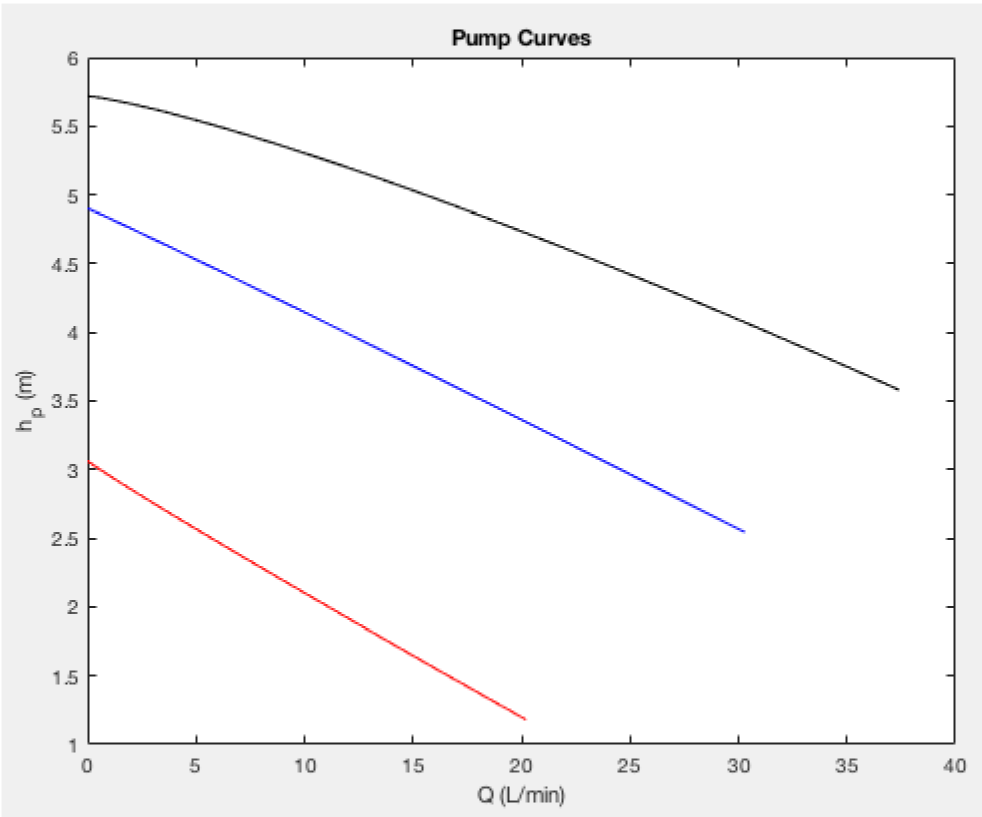


Figure 6.

Equation 1 (Setting 1) Red:

$$hp_{fitted1} = 3.063894737 - 0.107Q^{0.954}$$

Equation 2 (Setting 2) Blue:

$$hp_{fitted2} = 4.901838689 - 0.071Q^{1.027}$$

Equation 3 (Setting 3) Black:

$$hp_{fitted3} = 5.718811804 - 0.0238Q^{1.217}$$

Comparing the theoretical (this question) and experimental (Question 3) values for the head pump. From observation figures 3 and 5 are good fit. In Figure 6, the constructed curves for Settings 1 and 2 look very close to a linear model when it comes to the shape of the pump curve. This is done by trial and error using MATLAB. If we want to be accurate and precise we would need more data. This would mean there are more residuals or data points along for each fitting in order to get better approximations along the following the experimental pump curves.

Question 5 - Throttling valve purpose and implications

A throttling valve is used to control the flow rate of fluid by opening or closing a valve, as opposed to changing the power of the pump. It can affect the system curve by making its slope more steep so that it intersects the pump curve at the desired flowrate. However the valve produces more friction the more it is closed, decreasing the efficiency of the system.

If a throttling valve is placed before the pump, as opposed to after the pump, it can result in pump cavitation. As throttling increases the friction head on suction side of the pump (hfs), there is less Net Positive Suction Head (NPSH) Available at the inlet of the pump.

$$Net\ Positive\ Suction\ Head\ Available = (P1 - Pvapour)/(\rho g) + z1 - hfs$$

Where
- P1 is pressure in the tank in terms of Pascals (atmospheric in this case)
- Pvapour is the vapour pressure of the liquid in terms of Pascals
-ρ is the water density (at 20 degrees) (998kg/m3 in this case)
-g Earth's Gravitational Constant (9.81 m/s^2)
-z1 is the height or elevation in m. (height of liquid in tank)
-hfs is the head loss of the friction of suction side of pump.

As you can see as the hfs increases, the Net positive suction head available decreases.

This can result in NPSH Available being less than the NPSH Required by the pump, and hence the pressure at the inlet drops below the vapour pressure of the fluid and cavitation occurs, potentially damaging the pump.

Question 6 - Theoretical system curve for fully open conditions

We know $h_{sys} = h_p$. Now from the theory we know there is no pressure change or elevation change between the entry to the tank and exit, hence

$h_p = h_f = 2f(\frac{L + K(eq\ length)}{D})(\frac{u^2}{g}) + \sum K(\frac{u^2}{2g})$.

However because there are varying pipe diameters the velocity and friction factor is not the same throughout the system. We can add up the head along each section of the system: $h_p = h_p(DN25\ first\ pipe) + h_p(DN20\ pipe) + h_p(DN25\ last\ pipe)$ where minor losses use the velocity of the entering stream.

Now assuming the storage tank is large we can say $K_{exit} = 1$, and if we assume the vena contracta for the entry is large, we can assume $K_{entry} = 0$. Finally, according to page 59 of the pipe flow lecture notes, the equivalent length K values are:

Fittings		L_{eq}
45° elbow		15D
90° elbow		30-40D
45° elbow (square)		60D
Entry from leg of T-piece		60D
Entry into leg of T-piece		90D
Unions and couplings		Very small
Gate valve	Fully open	7D
	Half open	200D
	Quarter open	500D

Additionally for the orifice and the expansion and contractions it is mounted to has a resistance coefficient K value of $K = 2.7$

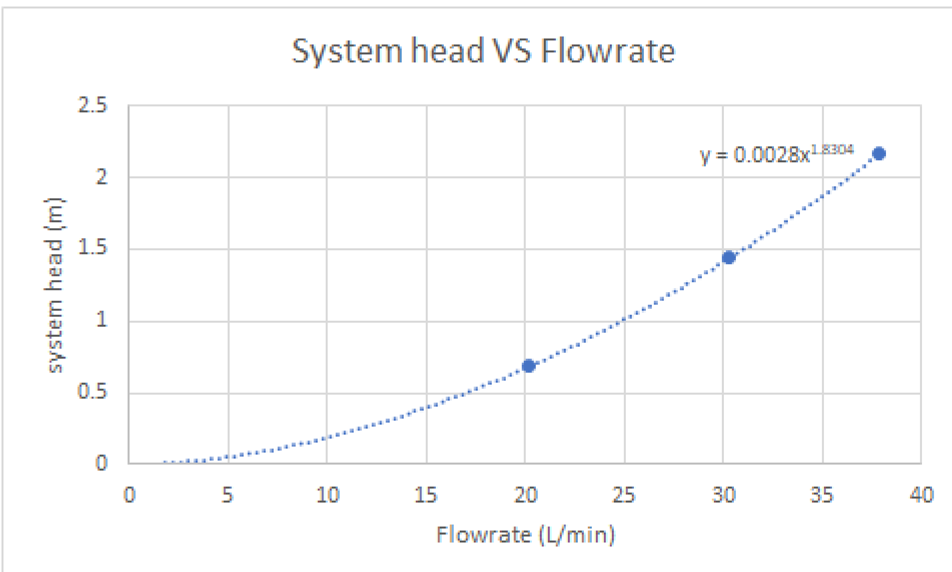
Additionally the expansions and contractions can be assume to be square and sudden, hence using the formulas from:
(https://neutrium.net/fluid-flow/pressure-loss-from-fittings-expansion-and-reduction-in-pipe-size/)
They can be found in appendix A.

Lastly instead of using the moody diagram, we can estimate the fanning friction factor using the formula $f = \frac{0.316}{Re^{1/4}}$according to
(https://www.engineersedge.com/calculators/pipe-flow-friction-factor3.htm) as we can assume the pipe is smooth and has turbulent flow.

The matlab code is shown in appendix B.
The values are hence tabulated below:

Q (L/min)	20.2	30.3	37.87
Theoretical Pump head (m)	0.6841	1.4357	2.1617

Now inputting the maximum flowrates for each of the 3 pump settings, we can construct a system head vs flowrate chart, and extrapolate the relationship using a power equation:

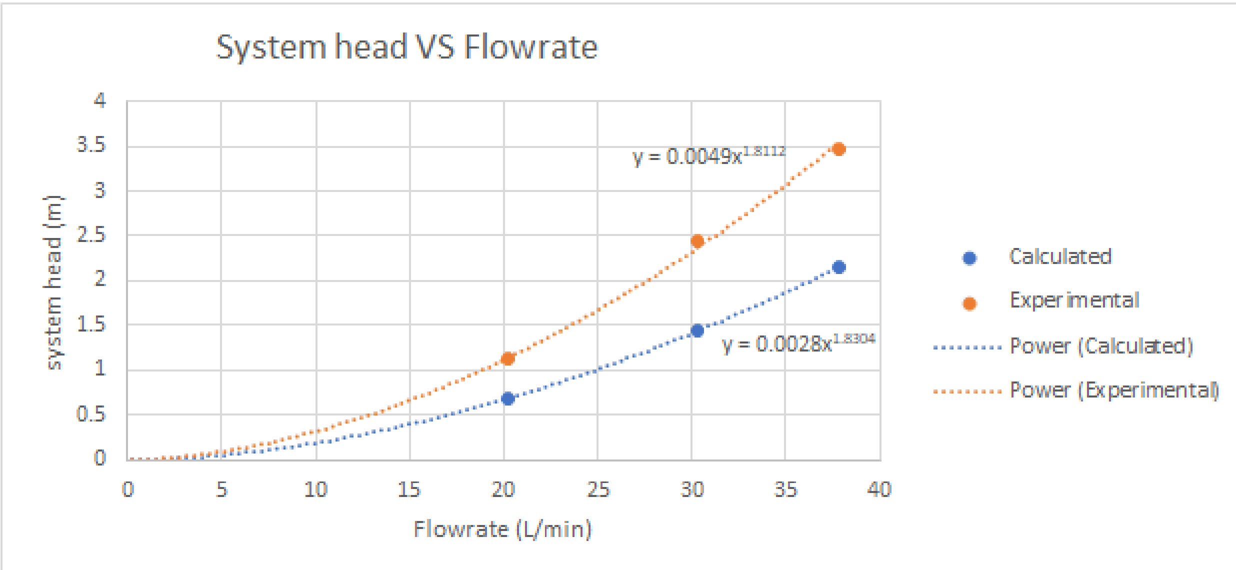


Question 7 - theoretical vs experimental system head loss

The experimentally obtained values can be calculated via $h_p = \frac{p4 - p3}{\rho g}$ where p3 is the pressure at the suction side of the pump and p4 is the pressure at the discharge side of the pump, where p4 is measured via the pressure gauge (gauge pressure) and p3 is assumed to be the atmospheric pressure.
Now using this formulas and the density value of $\rho = 998\ kg/m^3$ we get values of system head of:

Q (L/min)	20.2	30.3	37.87
Experimental Pump head (m)	1.1236	2.4514	3.4730

Hence graphing it against the theoretical values and extrapolating using a power equation:



Thus the discrepancy of the calculated values relative to the experimental values for the:

- 1st setting is $\frac{1.1236 - 0.6841}{1.1236} * 100\%$ = 39.11%
- 2nd setting is $\frac{2.4514 - 1.4357}{2.4514} * 100\%$ = 41.43%
- 3rd setting is $\frac{3.4730 - 2.1617}{3.4730} * 100\%$ = 37.75%

However the trend shows that the theoretical values underestimate the system head, and underestimate it more the higher the flowrate is.

A reason for this may be because the frictional losses are underestimated in the theoretical model - there are minor losses for joints which are thought to be negligible, and the minor losses for the flowmeter are constant, in reality it increases with higher flowrates.
Additionally, the pipe is assumed to be smooth, but in reality all pipes are rough to some extent, thus the frictional losses may be underestimated.
There may also be errors in calculation, the value of the friction factor uses a formulaic approach instead of the moody chart.
Lastly the shock and frictional losses of the pump are not accounted for.

Conclusion

All aims of the experiment were performed. Fitted values for the pump curve head for each settings from Pump setting 1,2 and 3 were found and are:

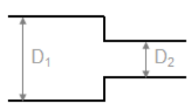
$$hp_{fitted1} = 3.063894737 - 0.107Q^{0.954}$$
$$hp_{fitted2} = 4.901838689 - 0.071Q^{1.027}$$
$$hp_{fitted3} = 5.718811804 - 0.0238Q^{1.217}$$

Additionally, the theoretical system head was found and compared against the experimental system head. The theoretical system head was 39.11 - 41.43% lower than the experimental system head. This may be due to underestimation of frictional and minor losses.

Appendix A

Formulas for the reduction and expansion from
https://neutrium.net/fluid-flow/pressure-loss-from-fittings-expansion-and-reduction-in-pipe-size/

3.1 Square Reduction



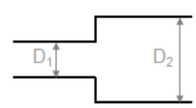
For $Re_1 < 2500$,

$$K = \left(1.2 + \frac{160}{Re_1}\right)\left[\left(\frac{D_1}{D_2}\right)^4 - 1\right]$$

For $Re_1 > 2500$,

$$K = (0.6 + 0.48f_1)\left(\frac{D_1}{D_2}\right)^2\left[\left(\frac{D_1}{D_2}\right)^2 - 1\right]$$

3.6 Square Expansion



For $Re_1 < 4000$

$$K = 2\left[1 - \left(\frac{D_1}{D_2}\right)^4\right]$$

For $Re_1 > 4000$

$$K = (1 + 0.8f_1)\left[1 - \left(\frac{D_1}{D_2}\right)^2\right]^2$$

For the reduction of DN25 -> DN20, we assume the fluid is at 20 degrees C, hence $\rho = 998\, kg/m^3$ and $\mu = 0.001\, Pa * s$ Now at the the lowest setting of the pump (setting 1), the slowest velocity occurs in the DN25 pipe, hence when $Q = 20.2\, L/min = 0.000337\, m^3/s$, $V = 0.000337/((\pi/4) * (25 * 10^{-3})^2 = 0.687 m/s$, thus $Re = \frac{998*0.687*25*10^{-3}}{0.001} = 17140$, hence the formula for Re>4000 will be used in all cases. Note the values for f are darcy friction factors.

Appendix B

Matlab code for Q6 - used Q for max flowrate setting 3

```
%Almaz Khalilov 1082560

g=9.81
rho = 998
mu = 0.001
Q = 0.000631 %in m^3/s
```

```
g =

    9.8100


rho =

   998


mu =

   1.0000e-03


Q =

   6.3100e-04
```

DN25 (first section)

```
D_1 = 25*10^-3; %m
A_1 = (pi/4)*(D_1)^2; %m^2
V_1 = Q/A_1; %m/s
L_1 = 108/100; %m
Re_1 = (rho*V_1*D_1)/mu;
%moody formula for smooth pipe (from https://www.engineersedge.com/calculators/pipe-flow-friction-factor3.htm)
f_1 = 0.316/Re_1^(1/4);


%Contains 2*90degree elbows(KL_1 = 35D), 1 fully open gate valve(KL_1 = 7D), and contraction (Kres_1 uses formula) (assume pressure valve loss very small)
%Equivalent length
KL_1 = 2*35*D_1+7*D_1;
%uses darcy friction factor so f_1 must be multiplied by 4
Kres_1 = (0.6+0.48*4*f_1)*(25/20)^2*((25/20)^2-1);

hp_1 = 2*f_1*((L_1+KL_1)/D_1)*(V_1^2/g) + Kres_1*(V_1^2/(2*g)) %m
```

```
hp_1 =

    1.0039
```

DN20 (2nd section)

```
D_2 = 20*10^-3; %mm
A_2 = (pi/4)*(D_2)^2;
V_2 = Q/A_2;
L_2 = 39/100;
Re_2 = (rho*V_2*D_2)/mu;
%moody formula for smooth pipe (from https://www.engineersedge.com/calculators/pipe-flow-friction-factor3.htm)
f_2 = 0.316/Re_2^(1/4);


%Contains 1 flow sensor (Kres_1 = 2.7), 1 expansion (expansion formula for Kres_1)
KL_2 = 0;
%uses darcy friction factor so f_1 must be multiplied by 4
Kres_2 = 2.7 + (1+0.8*4*f_2)*((20/25)^2)^2;

hp_2 = 2*f_2*((L_2+KL_2)/D_2)*(V_2^2/g) + Kres_2*(V_2^2/(2*g))
```

```
hp_2 =

    1.0036
```

DN25 (last section)

```
D_3 = 25*10^-3; %mm
A_3 = (pi/4)*(D_3)^2;
```

```
V_3 = Q/A_3;
L_3 = 22/100;
Re_3 = (rho*V_3*D_3)/mu;
%moody formula for smooth pipe (from https://www.engineersedge.com/calculators/pipe-flow-friction-factor3.htm)
f_3 = 0.316/Re_3^(1/4);


%Contains 1 exit (Kres_3 = 1)
KL_3 = 0;
Kres_3 = 1;

hp_3 = 2*f_3*((L_3+KL_3)/D_3)*(V_3^2/g) + Kres_3*(V_3^2/(2*g))
```

```
hp_3 =

    0.1542
```

Hence total pump head is:

```
hp = hp_1 + hp_2 + hp_3
```

```
hp =

    2.1617
```

Appendix D

Tabulated Results for Setting 1

Setting 1				
P (kPa)	P (Pa)	Q(L/min)	hp (m)	hp (m) fitted
11	11000	20.2	1.12342807	1.181594122
15	15000	18.18	1.531947368	1.434064278
17	17000	14.66	1.736207017	1.677536123
19	19000	11.96	1.940466667	1.922228065
21	21000	8.74	2.144726316	2.21747519
23	23000	7.15	2.348985965	2.36503223
25	25000	5.64	2.553245614	2.506575488
27	27000	3.65	2.757505263	2.69592579
29	29000	0.66	2.961764912	2.991911944
30	30000	0	3.063894737	3.063894737

Tabulated Results for Setting 2

Setting 2				
P (kPa)	P (Pa)	Q(L/min)	hp (m)	hp (m) fitted
24	24000	30.3	2.450919344	2.542990843
26	26000	25.97	2.655162623	2.888480521
28	28000	23.3	2.859405902	3.100759203
30	30000	21.13	3.063649181	3.272804751
32	32000	19.76	3.267892459	3.38118074
34	34000	17.15	3.472135738	3.587075293
36	36000	14.9	3.676379017	3.763895328
38	38000	12.8	3.880622295	3.928278094
40	40000	10.1	4.084865574	4.13853669
42	42000	7.9	4.289108853	4.308747638
44	44000	4.8	4.493352131	4.546294897
46	46000	2.2	4.69759541	4.742277802
48	48000	0	4.901838689	4.901838689

Tabulated Results for Setting 3

Setting 3				
P (kPa)	P (Pa)	Q(L/min)	hp(m)	hp (m) fitted
34	34000	37.87	3.472135738	3.547012318
36	36000	34.96	3.676379017	3.752317623
38	38000	31.34	3.880622295	4.001963573
40	40000	28.4	4.084865574	4.199669928
42	42000	25.97	4.289108853	4.359399744
44	44000	23.3	4.493352131	4.530766475
46	46000	20.65	4.69759541	4.696207382
48	48000	16.23	4.901838689	4.960596478
50	50000	11.8	5.106081968	5.208477913
52	52000	8.41	5.310325246	5.383712455
54	54000	2.75	5.514568525	5.635207591
56	56000	0	5.718811804	5.718811804

In this prac, we are using the Bernoulli equation in terms of head (derived from the video),

$$\frac{P_1}{\rho g} + \frac{u_1^2}{2g} + z_1 h_p = \frac{P_2}{\rho g} + \frac{u_2^2}{2g} + z_2 h_f$$

Equation 4.

Since we are dealing with a horizontal pipe both z values on the left and right side from Equation 5. Were also cancelling out both velocities from both sides since the tanks are both closed from either side.So the Bernoulli equation is in terms of Pressure. Later disregard Pressure 3, assume the Pressure at that point is small and negligible becomes close to zero.

$$h_p = \frac{P_4 - P_3}{\rho g} \approx \frac{P_4}{\rho g}$$

Where rho is the water density is at 20 degrees 998.19kg/m3 (used in the workshops) and g is Earth's gravitational constant which is 9.81m/s2.

Appendix E: Plotting the Matlab Script for fitted pump curves

```
%Pump Curve: Setting 1
Q1=[0:0.1:20.2];
a1=3.063894737;
b1=-0.107;
c1=0.954;


hpfit1=a1+b1.*Q1.^c1;
plot(Q1,hpfit1,'r')
title('Pump Curves')
xlabel('Q (L/min)')
ylabel('h_p (m)')
hold on


%Pump Curve: Setting 2
Q2=[0:0.1:30.3];
a2=4.901838689;
b2=-0.071;
c2=1.027;

hpfit2=a2+b2.*Q2.^c2;
plot(Q2,hpfit2,'b')
hold on

%Pump Curve: Setting 3
Q3=[0:0.1:37.4];
a3=5.718811804;
b3=-0.0238;
c3=1.242;
hpfit3=a3+b3.*Q3.^c3;
plot(Q3,hpfit3,'black')
hold on
```