Pump and piping installation

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Summary

Determining the operating points for an industrial process with water as its main component, integrated with a pumping system for which the specifications are provided by its manufacturer, under different conditions involves many parameters that need to be appropriately accounted for. An analysis based on assumptions was carried out on such a process in order to identify how its operating points changed under different circumstances including variations in the pumping system. It was found that two pumps of the same kind in parallel allowed for the highest additional flowrate capacity in the system by increasing it by 84.30 % compared to the single pump case. It was also established that the operating flowrates in the process were occurring within the turbulent flow regime which allowed for an improvement in terms of their estimated values. In terms of flow regulation, for three butterfly throttling valves positioned downstream of the process their settings for which different conditions imposed on the process were met, such as flow rate equality, were determined within the limits of the assumptions made.

1 Introduction

An industrial process involving a cycle whereby water is used to condense steam was investigated in order to establish different operating points for the process, with pumping installation **[1]**. Calculations were performed in order to determine the different operating conditions for the entire process when either the pump or system characteristic curves changed. Pumps in series, in parallel and one with a modified impeller rotational frequency **N** were being considered as well as different settings for 3 butterfly valves, with **K** as a function of valve position in degrees, installed downstream of the industrial process **[1]**.

In the investigation, the Bernoulli equation was applied across the piping installation by assuming only frictional losses within the turbulent flow regime and due to pipe bends in the system **[1]**. The pump being used was also assumed ideally isentropic **[2]** and in the calculations that followed the viscosity of water **μ** was taken at an average value of 0.000797 Pa s and its density **ρ** as 998.2 kg m^{-3}since water entered the tank from the condenser at 45 °C and 1 bara pressure **[1,3]**.

The fanning friction factor $\mathbf{C_f}$ was employed for head losses across the system by being initially guessed as 0.015 so as to establish a system characteristic. Velocity head terms were not ignored, and the velocity with which water entered the tank was taken as approximately zero based on the continuity equation. The **Re** numbers of the stream volumetric flow rates based on the initial guess of the operating point were all found to lie within the range of 2200 and 500000. Given the approximate roughness $\boldsymbol{\varepsilon}$ of the pipes as 0.046 mm, the appropriate correlation for $\mathbf{C_f}$ within the turbulent flow regime with both roughness ratio $\boldsymbol{\varepsilon}/\mathbf{D}$ and **Re** dependence **[4]** was used to obtain a better estimate of the system characteristic through iterative means.

With regard to the combination of pumps in series, a new combined pump curve was plotted by doubling the single pump head at any given flowrate. For the parallel combination, the combined pump curve was plotted by doubling the single pump flowrate at any given head. In the modified impeller scenario, dimensional analysis was employed assuming no $\mathbf{C_H}$ dependence on **Re** due to the high **Re** values established in the previous estimates **[4]**.

Concerning the downstream butterfly valve settings, in order to achieve $\mathbf{Q_D}=\mathbf{Q_C}$ only valve C was considered. Iterative and interpolative means allowed its angular position to be determined at a specific operating point. To achieve $0.85\mathbf{Q_B}$, a similar method was employed with an alteration in valve B setting only. For both the aforementioned conditions to be met simultaneously, iterative means were also employed with various combinations of valve B and C settings only.

In the remainder of this report, the results of the analysis are discussed and, where appropriate, conclusions are made.

2 Results and discussion

2.1 Results

Sample calculations of the investigation at $\mathbf{V_B}$=0.8 m s^{-1} can be found in Appendix 1.A, section 5. In addition, the tables and figures that follow list the results obtained for each part of the overall investigation.

Part 1

V_B / m s^{-1}	V_C / m s^{-1}	V_D / m s^{-1}	Q_B / m^3 s^{-1}	Q_C / m^3 s^{-1}	Q_D / m^3 s^{-1}	P_1 / Pa	P_2 / Pa	P_3 / Pa	$(P_2 - P_1)$ / Pa	P_{pump} / Pa
0.80	0.94	0.72	0.0083	0.0047	0.0036	14695.3	428734.9	425401.8	414039.7	414359.1
0.90	1.05	0.81	0.0093	0.0053	0.0041	14695.3	435870.1	431651.6	421174.8	421579.1
1.00	1.17	0.90	0.0104	0.0059	0.0045	14695.3	443844.6	438636.6	429149.3	429648.4
1.10	1.29	0.99	0.0114	0.0065	0.0050	14695.3	452658.5	446356.9	437963.3	438567.2
1.20	1.40	1.08	0.0125	0.0071	0.0054	14695.3	462311.9	454812.4	447616.7	448335.4
1.30	1.52	1.16	0.0135	0.0076	0.0059	14695.3	472804.7	464003.2	458109.5	458953.0
1.40	1.64	1.25	0.0145	0.0082	0.0063	14695.3	484137.0	473929.3	469441.7	470420.0
1.50	1.76	1.34	0.0156	0.0088	0.0068	14695.3	496308.6	484590.6	481613.4	482736.3
1.60	1.87	1.43	0.0166	0.0094	0.0072	14695.3	509319.7	495987.2	494624.5	495902.1
1.70	1.99	1.52	0.0177	0.0100	0.0077	14695.3	523170.2	508119.1	508475.0	509917.4

Table 1: Tabulated data of velocities and pressures in the system by taking $\mathbf{C_f}$ as an initial guess of 0.015.

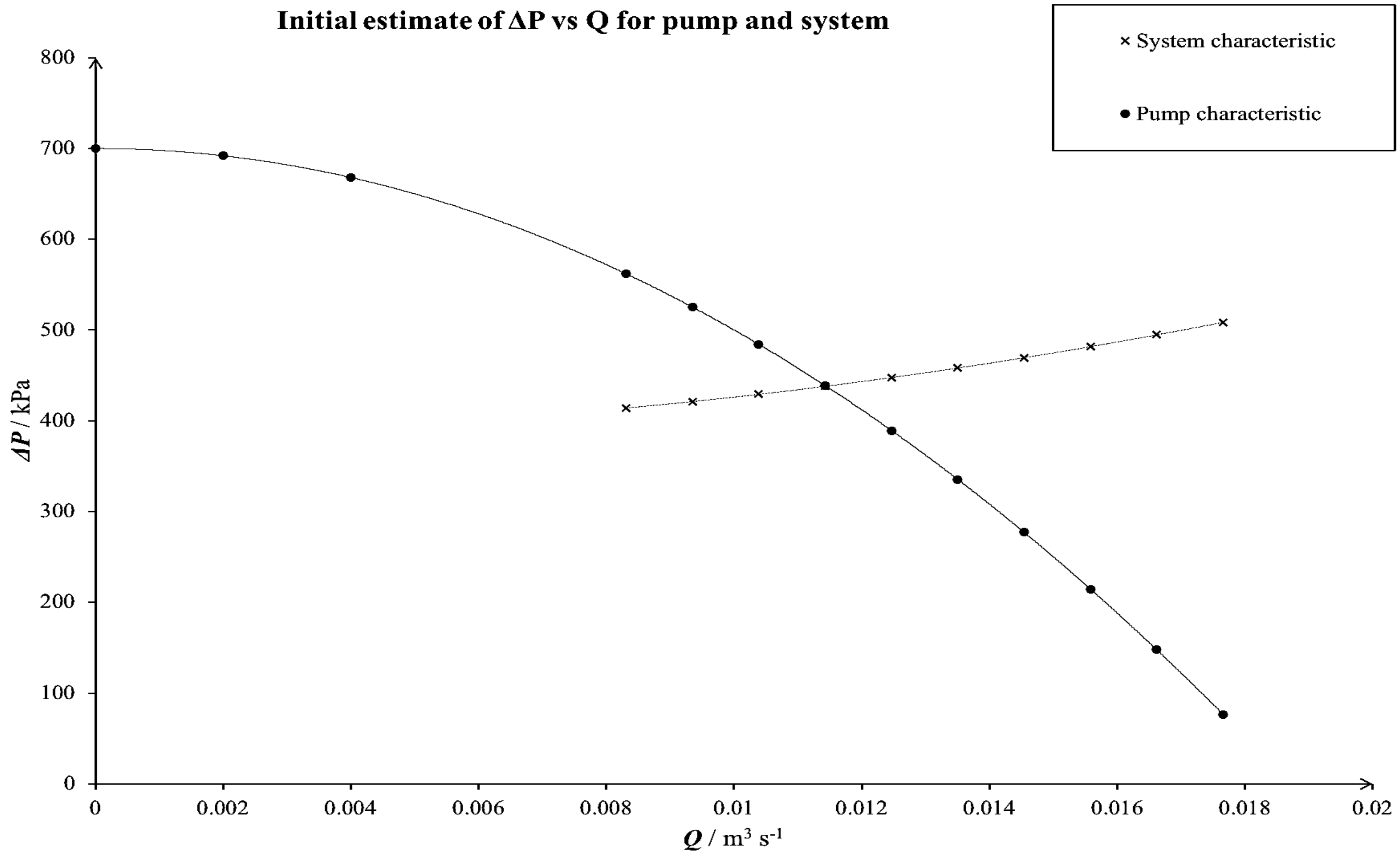


Figure 1: Plot of both system and pump characteristics by taking $\mathbf{C_f}$ as initial guess of 0.015.

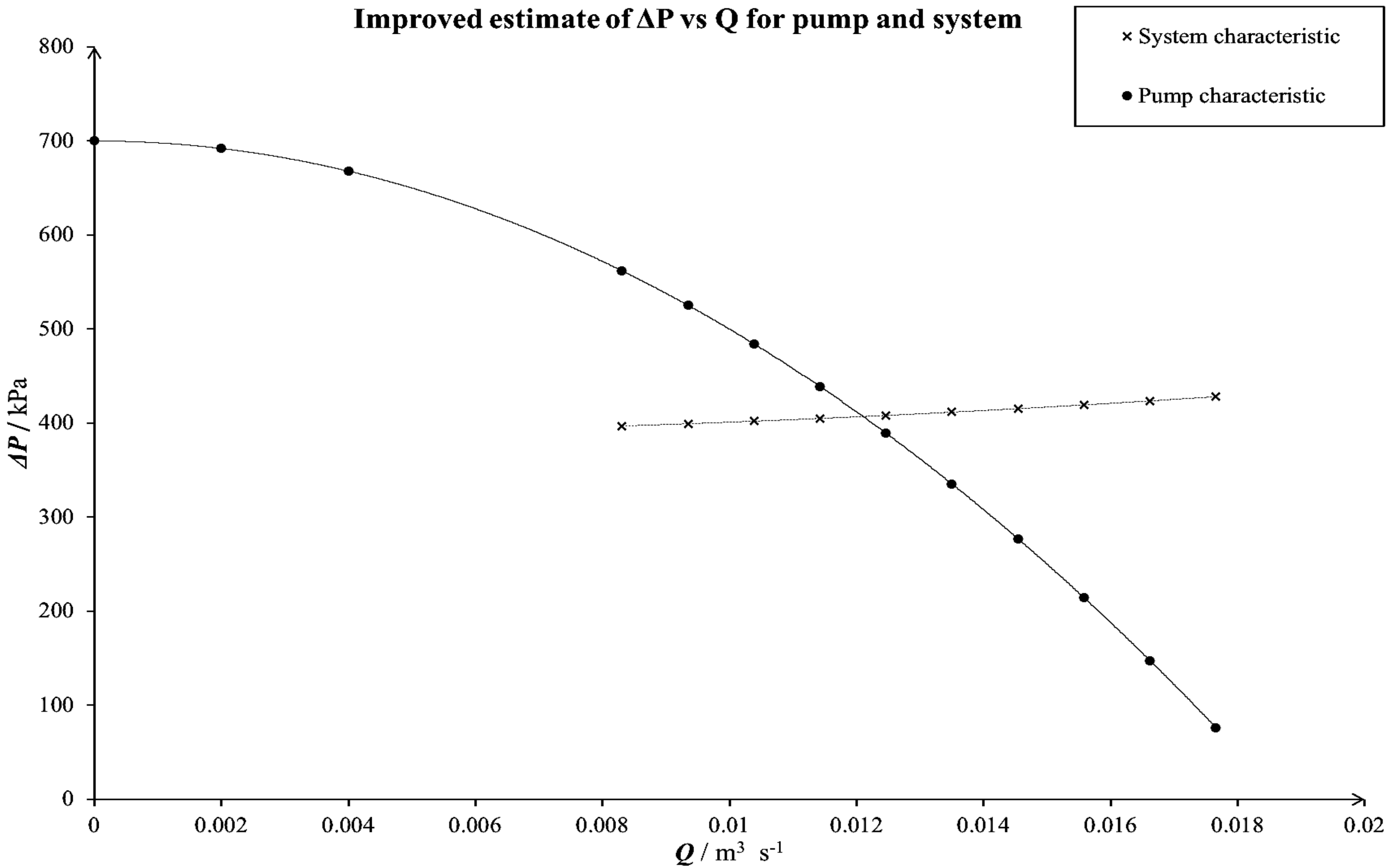


Figure 2: Plot of both pump and improved system characteristics by using correlation of $\mathbf{C_f}$ with **ε/D** and **Re** dependence.

Initial estimate of operating point			Improved estimate of operating point		
Q_B / m^3 s^{-1}	Q_C / m^3 s^{-1}	Q_D / m^3 s^{-1}	Q_B / m^3 s^{-1}	Q_C / m^3 s^{-1}	Q_D / m^3 s^{-1}
0.0114	0.0065	0.0049	0.0121	0.0069	0.0052

Table 2: Table of initial estimate of flowrates at operating point using $\mathbf{C_f}$ of 0.015 and improved estimate using correlation including roughness ratio **ε/D** and **Re** within the turbulent flow regime.

Part 2

Pumps in series operating point				Pumps in parallel operating point				Pump with 1.3N operating point			
Q_B / m^3 s^{-1}	Q_C / m^3 s^{-1}	Q_D / m^3 s^{-1}	ΔP / kPa	Q_B / m^3 s^{-1}	Q_C / m^3 s^{-1}	Q_D / m^3 s^{-1}	ΔP / kPa	Q_B / m^3 s^{-1}	Q_C / m^3 s^{-1}	Q_D / m^3 s^{-1}	ΔP / kPa
0.0157	0.0089	0.0068	419.68	0.0223	0.0127	0.0096	451.45	0.0193	0.0110	0.0083	435.93

Table 3: Table of detailed operating points for use of system with pumps in series, parallel and pump with modified impeller **N** respectively.

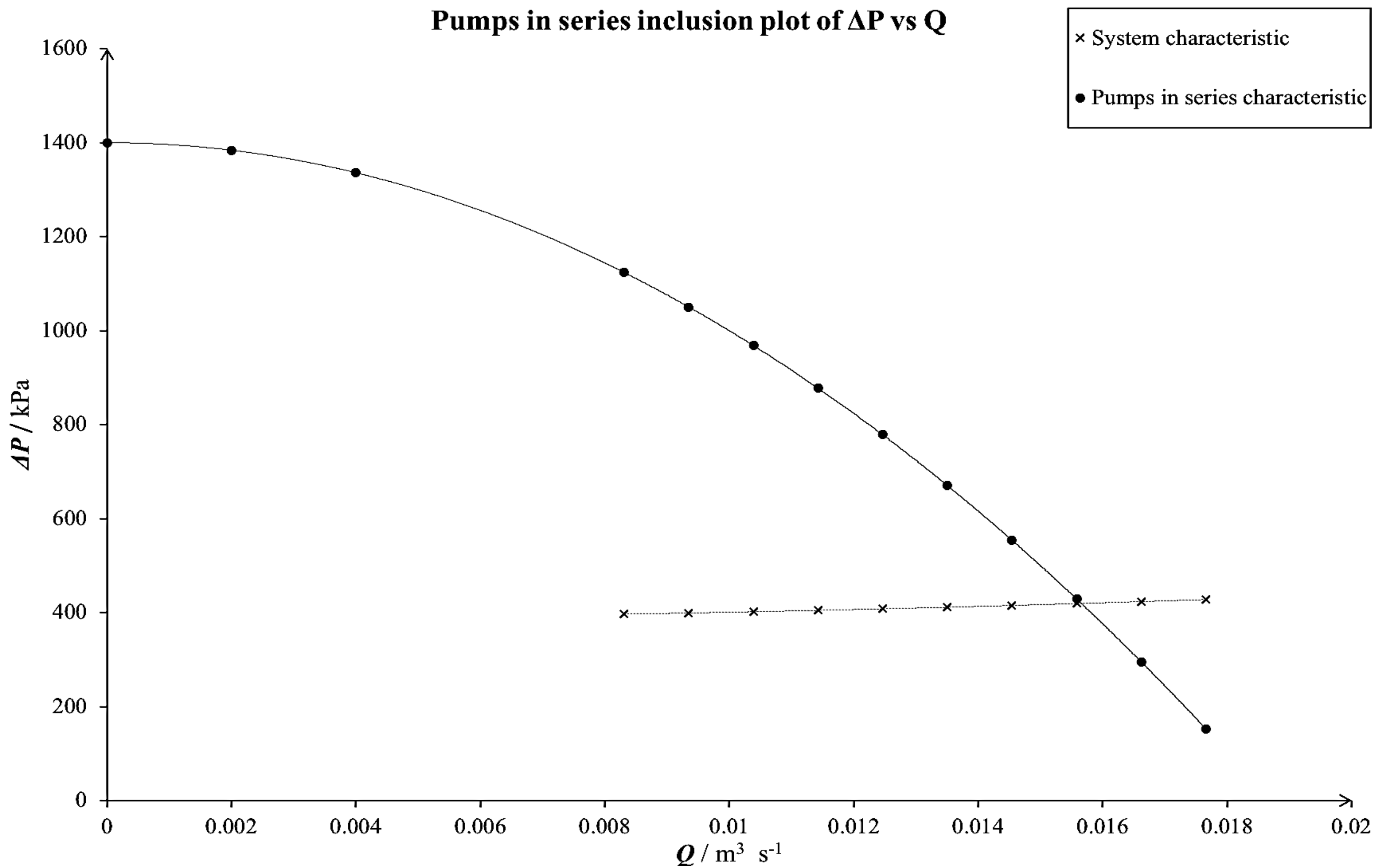


Figure 3: Plot of same pumps in series combined characteristic and system characteristic.

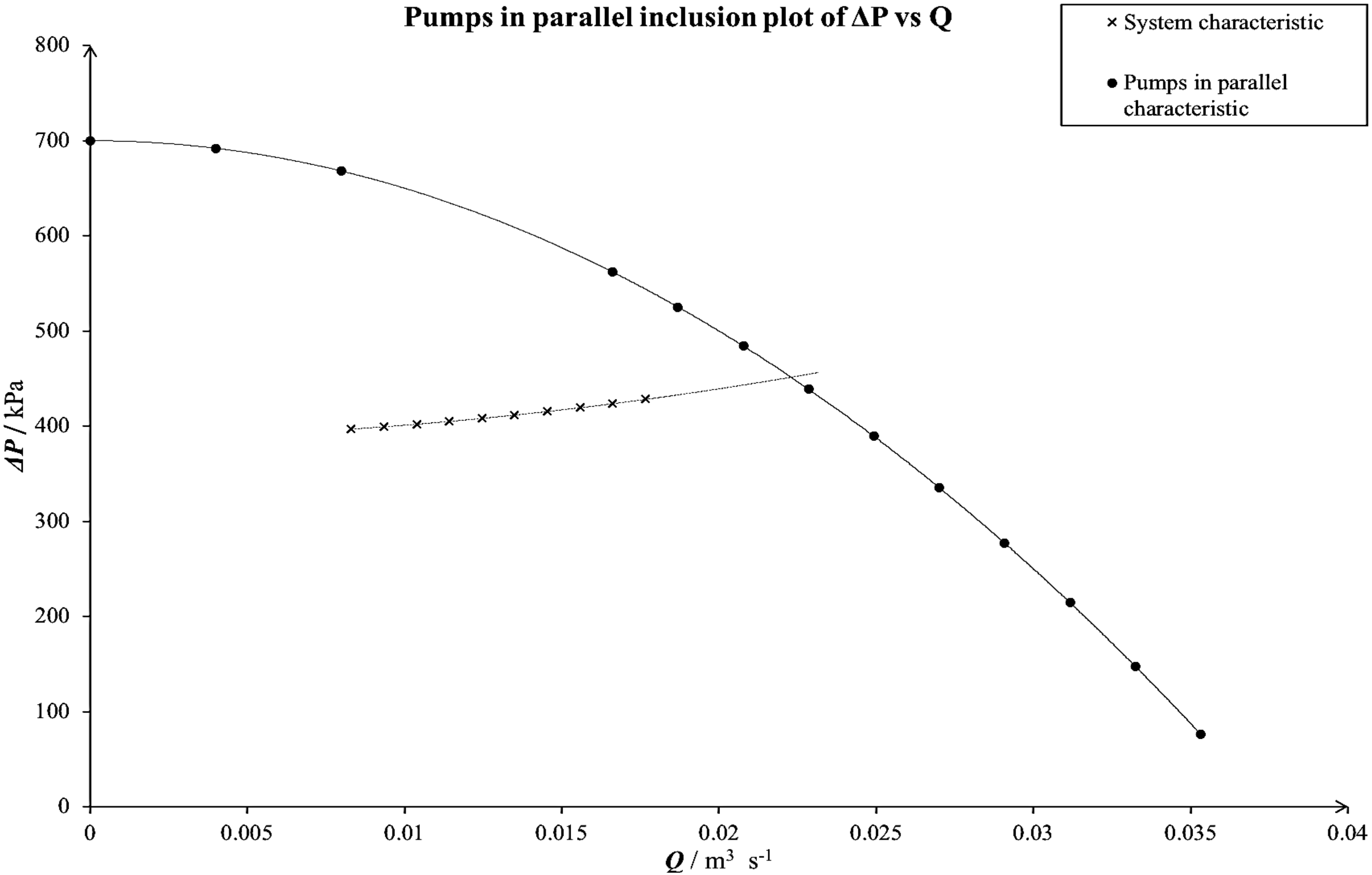


Figure 4: Plot of same pumps in parallel combined characteristic and system characteristic.

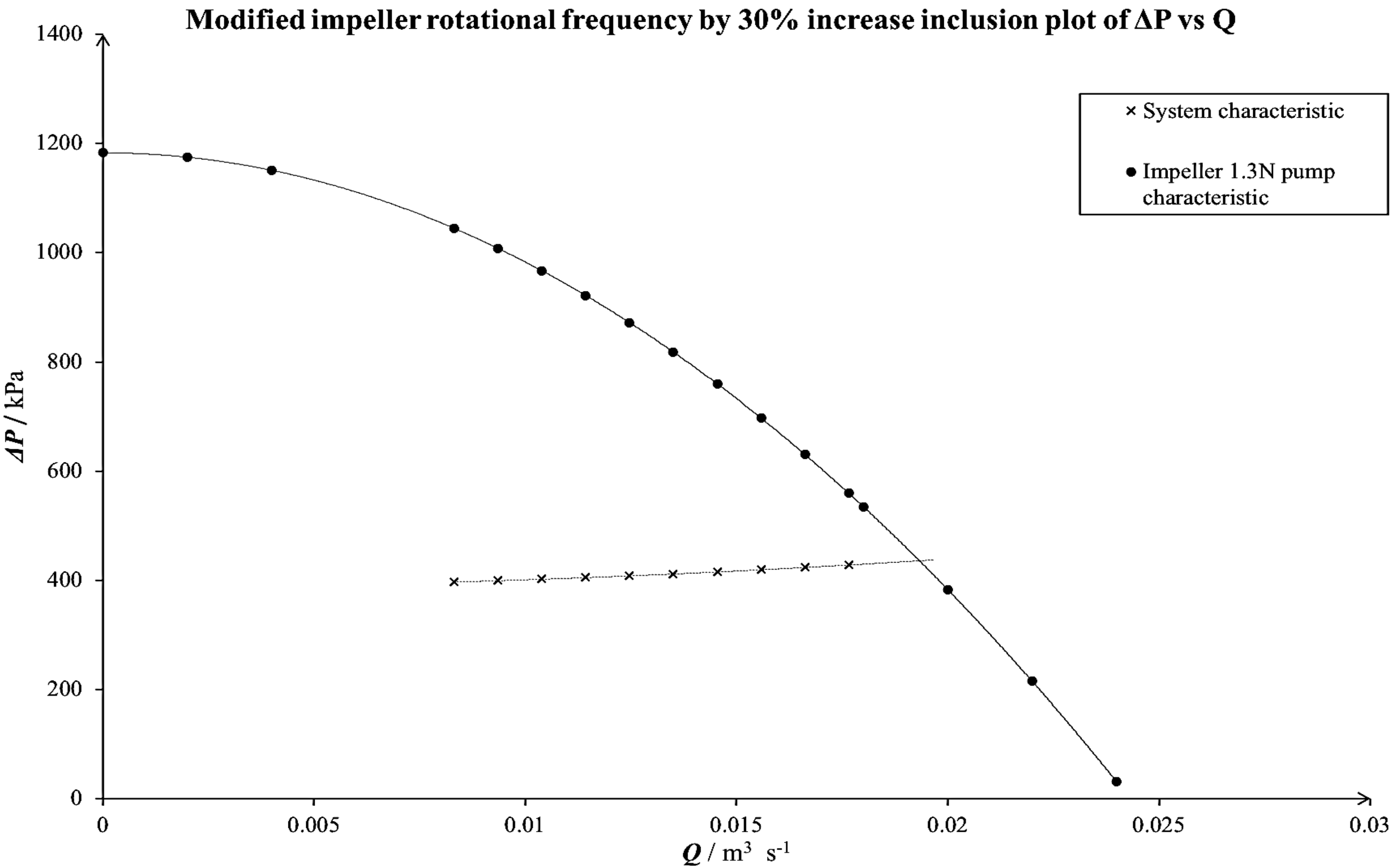


Figure 5: Plot of pump with 30% increase in impeller rotational frequency characteristic and system characteristic.

Part 3

V_B / m s^{-1}	Angle of valve C position / degrees
0.80	42.64
0.90	43.16
1.00	43.61
1.10	43.92
1.20	44.24
1.30	44.43
1.40	44.67
1.50	44.77
1.60	44.94
1.70	45.11
V_B at operating point / m s^{-1}	**Angle of valve C position at operating point / °**
1.48	44.12

Table 4: Table of valve C angular position at different $\mathbf{V_B}$ including valve C setting at operating $\mathbf{V_B}$ to achieve $\mathbf{Q_C}$=$\mathbf{Q_D}$.

V_B / m s^{-1}	K valve B	Angle of valve B position / °
0.99	188	64.40

Table 5: Table of operating $\mathbf{V_B}$ and optimal valve B setting to achieve 15% reduction in $\mathbf{Q_B}$.

V_B / m s^{-1}	K valve B	Angle of valve B position / °	V_C / m s^{-1}	K valve C	Angle of valve C position / °
0.93	175	63.75	0.96	21.0	44.62

Table 6: Table of operating $\mathbf{V_B}$ and $\mathbf{V_C}$ for valve B and C settings to achieve both $\mathbf{Q_C}$=$\mathbf{Q_D}$ and 15% reduction in $\mathbf{Q_B}$.

2.2 Discussion

Part 1

Table 1 indicates that for the initial estimate of the operating point, as $\mathbf{V_B}$ increased from 0.8 to 1.7 m s^{-1} $\mathbf{P_{pump}}$ also increased from 414.4 to 509.9 kPa. Intersections of the curves in figures 1 & 2 depict the operating conditions based on the $\mathbf{C_f}$ used in each case. The operating flowrates of the initial estimate shown in table 2 predict **Re** values lying within the range 2200-500000 which justify the use of the correlation for $\mathbf{C_f}$ with **ε/D** and **Re** dependence in the improved estimate **[4]**.

Table 2 shows that $\mathbf{Q_B}$ at operating point for the improved estimate increased by 6.14 % compared to $\mathbf{Q_B}$ for the initial estimate. Taking into account the relationship for $\mathbf{C_f}$ employed in the improved estimate scenario, the dependence on both **ε/D** and **Re** decreased the value of $\mathbf{C_f}$ overall which justifies the increase in $\mathbf{Q_B}$ at operating point relative to that of the initial estimate scenario, for rough pipes with **ε**=0.046 mm. The values of $\mathbf{Q_C}$ and $\mathbf{Q_D}$ at operating point were also found to increase by 6.15 and 6.12 % respectively relative to their initial estimates according to table 2.

Part 2

Figures 3, 4 & 5 depict the operating points of the system with the new, altered pump characteristics for pumps in series, parallel and one with modified 30 % increase in impeller **N** respectively. In all of figures 3, 4 & 5 the new operating pump combination head didn’t alter significantly based on the results tabulated in table 3 as well.

The highest pressure capacity and flowrate capacity at operating conditions was permitted by use of pumps in parallel. $\mathbf{Q_B}$ at operating point for the parallel combination and $\mathbf{\Delta P}$ were 0.0223 m^3 $s^{-1}$and 451.45 kPa respectively according to table 3. For the series combination $\mathbf{Q_B}$ at operating point increased by 29.75 % relative to the improved $\mathbf{Q_B}$ estimate tabulated in table 2. For the parallel combination it increased by 84.30 % and for the modified 1.3 **N** pump it increased by 59.50 %. The highest pressure capacity at operating conditions quoted as 451.54 kPa in table 3 was also provided by the parallel pump combination as opposed to the series combination which was what was initially expected **[2]**. The system characteristic was the limiting factor in this case.

Part 3

Table 4 shows that for the condition $\mathbf{Q_C}$=$\mathbf{Q_D}$ to be met with only valve C requiring adjustment so as to compensate for the additional head loss in pipeline D, for each $\mathbf{V_B}$ from 0.8 to 1.7 m s^{-1} the valve C setting in degrees increased overall from 42.64 to 45.11°. This was expected due to larger successive head losses in pipeline D which necessitated higher **K** values and therefore higher angle setting values for valve C. At operating conditions with operating $\mathbf{V_B}$ of 1.48 m s^{-1} the **K** value for valve setting C was 19.7 and its angle setting was 44.12° as shown in table 4.

Table 5 indicates that 0.85$\mathbf{Q_B}$ was achieved at new operating $\mathbf{V_B}$ of 0.99 m s^{-1} with a **K** for valve B only of 188 and therefore angular setting of 64.40°. The lower operating $\mathbf{V_B}$ was expected due to a larger **K** value for valve B as opposed to that for valve C in the condition that only $\mathbf{Q_C}$=$\mathbf{Q_D}$.

For both $\mathbf{Q_C}$=$\mathbf{Q_D}$ and 0.85$\mathbf{Q_B}$ conditions to be achieved simultaneously, table 6 indicates that valve B was set to a **K** value of 175 and valve C to a **K** value of 21.0 at an operating point with $\mathbf{V_B}$ and $\mathbf{V_C}$ of 0.93 and 0.96 m s^{-1} respectively. $\mathbf{V_B}$ at operating point of 0.93 m s^{-1} was lower relative to the $\mathbf{V_B}$ values obtained when either of the two conditions $\mathbf{Q_C}$=$\mathbf{Q_D}$ and 0.85$\mathbf{Q_B}$ were met individually. The new **K** values lied in between 19.7 and 188 as expected because both conditions had to be met at the same time as opposed to individually.

3 Conclusions

The operating points at different conditions imposed on the industrial process with pumping inclusion were effectively and quantitatively established. It can be concluded that, the initial guess for $\mathbf{C_f}$ of 0.015 was reasonably good since the increase in $\mathbf{Q_B}$ at operating point of the improved estimate by use of $\mathbf{C_f}$ with **Re** and **ε/D** dependence **[4]** relative to the initial estimate was only 6.14 % according to table 2.

In addition, with regard to changing the pumping characteristic, the best performance was undoubtedly achieved by use of two pumps in parallel giving a total operating $\mathbf{Q_B}$ of 0.0223 $m^3\ s^{-1}$ and a $\mathbf{\Delta P}$ of 451.45 kPa by also considering the limitations of the assumptions made in the entirety of the calculations, according to table 3. The pumps in series for this process gave the lowest additional flowrate capacity in the system at operating conditions. The modified 1.3**N** was intermediate with regard to performance enhancement pertinent to additional flowrate capacity for the entire process.

Furthermore, concerning alterations in the system characteristic, it can be conclusively said that for $\mathbf{Q_C}$=$\mathbf{Q_D}$ and 0.85$\mathbf{Q_B}$ to be achieved simultaneously the angular position of valve B must be 1.01 % less than its setting used to achieve only 0.85$\mathbf{Q_B}$ and that of valve C must be 1.13 % more than its setting used to achieve only $\mathbf{Q_C}$=$\mathbf{Q_D}$ according to tables 4, 5 & 6.

To sum up, all these key factors must be thoroughly considered when implementing the desired conditions in the industrial process.

4 References

[1] Chemical Engineering Tripos Part I, Exercise 2 – Fluid Mechanics MT 2018, Pump and piping installation, Department of Chemical Engineering and Biotechnology, University of Cambridge, handout page 1 figure 1, page 2 tables 1-2 and pump characteristic information.

[2] Massey B. revised by Ward-Smith J. (2006) MECHANICS OF FLUIDS 8th EDITION, Oxon, Taylor & Francis, pages 167-182, 245-249, 277-283, 591-592 & 651-656.

[3] J.T.R Watson, R. S. Basu, J. V. Sengers, In "An Improved Representative Equation for the Dynamic Viscosity of Water Substance", Journal of Physical Chemistry Reference Data 9 1255 (1980); doi: 10.1063/1.555631, vol. 9, No.4, 1980.

[4] Chemical Engineering Tripos Part I, Fluid Mechanics course section 5, Turbulent Flow in Pipes, Department of Chemical Engineering and Biotechnology, University of Cambridge, pages 5-7, MT 2018.

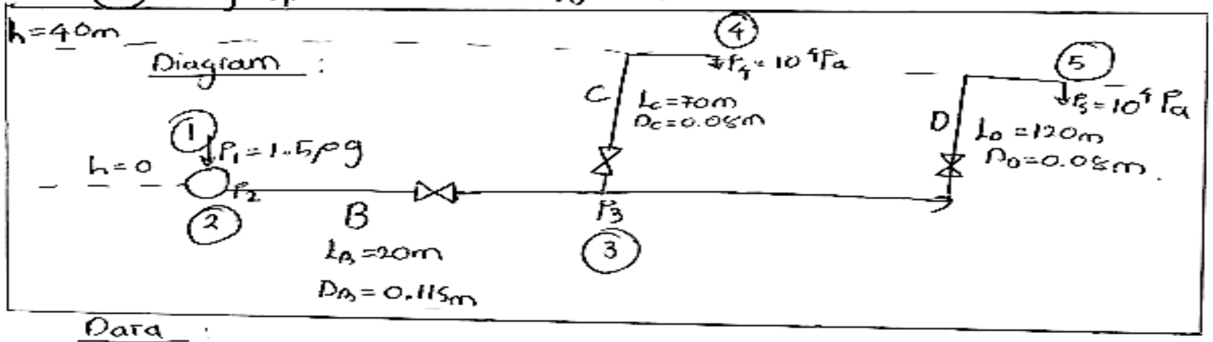
5 Appendices

Appendix 1.A: Sample calculations for part of the analysis in the investigation

SAMPLE CALCULATIONS :

Part 1 :

- Taking $C_f = 0.015$ for $V_B = 0.8\ ms^{-1}$.



Data :

$\varepsilon = 0.046\ mm$

k_f for bends $= 1$

→ calculation :

$V_B = 0.8\ ms^{-1}$ $\therefore Q_B = \dfrac{\pi[0.8][0.115]^2}{4} = 0.00830951\ m^3s^{-1}$

- By continuity in volometric flowrate :

$$Q_B = Q_C + Q_D = \frac{\pi[0.08]^2}{4} \cdot V_C + \frac{\pi[0.08]^2}{4} \cdot V_D$$

- Bernoulli between (3) and (4) and (3) and (5) :

$\therefore$ Since $P_4 = P_5 = 10^4 Pa$ and $h_4 = h_5 = 40m$

$\therefore \Delta H[(3) \rightarrow (4)] = \Delta H[(3) \rightarrow (5)]$

$\Delta H = 4C_f \cdot \frac{L}{D} \cdot \frac{V^2}{2g}$

$$\therefore \left[2 + 4 \cdot 0.015 \cdot \frac{70}{0.08}\right]\left(\cancel{\frac{Q_c \cdot 4}{\pi[0.08]^2}}\right)^2 = \left[3 + 4 \cdot 0.015 \cdot \frac{120}{0.08}\right] \cdot \left(\cancel{\frac{Q_D \cdot 4}{\pi[0.08]^2}}\right)^2$$

$$(54.5)Q_C^2 = 93 \cdot Q_D^2 \quad \therefore (54.5)V_C^2 = 93 V_D^2$$

but from continuity $\rightarrow$ $V_C + V_D = V_B \left(\frac{0.115}{0.08}\right)^2$.

and $\frac{V_C}{V_D} = \sqrt{\frac{93}{54.5}}$

$$\therefore \sqrt{\frac{93}{54.5}} \cdot V_D + V_D = 0.8 \left(\frac{0.115}{0.08}\right)^2$$

$\therefore$ $V_D = 0.71678635 \ ms^{-1}$ and $V_C = 0.93633865 ms^{-1}$

$\therefore$ $Q_D = 0.00360296 m^3 s^{-1}$ and $Q_C = 0.00470655 \ m^3 s^{-1}$

- Applying Bernoulli between (3) and (4) :

Taking $\rho_{water} = 998.2 \ kg m^{-3}$ approximately.

$$\therefore \quad P_3 = 998.2 \left[40g + \Delta H[(3) \rightarrow (4)] \cdot g + \frac{10^4}{998.2} - \frac{1}{2} \cdot (0.8)^2 \right]$$

with $\Delta H[(3) \rightarrow (4)] = \left(\frac{54.5}{2g}\right) \cdot V_C^2$ where $V_C = 0.93633865 ms^{-1}$

$$P_3 = 998.2 \left[40g + \left(\frac{54.5}{2}\right)(0.93633865)^2 + \frac{10^4}{998.2} - \frac{1}{2}(0.8)^2 \right]$$

$\therefore$ $P_3 = 425401.823 \ Pa$.

- Applying Bernoulli between (2) and (3) :

$$P_2 = P_3 + 998.2 \left[4 \cdot 0.015 \cdot \frac{20}{0.115} \right] \cdot \frac{0.8^2}{2}$$

$\therefore$ $P_2 = 428734.94 \ Pa$

• Applying Bernoulli across Pump from 1 to 2 :

$$P_{pump} = P_2 - 1.5 \cdot 998.2 \cdot g + 998.2 \cdot \frac{[0.8]^2}{2}$$

or $P_{pump} = P_2 - 1.5 \cdot 998.2 \cdot g + \frac{998.2}{2} \cdot [V_B]^2$

$\therefore$ $P_{pump} = 414359.116\ Pa$.

• Improving initial estimate by using correlation for

$$C_f = 1.375 \cdot 10^{-3}\left[1 + \left(\frac{2 \cdot 10^4 \cdot \varepsilon}{D} + \frac{10^6}{Re}\right)^{\frac{1}{3}}\right]$$

Correlation used because from estimate using $C_f = 0.015$:

- $Re_{V_B} = 115225$
- $Re_{V_C} = 93817$
- $Re_{V_D} = 71819$

→ Assumption:

$\mu_{water} = 7.97 \times 10^{-4}\ Pa\,s$

$\therefore$ correlation for C_f applicable.

since $2200 \leq Re \leq 5 \cdot 10^5$

and $\frac{\varepsilon}{D} \neq 0$ for all pipes.

• Finding new Q_C for $V_B = 0.8\,ms^{-1}$:

(I) $\Delta H[3 \rightarrow 4] = \Delta H[4 \rightarrow 5]$

(II) $Q_B = Q_C + Q_D$

$\therefore$ From (I):

$$\left[\frac{Q_C \cdot 4}{\pi \cdot [0.08]^2}\right]^2\left[2 + \frac{70 \cdot 4}{0.08} \cdot 1.375 \cdot 10^{-3}\left[1 + \left[\left(\frac{2 \cdot 10^4 \cdot 0.046 \cdot 10^{-3}}{0.08}\right) + \frac{10^6 \cdot 7.97 \cdot 10^{-4} \cdot \pi \cdot 0.08}{998.2 \cdot Q_C \cdot 4}\right]^{\frac{1}{3}}\right]\right]$$

$$= \left(\frac{(Q_B - Q_C) \cdot 4}{\pi \cdot [0.08]^2}\right)^2 \cdot \left[3 + \frac{120}{0.08} \cdot 4 \cdot 1.375 \cdot 10^{-3}\left[1 + \left[11.5 + \frac{10^6 \cdot 7.97 \cdot 10^{-4} \cdot \pi \cdot 0.08}{998.2 \cdot [Q_B - Q_C] \cdot 4}\right]^{\frac{1}{3}}\right]\right]$$

Using solver in excel for the above function with Q_B unknown as $0.0083095 1\ m^3 s^{-1}$

$$Q_C = 0.0047317 7\ m^3 s^{-1}$$

$$\therefore Q_D = Q_B - Q_C = 0.0035777 4\ m^3 s^{-1}$$

$$\therefore V_C = \frac{Q_C \cdot 4}{\pi [0.08]^2} = 0.9413565 1\ ms^{-1}$$

• <u>Applying Bernoulli between (3) and (4):</u>

$$P_3 = 998.2\left[40g + \frac{1}{2}\cdot(0.9413565 1)^2 + \frac{10^4}{998.2} - \frac{1}{2}\cdot 0.8^2\right]$$
$$+ 998.2\left[1 + 4\cdot 875\cdot 1.375\cdot 10^{-3}\left[1 + \left[11.5 + \frac{797\ \pi}{50\cdot 998.2\cdot Q_C}\right]^{\frac{1}{3}}\right]\right]\left(\frac{Q_C \cdot 4}{\pi[0.08]^2}\right)^2$$

$$\therefore P_3 = 410540.22\ Pa$$

• <u>Applying Bernoulli between (2) and (3):</u>

$$P_2 = 410540.22 + \frac{998.2\cdot(0.8)^2}{2}\cdot\left[\frac{4\cdot 120}{0.115}\cdot 1.375\cdot 10^{-3}\left[1 + \left[8 + \frac{797}{998.2\cdot 0.8\cdot 0.115}\right]^{\frac{1}{3}}\right]\right]$$

$$\therefore P_2 = 411626.393\ Pa$$

$$P_2 - P_1 = 411626.393 - 1.5\cdot 998.2\cdot 9.8145 = 396931.142\ Pa$$

Part 2 :

i) Pumps in series characteristic.

2 · ΔP_{pump} for any given fixed flowrate.

ii) Pumps in parallel characteristic.

2 · Q_B for any given single P_{pump}.

iii) Assume $C_H = f(C_Q)$ due to high Re.

$$\therefore \frac{\Delta p}{\rho N^2 D^2} = A_0 \cdot \left(\frac{Q}{ND^3}\right)^0 + A_2\left(\frac{Q}{ND^3}\right)^2.$$

If $N' = 1.3N$

New pump characteristic :

$$\Delta p = (1.3)^2 \cdot 7 \cdot 10^5 - 2 \cdot 10^9 Q^2$$

$$\Delta p = 11.83 \cdot 10^6 - 2 \cdot 10^9 Q^2$$

Part 3 :

> linear interpolation between u and angle values and iterative means for obtaining angle position of each valve using solver in excel at the new evaluated operating conditions.