



Hydraulic Performance Evaluation of Cooling Water Systems in Air Separation Units Using Pressure Drop

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Abstract: Cooling water systems are crucial for maintaining the reliability of industrial processes. Excessive pressure losses in the pipeline network increase the system head requirements, resulting in higher pump power consumption and reduced hydraulic performance. This study aims to evaluate the hydraulic performance of the cooling water system through pressure drop analysis and pump operating point evaluation under actual operating conditions. Major losses were calculated using the Darcy–Weisbach equation, while minor losses were determined using the Crane loss coefficient method. The total pressure drop was converted to system head and then used to calculate hydraulic power, pump shaft power, and pump operating point. The results showed a total major loss of 243,459.40 Pa, a total minor loss of 488,497.74 Pa, and a total pressure drop of 731,957.15 Pa, which corresponds to a system head of 74.61 m. The calculated hydraulic power and pump shaft power were 14,233 kW and 21,896 kW, respectively. The operating point evaluation confirmed that excessive hydraulic resistance affected the pressure distribution in the cooling water system. The proposed pump selection meets the calculated hydraulic requirements and provides an engineering basis for improving system reliability, hydraulic efficiency, and pump performance.

Keywords: hydraulic; cooling; pressure; centrifugal; pump



SDGs Problem Solving

This research supports SDGs Chapter #9 by evaluating pressure losses and pump operating conditions in an industrial cooling water system. The proposed hydraulic analysis improves pump selection accuracy, enhances energy efficiency, increases system reliability, and contributes to sustainable operation and infrastructure performance.

Conflict of Interest Statement: The author(s) declares that the research was conducted in the absence of any commercial or financial relationship that could be construed as a potential conflict of interest.

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1. INTRODUCTION

The cooling water system is an important component in the process industry because it functions to maintain the stability of the equipment's operating temperature within safe limits, ensuring process reliability, operational continuity, and efficient heat removal (Marzouk *et al.*, 2023; Wang *et al.*, 2023). In an Air Separation Unit (ASU), temperature stability is crucial for the success of the gas separation process and operational continuity. The performance of a cooling water system is greatly influenced by the system's ability to distribute fluid continuously with a flow rate and pressure appropriate to the process requirements.

Optimal fluid flow distribution is influenced by the balance between the system head curve and the pump curve, as the actual system flow rate is determined by the operating point, which is the intersection of the system head requirement and the pump characteristics (Salomons, Shamir and Housh, 2021). The system head curve determines losses that increase with fluid flow rate, while the pump curve has a head characteristic that decreases with fluid flow rate. From the balance of both, the optimal fluid flow rate will be obtained and if not, it can cause decreased efficiency, increased energy consumption, and deviation from the optimal operating point (Tan, Yuan and Zhang, 2021). thus directly affecting the performance of fluid distribution.

Determining the pump head must be adjusted to the system head requirements because the key factor that influences the system head is the pressure drop that occurs throughout the pipe line, which arises from the main fluid friction (major losses) as well as small resistances from elements such as valves, connections, and filters (minor losses) (Gideon and Betesda, 2025). If the pressure drop increases significantly, the system head requirement will also increase and directly burden the pump's performance. Cooling water systems with excessive pressure drop tend to lose heat transfer effectiveness while consuming more energy due to the increased pump power required (Li and Ruan, 2023).

Several previous studies have emphasized the use of numerical simulation and theoretical modeling approaches for system analysis and development. For example, a study by Li and Ruan used experimental analysis and design optimization methods to develop a cooling system with low pressure drop (Li and Ruan, 2023). The results showed that reducing pressure drop can significantly improve cooling system performance.

Another study by Wang *et al.*, which focused on using a Computational Fluid Dynamics (CFD) approach to analyze flow distribution and cooling system performance, showed that fluid flow distribution significantly influences cooling system performance, particularly in terms of heat transfer efficiency (Wang *et al.*, 2023). However, this approach has limitations because it relies on specific model assumptions and boundary conditions, making it less representative of actual operational conditions in the field. Similar findings were also reported in a study by Koopman *et al.*, which used a thermal system-based mathematical modeling method, incorporating pressure drop parameters into a heat pump performance model (Koopman, Zhu and Rohlf, 2024). The results showed that increasing pressure drop leads to decreased system efficiency and increased energy consumption.

Furthermore, a study by Zou *et al.*, which used a machine learning approach combined with a numerical model to predict pump performance in a cooling system, focused more on developing a predictive model and did not conduct a direct evaluation of existing systems in the field (Zou *et al.*, 2025).

Unlike previous studies that primarily relied on numerical simulations, CFD analysis, optimization models, or predictive approaches, this study evaluates the hydraulic performance of industrial cooling water systems using actual operational data obtained from operating ASU. The primary scientific contribution of this study lies in the integration of pressure drop analysis, system head determination, and pump operating point evaluation. This integrated approach allows for the direct identification of hydraulic deficiencies under real-world operating conditions and provides practical engineering recommendations that can be easily applied to existing industrial cooling water systems without the need for complex numerical models or extensive computing resources.

2. METHODOLOGY

The analysis was conducted on the cooling water system of the ASU owned by PT XYZ. This study uses a quantitative approach based on engineering analysis with a focus on evaluating the performance of the cooling water system. This approach was chosen because the problems studied have measurable properties and can be studied using fluid mechanics equations and numerical data obtained from actual operating conditions in the field. The research stages start from identifying the system configuration, collecting and analyzing operational data, calculating pressure drop, determining the system head, analyzing the pump operating point, and evaluating the overall system performance.

The analytical framework adopted in this study was validated through engineering consistency among the calculated pressure drop, system head, hydraulic power, and pump operating point. Rather than relying solely on individual hydraulic parameters, the calculated results were cross-checked against actual operational pressure measurements and the manufacturer's pump performance curve to ensure that the predicted hydraulic behavior remained physically consistent with the observed operating conditions as mentioned by Salomons *et al.*, Tan *et al.*, and Gevorkov *et al.*, which also uses actual operation and pump performance curves to evaluate system performance by determining its operating point (Salomons, Shamir and Housh, 2021; Tan, Yuan and Zhang, 2021; Gevorkov *et al.*, 2022).

2.1. System Configuration Identification

The research stage begins with identifying the system configuration, namely understanding the configuration of the cooling water system in the ASU. At this stage, an assessment is carried out on the piping scheme, fluid flow direction, and the main components that contribute to flow resistance such as pipes, elbows, tees, valves, and fittings. This identification is the basis for determining the analysis limits and ensuring that calculations are carried out on the correct flow path.

2.2. Data Collection and Actual Data Analysis

Data collection includes operating conditions such as fluid density, fluid viscosity, design capacity, and roughness factor of the pipe material used. Operating condition data is required not only for

system profiling but also as an independent variable to support analysis if problems are detected in the system. Operational data, meanwhile, is a collection of actual operating parameters recorded during system operation. This data describes the actual state of the system, including pressure in each pipeline under various normal operating conditions and varying loads. Operational data is not only used for monitoring the system but also serves as a basis for evaluating system performance, analyzing disturbances, and developing predictive and diagnostic models for processes as mentioned in research by Ji and Sun and Sun *et al.* (Ji and Sun, 2022; Sun *et al.*, 2023).

Pressure measurements are obtained using Pressure Indicators (PI-801, PI-802, and PI-803/804) permanently installed and integrated into the ASU instrumentation system. These pressure indicators continuously monitor the operating pressure in the suction and discharge pipes and provide real-time operational data through the plant monitoring system. The recorded pressure values used in this study represent the actual operating conditions of the cooling water system, collected over six months of normal operation. The installed pressure gauges are routinely maintained and calibrated in accordance with the company's instrumentation maintenance procedures. The pressure gauges used as measuring instruments are shown in Figure 1.



Figure 1. Pressure indicator

2.3. Pressure Drop Calculation

In accordance with the method examined in this study, the next calculation of pressure drop in the piping system will be carried out when suboptimality or errors in the installed system are identified. This calculation includes the calculation of major losses due to friction along the pipe which are calculated using the Darcy-Weisbach method in equation 1 and minor losses due to pipe components such as elbows, tees, valves and fittings which are calculated using equation 8. The equations used in this study are based on technical book based on engineering data by CRANE (Valves, 1998):

$$\Delta P_{major} = f \frac{L}{D} \frac{\rho v^2}{2} \quad (1)$$

where ΔP_{major} is Major Pressure Drop (Pa), f is Friction Factor, L is the Length of the pipe (m), D is the inner Diameter of the pipe (m), ρ is Density (kg/m³), v is the average Velocity of the fluid (m/s).

Calculation of Reynolds number using equation 2 is carried out to determine the flow properties that occur in the pipe to determine the Friction Factor value and v using equation 3.

$$Re = \frac{\rho v D}{\mu} \quad (2)$$

where Re is Reynolds Number and μ is Fluid Viscosity.

$$v = \frac{Q}{A} \quad (3)$$

where Q is the Flow Rate in the pipe (m^3/s) which is determined following the maximum value of the design capacity and A is the inner cross-sectional Area of the pipe (m^2) which is measured using equation 4.

$$A = \pi \frac{D^2}{4} \quad (4)$$

The interpretation of the Reynolds number aims to determine the behavior of fluid flow, which can be categorized as laminar, transient, or turbulent. The Reynolds number allows the characterization of flow behavior without having to solve the Navier-Stokes equations, thus acting as a key criterion in experimental design and engineering applications ([Saldana et al., 2024](#)). The classification of fluid flow according to the Reynolds number and its characteristics is shown in [Table 1](#).

Table 1. Fluid characteristics based on Reynolds number

Flow	Re	Characteristic
Laminar	< 2000	The flow is orderly, particle trajectories are parallel, interlayer mixing is minimal, and the velocity profile is parabolic.
Transient	$2000 < Re < 4000$	The flow begins to become unstable and is sensitive to disturbances, allowing it to transition from laminar to turbulent.
Turbulent	> 4000	Random fluctuations in velocity and pressure, intense mixing, and increased heat transfer and friction losses.

Source (edited): ([Ferrari, Rossi and Di Bernardino, 2022](#); [Avila, Barkley and Hof, 2023](#))

For flow properties that will determine the Reynolds number and friction factor in the pipe, turbulent flow is the flow that is generally sought to be formed in heat exchange systems such as cooling water systems because it can improve fluid mixing, reduce the thickness of the thermal boundary layer, and increase the convection heat transfer coefficient. This occurs because the formation of turbulence and eddies in the heat exchanger channel can significantly increase the heat transfer rate compared to laminar flow. Therefore, many heat exchanger designs use high flow velocities and use relatively small channel diameters to generate or amplify turbulence so that heat transfer performance is improved, although accompanied by an increase in pressure drop as mentioned in the study by Marzouk *et al.* ([Marzouk et al., 2023](#)).

In the case of laminar flow, f is calculated as a function of the Reynolds number, as described in equation 5:

$$f = \frac{64}{Re} \quad (5)$$

However, if the flow is turbulent ($Re > 2000$), f is solved iteratively using the Colebrook equation in equation 6 ([Fahlbeck, Nilsson and Salehi, 2022](#)):

$$\frac{1}{\sqrt{f}} = -2 \log_{10} \left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{Re\sqrt{f}} \right) \quad (6)$$

Because Colebrook requires iteration, the calculation requires an explicit approach. The Haaland equation can be used to provide an initial estimate of the friction factor value. The formula is written in equation 7 (Fahlbeck, Nilsson and Salehi, 2022):

$$\sqrt{f} \approx \frac{1}{-1.8 \log_{10} \left[\left(\frac{\varepsilon/D}{3.7} \right)^{1.11} + \frac{6.9}{Re} \right]} \quad (7)$$

where ε is the surface roughness.

$$\Delta P_{minor} = K \frac{\rho v^2}{2} \quad (8)$$

where ΔP_{minor} is Minor Pressure Drop (Pa) and K is the loss coefficient of the pipe component.

Meanwhile, in calculating minor losses, a K factor value is required, which is the loss coefficient value of the pipe components. According to the list of pipe components shown in Table 2 the K factor value is determined as follows following the technical book based on engineering data by CRANE (Valves, 1998):

$$K = 30f_T \quad (9)$$

for 90° elbow.

$$K = 20f_T \quad (10)$$

for run tee.

$$K = 60f_T \quad (11)$$

for branch tee.

$$K = 45f_T \quad (12)$$

for butterfly valve.

$$K \approx 0 \quad (13)$$

for flange.

$$K = \frac{0.5(1-\beta^2)}{\beta^4} \quad (14)$$

for straight pipe reducers.

$$K = \frac{(1-\beta^2)^2}{\beta^4} \quad (15)$$

for straight pipe increasers.

where f_T is the friction data value developed by CRANE for clean commercial steel pipe with flow in a zone of complete turbulence, using a Moody diagram as a reference. The Moody diagram itself represents the Reynolds number function for f in laminar flow, and the Colebrook equation for turbulent flow as mentioned in research by Huang and Mendes (Huang, 2022; Mendes and R, 2024). While β is the ratio of the diameter of the small pipe to the large pipe.

Table 2. Pipe component data for the cooling water system

Component	Quantity			
	50 mm	80 mm	100 mm	150 mm
Elbow 90°	7	4	10	10
Run Tee	2		2	2
Branch Tee			2	3
Butterfly Valve	4	4		
Flange	8	10	12	9
	50/100 mm	80/100 mm	100/150 mm	
Reducer		2	4	
Increaser		2		

2.4. Determining Pump Power

The results of the major and minor losses calculated as pressure in Pascals (Pa) then need to be converted to the total head in meters of fluid, denoted as H , to determine the amount of head loss applied to the system. The conversion to head aims to equate the calculation with the pump head to determine the operating point, namely the operating condition at which the system head and pump head are balanced. Pumps use head because the pump's ability to move fluid is independent of the fluid type or density, while pressure (Pa) is dependent on the fluid density. The conversion of pressure drop to head in meters is calculated using equation 16, which uses the Bernoulli equation divided by the fluid density and gravitational acceleration to eliminate the influence of density, as written in the research Pal *et al.* and Fahlbeck *et al.* (Pal, Hanmaiahgari and Karney, 2021; Fahlbeck, Nilsson and Salehi, 2022):

$$H = \frac{\Delta P}{\rho g} \quad (16)$$

where H is the head losses in meters of fluid applied to the system (m), ΔP is the total pressure drop from major and minor losses, and g is the gravitational acceleration (9.81 m/s^2).

After obtaining the total system head from the pressure drop calculation, the hydraulic power required by the cooling water system is determined to evaluate the energy requirements of the installed pump. Hydraulic power represents the rate of energy transfer from the pump to the working fluid to overcome the total system head while maintaining the required flow rate. Hydraulic power is calculated using equation 17, which is derived from the conservation of mechanical energy in fluid flow, as described in the studies Nnaji *et al.* (Nnaji, Udokpoh and Ifeakor, 2024):

$$P_h = \frac{\rho g Q H}{1000} \quad (17)$$

where P_h is the hydraulic power (kW). Since hydraulic power only represents the useful energy transferred to the fluid, the actual shaft power required by the pump depends on the pump efficiency. Therefore, the required pump power is calculated using equation 18:

$$P_s = \frac{P_h}{\eta} \quad (18)$$

where P_s is the required pump shaft power (kW) and η is the pump efficiency.

2.5. Plotting the Operating Point

The final stage of the analysis is to match the pump operating point to evaluate whether the cooling water system is operating under optimal hydraulic conditions. The operating point is defined as the intersection of the pump head curve and the system head curve. This intersection determines the most optimal operating conditions for the flow rate with $H_{\text{pump}} = H_{\text{system}}$ at which the pump is operating (Salomons, Shamir and Housh, 2021; Gevorkov et al., 2022).

The system head curve is developed from the calculated pressure loss across the piping network, which is then converted to head loss. The pump characteristic curve is obtained from the manufacturer's performance data. The operating point is determined by plotting both curves on the same head-flow (H-Q) graph and identifying the point of intersection, which represents the point at which the system is operating optimally (Gevorkov et al., 2022).

The plotted operating point is then compared to the Best Efficiency Point (BEP) specified by the pump manufacturer. Pump operation near the BEP provides the highest hydraulic efficiency, lower energy consumption, and improved operational reliability (Oshurbekov et al., 2021; Gevorkov et al., 2022; Yang et al., 2022). Conversely, a significant deviation from the BEP indicates that the pump is operating outside its preferred operating region, which may increase hydraulic losses, vibration, and energy consumption while reducing service life. To indicate how far the pump is operating from the BEP when at the operating point position, it can be calculated using equation 19 as used in the study by Yang et al. (Yang et al., 2022).

$$\% \text{ BEP} = \frac{Q_{\text{operation}}}{Q_{\text{BEP}}} 100\% \quad (19)$$

where % BEP is the rated operating range relative to BEP, $Q_{\text{operation}}$ is the flow at the operating point, and Q_{BEP} is the flow at BEP.

3. RESULTS AND DISCUSSION

3.1. System Configuration Identification

System configuration data was obtained from an isometric drawing design analysis applied to the cooling water system of the ASU operated by PT XYZ. The isometric drawing provides a clear depiction of the installed piping scheme and the direction of fluid flow. The isometric drawing reveals that the system employs a closed-loop scheme, where fluid is distributed repeatedly in a closed circuit without any discharge to the environment. The closed-loop scheme eliminates static head in the system because in a closed circuit, no water rises to the atmosphere.

The isometric drawing also includes piping component data, such as pipe lengths and diameters, elbows, tees, valves, and fittings installed along the pipeline. The piping lines analyzed are classified into two types, namely Cooling Water Supply (CWS) which distributes coolant throughout the system network and Cooling Water Return (CWR) which transports coolant that has absorbed heat from the equipment to the cooling tower to undergo a cooling and redistribution process. The list of CWS and CWR piping lines along with their lengths and inner diameters as well as their components are shown in Table 2 and Table 3.

Table 3. CWS and CWR piping data for the cooling water system

No	Pipeline	Inner Diameter (m)	Pipe Length (m)
1	CWS-808	0.1016	0.9
		0.1524	5.6
2	CWS-810	0.1524	6.5
3	CWS-811	0.0508	2.6
4	CWS-813	0.0762	1.3
		0.1016	6.6
5	CWS-815	0.0762	2.9
		0.1016	7.3
6	CWS-817	0.0508	3.9
7	CWR-800	0.1524	16
8	CWR-812	0.0508	1.9
9	CWR-814	0.0762	1.7
		0.1016	4.9
10	CWR-816	0.0762	2
		0.1016	6.3
11	CWR-818	0.0508	3.6

It can be seen in [Table 3](#) that PT XYZ cooling water system uses 4 variations of pipe diameters whose configuration is assisted using piping components shown in [Table 2](#) whose diameter sizes also adjust to the size of each pipe connected by the component. As mentioned in the study by Joshi *et al.* that variations in pipe diameter cause changes in head loss and pressure drop where these changes are very necessary in the Cooling Water System fluid distribution process ([Joshi, Parkash and Krishan, 2022](#)), because in the main line a larger pipe diameter is needed so that the fluid flows with a large discharge and low speed to reduce the pressure drop before the fluid passes through the branching pipe with a smaller diameter when it will be distributed to the equipment to absorb the heat generated from the equipment's work. In pipes with a small diameter where high fluid velocity is very necessary to increase turbulence which functions to increase the ability to absorb heat from the fluid as mentioned in the study by Manolis and Sidiropoulos and Marzouk *et al.* ([Manolis and Sidiropoulos, 2022](#); [Marzouk et al., 2023](#)).

3.2. Data Collection and Actual Data Analysis

The data collected included operating conditions such as fluid density, fluid viscosity, design capacity, and pipe material roughness factor, obtained from the company's operational setup. Operating condition data are shown in [Table 4](#). Furthermore, the operating condition data displayed in [Table 4](#) will become an independent variable whose value will affect all work on the system.

Operational data such as pressure on the suction and discharge sides of the pump are also collected to determine the actual operating conditions of the system. From the collected data, operational data analysis was performed over a six-month period to prevent data ambiguity. The analysis is based on the average and highest values of fluid pressure that occurs in the piping network and through observations of the values and differences in fluid pressure on the suction and discharge sides of the pump. From this analysis, conclusions will be drawn regarding the condition of the system, whether

the system configuration meets the conditions for achieving optimal work or not. The fluid pressure flowing through the pipe was measured using a pressure indicator, as shown in [Figure 1](#).

Table 4. Cooling water system operating conditions data

Operating Condition	Value
Fluid Density (ρ)	1000 kg/m ³
Viscosity (μ)	0.00098 Pa.s
Design Capacity (Q)	70 m ³ /h
Surface Roughness for Commercial Steel (ϵ)	0.00005

The analysis is based on the average and highest values of fluid pressure that occurs in the piping network and through observations of the values and differences in fluid pressure on the suction and discharge sides of the pump. From this analysis, conclusions will be drawn regarding the condition of the system, whether the system configuration meets the conditions for achieving optimal work or not. The operational data analyzed next is presented in [Table 5](#).

Table 5. Pressure data on pipelines

Month	PI-803/804 (barg)		PI-801 (barg)		PI-802 (barg)	
	Avg	Max	Avg	Max	Avg	Max
1	4.9	5.3	2.0	2.5	0	0
2	4.9	5.3	2.3	2.7	0	0
3	4.9	5.3	2.4	2.63	0	0
4	4.9	5.2	2.4	2.7	0	0
5	4.5	5.1	2.3	2.7	0	0
6	4.5	5.1	2.2	2.8	0	0

The Piping and Instrumentation Diagram (P&ID) design for the cooling water system in the company's ASU was also used to clarify the analysis and serve as a reference for collecting operational data. It can be seen from the operational data in [Table 5](#) that there is an abnormality in the operating conditions, where the Pressure Indicator (PI), which is a tool for measuring fluid pressure in the pipe on the suction side or precisely PI-802, reads 0 barg consistently for 6 months of operation. In a closed-loop scheme, the energy supplied by the pump to the fluid should be sufficient to overcome all hydraulic resistance throughout the circuit. This suggests that the available hydraulic energy may have been significantly consumed by upstream hydraulic losses, although this observation should be verified against system head calculations and pump performance curves before concluding that the pump head is insufficient.

Such a condition indicates abnormal hydraulic conditions because the suction side of a centrifugal pump must maintain sufficient pressure to provide adequate Net Positive Suction Head Available (NPSHa). If the available suction pressure is completely exhausted before the fluid reaches the pump inlet, the pump no longer receives the minimum pressure required for stable operation, increasing the risk of cavitation, pressure loss, and flow instability. Therefore, a pressure reading of 0 barg on the suction line should not occur under normal operating conditions and indicates excessive hydraulic losses, an undersized pump, or an instrumentation problem requiring further verification.

This is indicated by studies by Jiang *et al.* and Ambarwati and Suryanto (Jiang *et al.*, 2022; Ambarwati and Suryanto, 2025).

3.3. Pressure Drop Calculation

Operational data analysis identified suboptimality or operational errors in the system, where the system experienced a loss of pressure before entering the suction session. This indicates that the supplied energy is unable to overcome the system head applied to the cooling water system. To address the pressure, drop problem, a pressure drop calculation is necessary, including major and minor losses in the system's piping network. Major losses are calculated using the Darcy-Weisbach equation, equation 1 and minor losses are calculated using the formula in equation 8.

Before that, the Reynolds number calculation using equation 2 needs to be carried out to determine the flow properties that occur in the pipe to determine the Friction Factor value. Previously, the list of calculation results for A and v for each inner pipe diameter was shown in Table 6 long with the Reynolds number value.

Table 6. Reynold's number data for each pipe diameter

No	D (m)	A (m ²)	v (m/s)	Reynold Number
1	0.0508	0.0020	9.598	497549.270
2	0.0762	0.0046	4.266	331699.513
3	0.1016	0.0081	2.400	248774.635
4	0.1524	0.0182	1.066	165849.757

As mentioned in Table 1 regarding flow classification and the Reynolds number list in Table 6, it can be said that the overall flow in the cooling water system is turbulent because Reynolds Number in each pipe is > 4000 . These results confirm previous research by Marzouk *et al.*, which states that turbulent flow is a flow that is generally formed in heat exchange systems such as cooling water systems (Marzouk *et al.*, 2023). This statement is proven by the results of the Reynolds number calculations in Table 6 which show that the smaller the pipe diameter, the higher the flow velocity and as a result increases the turbulence in the flow (Nnaji, Udokpoh and Ifeakor, 2024).

Table 7. Friction factor data from CRANE and the Colebrook equation

Component Diameter (mm)	Friction Factor (f_T)	Friction Factor (f)
50	0.019	0.01956
80	0.018	0.01777
100	0.017	0.01664
150	0.015	0.01523

As mentioned in research by Huang and Mendes the Moody diagram is built based on the relationship between Reynolds number, relative roughness, and Darcy friction factor derived from the Colebrook formulation for turbulent flow (Huang, 2022; Mendes and R, 2024). Meanwhile, the friction data for clean commercial steel pipes with flow in a complete turbulence zone by Valves (Valves, 1998) is an adjustment from CRANE to facilitate direct field calculations. Therefore, f_T in the equation for determining the K factor in this study will be modified by using f from the Colebrook equation to provide accurate calculation results according to actual field conditions. A comparison of f_T by CRANE with f from calculations using the Colebrook equation is shown in Table 7.

After the variable data needed to calculate major losses in the pipe is fulfilled as written in equation 1, the results of the major losses calculation are obtained, which are displayed in [Table 8](#).

Table 8. Major losses calculation data

No	Pipeline	Inner Diameter (m)	Pipe Length (m)	Major Losses (Pa)
1	CWS-808	0.1016	0.9	424.383
		0.1524	5.6	318.175
2	CWS-810	0.1524	6.5	369.310
3	CWS-811	0.0508	2.6	46115.831
4	CWS-813	0.0762	1.3	2758.075
		0.1016	6.6	3112.139
5	CWS-815	0.0762	2.9	6152.628
		0.1016	7.3	3442.215
6	CWS-817	0.0508	3.9	69173.747
7	CWR-800	0.1524	16	909.071
8	CWR-812	0.0508	1.9	33700.030
9	CWR-814	0.0762	1.7	3606.713
		0.1016	4.9	2310.528
10	CWR-816	0.0762	2	4243.192
		0.1016	6.3	2970.678
11	CWR-818	0.0508	3.6	63852.689

Table 9. K factor and minor losses data for pipe components

Component	K Factor			
	50 mm	80 mm	100 mm	150 mm
Elbow 90°	0.587	0.533	0.499	0.457
Run Tee	0.391	0.355	0.333	0.305
Branch Tee	1.174	1.066	0.998	0.914
Butterfly Valve	0.880	0.800	0.749	0.685
Flange	0	0	0	0
	50/100 mm	80/100 mm	100/150 mm	
Reducer	6	0.439	1.406	
Increaser	9	0.316	1.563	
Component	Minor Losses (Pa)			
	50 mm	80 mm	100 mm	150 mm
Elbow 90°	189216.802	19399.874	14372.425	2597.671
Run Tee	36041.296		1916.323	346.356
Branch Tee			5748.970	1558.602
Butterfly Valve	162185.830	29099.811		
Flange	0	0	0	0
	50/100 mm	80/100 mm	100/150 mm	
Reducer		7997.319	16194.572	
Increaser		1821.889		

Then, to calculate minor losses using equation 8, the K factor value for each component is first required to determine the resistance value of each component installed in the system. This K factor value will then be used to calculate the minor losses that occur as fluid passes through each piping component in the system (Table 2). Therefore, the list of K values for each component and the magnitude of the minor losses is shown in Table 9.

Based on the calculation results in Table 8 and Table 9, the 50 mm diameter pipe exhibits the greatest pressure loss compared to other pipe diameters. This is due to its smaller cross-sectional area, resulting in a higher flow velocity. According to the Darcy–Weisbach equation, energy loss due to friction is directly proportional to the square of the flow velocity. Therefore, even though the pipe length is relatively short, pressure loss remains substantial due to the high fluid velocity (Manolis and Sidiropoulos, 2022; Marzouk *et al.*, 2023; Ambarwati and Suryanto, 2025).

The obtained pressure losses indicate that the hydraulic resistance of the cooling water system is influenced not only by pipe friction but also by the cumulative resistance generated by numerous piping components. Although the primary losses increase proportionally with pipe length, this system demonstrates that component losses contribute more significantly to the total hydraulic resistance because the network contains numerous elbows, valves, reducers, and tee branches. Consequently, the pump must convert a greater portion of its mechanical energy to overcome hydraulic resistance than to maintain useful pressure on the suction side. From a hydraulic engineering perspective, this condition shifts the system head curve upward, forcing the operating point toward a lower flow rate and causing the pump to operate far from its optimal hydraulic condition. Such behavior is consistent with centrifugal pump theory, where increasing system resistance reduces the generated flow while increasing the required head (Oshurbekov *et al.*, 2021; Li and Ruan, 2023).

3.4. Determining Pump Power

The calculated pressure drop obtained from the accumulation of major and minor losses is then converted to total system head using equation 16. This total head value is then used to calculate hydraulic power and pump shaft power using equations 17 and 18.

Table 10. Cooling water system performance

Parameters	Value
Total Major Losses	243459.405 Pa
Total Minor Losses	488497.742 Pa
Total Pressure Drop	731957.146 Pa
Total Head	74.613 m
Hydraulic Power	14.233 kW
Pump Shaft Power	21.896 kW

The large, accumulated pressure loss throughout the piping network results in a greater system head for the pump to overcome. This increase in system head directly increases pump power requirements because hydraulic power is directly proportional to flow rate and total head. This finding aligns with research Oshurbekov *et al.*, and Li and Ruan, which shows that increasing system hydraulic resistance increases pump energy requirements, thereby decreasing pump operating

efficiency (Oshurbekov *et al.*, 2021; Li and Ruan, 2023). The results of the total pressure drop, total head, hydraulic power, and pump shaft power calculations are presented in Table 10.

To meet the system's head requirement at Table 10 which is 74,613 m, pump model 3L 65-250 manufactured by Ebara was selected, the specifications of which are shown in Table 11. The pump shaft power calculated using equation 17 also requires the efficiency values of the pump products listed in Table 11.

Table 11. Pump performance

Performance	Value
Flow (Q)	25-130 m ³ /h
Head (H)	15-85 m
Max Power (P_h)	37 kW
BEP Flow (Q_{BEP})	106.6 m ³ /h
Efficiency (η)	65%

Based on Table 11, the pump has an operating capacity range at a flow rate of 25–130 m³/h with a head capacity of 15–85 m. The maximum shaft power required for pump operation is 37 kW. These three parameters indicate that the 3L 65-250 pump manufactured by Ebara can meet the minimum system requirements as shown in Table 10.

Based on these characteristics, the BEP is at a flow rate of 106.6 m³/h, the operating condition where the pump achieves its highest efficiency of 65%. Pump operation around the BEP generally produces the most optimal performance because energy consumption is more efficient, vibration and noise are lower, and the risk of component wear due to unbalanced hydraulic forces can be minimized (Oshurbekov *et al.*, 2021; Gevorkov *et al.*, 2022; Yang *et al.*, 2022). Therefore, the characteristic data in this table is an important reference in evaluating the suitability of the actual operating point of the pump to the operating conditions recommended by the manufacturer.

The hydraulic analysis presented in this study is subject to uncertainties originating from both measurement instruments and engineering assumptions. The pressure data were obtained from permanently installed pressure indicators in the ASU, whose readings are inherently affected by instrument accuracy, calibration tolerance, and operational stability. In addition, the hydraulic calculations assume constant fluid properties, nominal commercial steel pipe roughness, and K factor adopted from CRANE (Valves, 1998). These parameters introduce uncertainty that propagates through the pressure drop, system head, and hydraulic power calculations because each calculated quantity depends on the preceding variables. According to the Guide to the Expression of Uncertainty in Measurement (GUM), uncertainties associated with measured and assumed input quantities should be propagated through the mathematical model to assess the confidence of the final calculated results as stated by Cox and Hagan and Muste *et al.*, (Cox and O'Hagan, 2022; Muste *et al.*, 2024). However, since detailed calibration certificates and instrument tolerance specifications were not available from the plant, a quantitative uncertainty propagation analysis could not be performed in the present study. Nevertheless, the substantial magnitude of the calculated pressure drops and the consistent observation of 0 barg at the pump suction over a six-month operating period indicate that the identified hydraulic deficiency is significantly larger than the expected uncertainty associated with routine industrial pressure measurements. Therefore, the engineering

conclusions regarding excessive hydraulic resistance and its influence on the operating point remain valid, although future studies are recommended to incorporate a formal uncertainty analysis based on instrument specifications and uncertainty propagation methods.

3.5. Plotting the Operating Point

The final evaluation of cooling system performance is performed by comparing the pump performance curve with the system head curve. The intersection of these two curves is the operating point, the optimal condition where the pump's head equals the system's required head at a given flow rate. The system head curve is constructed based on the calculated total pressure drop converted to head, while the pump characteristic curve is obtained from pump performance data provided by the manufacturer. Both curves are then plotted on a head-flow (H - Q) graph to determine the system's operating point. A plot of both curves is shown in Figure 2.

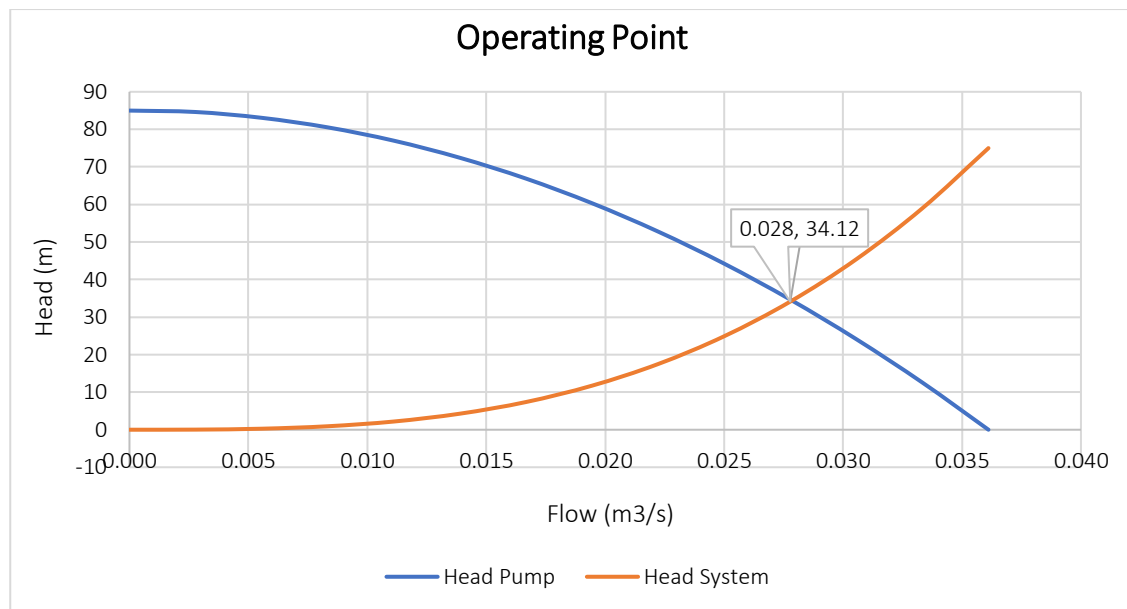


Figure 2. Operating point chart

Based on the plotting results, the operating point was at a flow rate of $0.028 \text{ m}^3/\text{s}$ with a total head of 34.12 m. This flow rate was then compared with the Best Efficiency Point (BEP) of the pump performance curve shown in Table 11 using equation 19. The deviation calculation using equation 19 showed that the operating point was not within the Best Efficiency Point (BEP) region but was operating at 96.154% of the BEP flow rate. This shift resulted from the increased system head requirements and indicated that most of the pump's energy was being used to overcome hydraulic resistance throughout the piping network, reducing the remaining energy to maintain fluid pressure.

These results are consistent with operational data in Table 5, which shows that the PI-802 Pressure Indicator consistently recorded a pressure of 0 barg over the six months of observation. This indicates that the pump's head was being used to overcome pressure losses before the fluid reached the pump's suction side. In other words, the system requires a head greater than the pump's capacity under these operating conditions. Based on the pump adjustments made through the evaluation in this study, it was found that the 3L 65-250 pump model produced by Ebara, meets the calculated head and discharge requirements, so it is an analytically suitable candidate for PT XYZ's Cooling

Water System. The operating point is within the tolerance limit if the operating flow rate is within the range of 70–120% of the Best Efficiency Point (Q_{BEP}). This statement is in accordance with research from Oshurbekov *et al.*, which states that the preferred operating area ranges from $0.7 Q_{BEP}$ and $1.2 Q_{BEP}$ (Oshurbekov *et al.*, 2021).

This finding aligns with research by Oshurbekov *et al.*, which explains that centrifugal pumps should operate as close to the Best Efficiency Point (BEP) as possible or within the Preferred Operating Region (POR) (Oshurbekov *et al.*, 2021). Operation outside these areas results in decreased hydraulic efficiency, increased energy consumption, increased vibration, and accelerated wear of pump components.

4. CONCLUSION

This study successfully evaluated the hydraulic performance of the cooling water system through pressure drop analysis and pump operating point evaluation under actual operating conditions. The analysis showed that the piping system generated a total pressure drop of 731,957.15 Pa, consisting of 243,459.40 Pa as major losses and 488,497.74 Pa as minor losses, which corresponds to a system head requirement of 74.61 m. The results also indicated that the 50 mm diameter pipe produced the greatest pressure loss due to its higher flow velocity compared to larger diameter pipes.

Based on the calculated system head, the hydraulic power required by the cooling water system was 14,233 kW, while the required pump shaft power was 21,896 kW after considering pump efficiency. Furthermore, the operating point evaluation confirmed that excessive hydraulic resistance significantly affected the pump operating conditions and explained the abnormal pressure distribution indicated by the continuous 0 barg readings from the PI-802 Pressure Indicator during the six-month observation period. Therefore, pressure drop analysis combined with pump operating point evaluation proved to be an effective engineering approach for assessing hydraulic performance and selecting pumps capable of meeting the calculated system requirements.

The main advantage of this study is the integration of actual plant operational data, hydraulic calculations, and pump performance analysis, allowing for a comprehensive evaluation of the cooling water system. However, this study was limited to hydraulic analysis and did not consider thermal performance, transient operating conditions, piping aging, or experimental validation after pump implementation. Consequently, the proposed pump selection was an analytical recommendation based on the calculated hydraulic requirements. The proposed pump specification presented in this study should not be interpreted as the primary contribution of the research but rather as one engineering implication derived from the hydraulic evaluation. The principal contribution lies in the integrated methodology for assessing hydraulic performance through pressure drop analysis, system head determination, and operating point evaluation using actual industrial operational data.

Further research is recommended to include validation of the proposed pumps under actual operating conditions after installation. Additionally, numerical simulations using CFD or system-level hydraulic modeling are recommended to investigate local flow behavior, identify dominant pressure loss regions, and evaluate alternative piping configurations to improve hydraulic efficiency and reduce pump energy consumption.

REFERENCES

- Ambarwati, M. and Suryanto, H. (2025) 'Pengaruh Tekanan Diferensial Pada Suction Strainer Terhadap Potensi Kavitasi Water Injection Transfer Pump Di Lapangan Gas JTB PT Pertamina EP Cepu', *JME (Jurnal Mekanika dan Energi)*, 4(2), pp. 13–21. Available at: <https://doi.org/10.51901/jme-sttr>.
- Avila, M., Barkley, D. and Hof, B. (2023) 'Transition to Turbulence in Pipe Flow', *Annual Review of Fluid Mechanics*, 55 (Volume 55, 2023), pp. 575–602. Available at: <https://doi.org/10.1146/annurev-fluid-120720-025957>.
- Cox, M. and O'Hagan, A. (2022) 'Meaningful Expression Of Uncertainty In Measurement', *Accreditation and Quality Assurance*, 27(1), pp. 19–37. Available at: <https://doi.org/10.1007/s00769-021-01485-5>.
- Fahlbeck, J., Nilsson, H. and Salehi, S. (2022) 'A Head Loss Pressure Boundary Condition for Hydraulic Systems', *OpenFOAM® Journal*, 2, pp. 1–12. Available at: <https://doi.org/10.51560/ofj.v2.69>.
- Ferrari, S., Rossi, R. and Di Bernardino, A. (2022) 'A Review of Laboratory and Numerical Techniques to Simulate Turbulent Flows', *Energies*, 15(20), pp. 1–56. Available at: <https://doi.org/10.3390/en15207580>.
- Gevorkov, L. et al. (2022) 'Comparative Simulation Study of Pump System Efficiency Driven by Induction and Synchronous Reluctance Motors', *Energies*, 15(11), p. 4068. Available at: <https://doi.org/10.3390/en15114068>.
- Gideon, S. and Betesda, Y.C. (2025) 'Evaluasi Kuantitatif serta Analisis Kerugian Mayor dan Minor pada Sistem Perpipa NaOH 29–31% di Chlor Alkali Plant PT X, Porsea', *Jupiter: Publikasi Ilmu Keteknikan Industri, Teknik Elektro dan Informatika*, 3(4), pp. 110–120. Available at: <https://doi.org/10.61132/jupiter.v3i4.952>.
- Huang, S. (2022) 'Reading The Moody Chart With A Linear Interpolation Method', *Scientific Reports*, 12(1), pp. 1–5. Available at: <https://doi.org/10.1038/s41598-022-10552-x>.
- Ji, C. and Sun, W. (2022) 'A Review on Data-Driven Process Monitoring Methods: Characterization and Mining of Industrial Data', *Processes*, 10(2), pp. 1–36. Available at: <https://doi.org/10.3390/pr10020335>.
- Jiang, L. et al. (2022) 'Experimental Study on the Effect of Gas Volume Fraction on the Cavitation Performance of a Low-Specific-Speed Centrifugal Pump', *Water*, 14(5), pp. 1–15. Available at: <https://doi.org/10.3390/w14050798>.
- Joshi, T., Parkash, O. and Krishan, G. (2022) 'Numerical Investigation of Slurry Pressure Drop at Different Pipe Roughness in a Straight Pipe Using CFD', *Arabian Journal for Science and Engineering*, 47(12), pp. 15391–15414. Available at: <https://doi.org/10.1007/s13369-022-06583-1>.
- Koopman, T., Zhu, T. and Rohlf, W. (2024) 'Performance Evaluation Of Air-Source Heat Pump Based On A Pressure Drop Embedded Model', *Heliyon*, 10(4), p. e24634. Available at: <https://doi.org/10.1016/j.heliyon.2024.e24634>.
- Li, Z. and Ruan, L. (2023) 'Design Optimization and Performance Evaluation of a Low-Pressure Drop Air-Cooled Condenser for Self-Circulating Evaporative Cooling Systems', 41(2), pp. 385–391. Available at: <https://doi.org/10.18280/ijht.410212>.
- Manolis, A. and Sidiropoulos, E. (2022) 'A New Approach to the Optimization of Looped Water Distribution Networks with Velocity Constraints', *Hydrology*, 9(5), pp. 1–20. Available at: <https://doi.org/10.3390/hydrology9050073>.
- Marzouk, S.A. et al. (2023) 'A Comprehensive Review Of Methods Of Heat Transfer Enhancement In Shell And Tube Heat Exchangers', *Journal of Thermal Analysis and Calorimetry*, 148(15), pp. 7539–7578. Available at: <https://doi.org/10.1007/s10973-023-12265-3>.
- Mendes, de S. and R, P. (2024) 'A Note on the Moody Diagram', *Fluids*, 9(4), pp. 1–6. Available at: <https://doi.org/10.3390/fluids9040098>.
- Muste, M. et al. (2024) 'Implementation of Standardized Uncertainty Analysis for Streamflow Measurements Acquired with Acoustic Doppler Velocimeters', *Journal of Hydraulic Engineering*, 150(6), p. 04024041. Available at: <https://doi.org/10.1061/JHEND8.HYENG-13850>.

- Nnaji, C.C., Udokpoh, U.U. and Ifeakor, A.R. (2024) 'Assessing the efficiencies of domestic water pumps and distribution systems for household water supply in Enugu State, Nigeria', *Indian Journal of Engineering*, 21(55), pp. 1–25. Available at: <https://doi.org/10.54905/disssi.v21i55.e5ije1680>.
- Oshurbekov, S. et al. (2021) 'Improving Reliability and Energy Efficiency of Three Parallel Pumps by Selecting Trade-Off Operating Points', *Mathematics*, 9(11), pp. 1–19. Available at: <https://doi.org/10.3390/math9111297>.
- Pal, S., Hanmaiahgari, P.R. and Karney, B.W. (2021) 'An Overview of the Numerical Approaches to Water Hammer Modelling: The Ongoing Quest for Practical and Accurate Numerical Approaches', *Water*, 13(11), pp. 1–34. Available at: <https://doi.org/10.3390/w13111597>.
- Saldana, M. et al. (2024) 'The Reynolds Number: A Journey from Its Origin to Modern Applications', *Fluids*, 9(12), pp. 1–34. Available at: <https://doi.org/10.3390/fluids9120299>.
- Salomons, E., Shamir, U. and Housh, M. (2021) 'Optimization Methodology for Estimating Pump Curves Using SCADA Data', *Water*, 13(5), pp. 1–14. Available at: <https://doi.org/10.3390/w13050586>.
- Sun, W. et al. (2023) 'Industrial Application of Data-Driven Process Monitoring with an Automatic Selection Strategy for Modeling Data', *Processes*, 11(2), pp. 1–23. Available at: <https://doi.org/10.3390/pr11020402>.
- Tan, L., Yuan, Y. and Zhang, M. (2021) 'Hydraulic Performance Prediction And Optimization Of An Engine Cooling Water Pump Using Computational Fluid Dynamic Analysis', *PLOS ONE*, 16(6), p. e0253309. Available at: <https://doi.org/10.1371/journal.pone.0253309>.
- Valves, C. (1998) *Flow of Fluids Through Valves, Fittings & Pipe: Technical Paper 410 Metric Version*. Vervante. [Print].
- Wang, L. et al. (2023) 'Modeling and Performance Analysis of a Pump-Driven Chip-Level Two-Phase Cooling System in Data Centers', *Applied Sciences*, 13(13), pp. 1–27. Available at: <https://doi.org/10.3390/app13137472>.
- Yang, S. et al. (2022) 'Comparative Evaluation Of The Pump Mode And Turbine Mode Performance Of A Large Vaned-Voluted Centrifugal Pump', *Frontiers in Energy Research*, 10, pp. 1–17. Available at: <https://doi.org/10.3389/fenrg.2022.1003449>.
- Zou, Y. et al. (2025) 'Performance Prediction Of Electronic Fan And Water Pump Of Engine Cooling System Based On Joint Simulation And Machine Learning', *Scientific Reports*, 15(1), p. 15672. Available at: <https://doi.org/10.1038/s41598-025-00313-x>.
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