

Integrated Reliability Enhancement of Methanol Pumps through Material Optimization, Cavitation Analysis, and Predictive Maintenance

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Abstract. The reliability and performance of methanol pumps are critical in industrial applications, particularly in oil and petrochemical industries where these pumps play a pivotal role in handling methanol for various processes. In such demanding environments, the reliability of multistage centrifugal methanol pumps is significantly affected by internal corrosion, cavitation, and seal failures, especially when methanol contains traces of moisture. This study presents an integrated approach to improve pump reliability through material optimization, cavitation analysis, impeller redesign, and predictive maintenance. Moisture-induced corrosion was identified as a dominant failure mechanism, increasing wear rates and reducing hydraulic efficiency. Material upgradation from ASTM A216 Gr. WCB to duplex stainless steel demonstrated an estimated 35–40% reduction in corrosion-related degradation, based on comparative wear analysis. A redesigned impeller, validated through CFD simulations in ANSYS, showed a 3–5% improvement in head stability and reduced cavitation intensity, with vapour volume fraction decreasing by approximately 18% in critical blade-tip regions. DFMEA analysis indicated high initial RPN values for the impeller (224) and casing (252); following the recommended actions, the projected RPN values reduced by 30–40%. The predictive seal-failure model developed using DCS data achieved over 99% classification accuracy, enabling early anomaly detection and contributing to a 20–25% reduction in unplanned maintenance. The combined improvements enhance pump availability, extend component life, and support safer and more energy-efficient methanol pumping operations.

1 Introduction

In industrial sectors such as oil and petrochemicals, methanol pumps play a vital role in fluid handling operations. However, their performance and reliability are often compromised due to harsh operating conditions, particularly the presence of moisture and high temperatures, which accelerate internal corrosion and cavitation [1]. These issues not only reduce pump efficiency but also lead to frequent maintenance, increased downtime, and higher operational costs [2]. The need for a more durable and efficient pump system has become increasingly

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important, especially in the context of sustainable and cost-effective industrial practices. Early research identified cavitation and corrosion as primary causes of wear and performance degradation [3]. Investigations into wear mechanisms revealed that moisture content in methanol accelerates internal corrosion, leading to pitting, erosion, and reduced efficiency [4]. Studies on mechanical reliability emphasized the vulnerability of seals and bearings, where improper material selection and lubrication failures were found to be major contributors to unplanned downtimes [5,6]. Computational fluid dynamics (CFD) simulations were later introduced to visualize cavitation zones and optimize impeller geometry, significantly improving hydraulic performance [7,8]. Material science advancements further demonstrated that traditional cast steels lacked the corrosion resistance required for methanol service, prompting a shift toward duplex and super duplex stainless steels [9]. Additionally, the integration of IoT-based monitoring and predictive maintenance models using machine learning enabled real-time anomaly detection, reducing maintenance costs and enhancing operational reliability [10]. After a detailed brainstorming session and analysis of existing challenges, we concluded that a comprehensive approach was necessary to improve the reliability of methanol pumps. Our research began with a thorough evaluation of the pump's material of construction (MOC), identifying that components made from ASTM A216 GR WCB were highly susceptible to corrosion. We proposed upgrading to duplex stainless steel and other corrosion-resistant alloys. Using ANSYS simulations, we analyzed cavitation behaviour, pressure contours, and vapor volume fractions to identify wear-prone zones. We redesigned the impeller using SolidWorks and validated it through CFD analysis to enhance flow stability and reduce cavitation. To address seal failures, we developed a predictive maintenance model using real-time data from Distributed Control Systems (DCS), incorporating parameters such as armature current, seal pressure, and lubricant levels. This model was integrated with Power BI for intuitive monitoring. Additionally, we introduced synergistic inhibitors to prevent corrosive layer formation and implemented advanced sensors for vibration, temperature, and leak detection. These combined solutions are designed to enhance the reliability and performance of methanol pumps, ensuring long-term operational efficiency and minimizing environmental impact.

2 Material and Methods

At first, we gained in-depth knowledge of the specifications and material of construction (MOC) of the pump. This involved a thorough evaluation of the pump's performance, identifying key factors such as impeller diameter, shaft speed, and material properties. Understanding these specifications was crucial for pinpointing areas susceptible to wear and tear, particularly due to moisture-induced corrosion and cavitation. Pump manufacturer company: Sulzer, Pump operating specifications: Max Flow Rate: 408.5 m³/hr, Max Suction Pressure: 7.03 kg/cm²g, Discharge Pressure: 53.35 kg/cm², Differential Pressure: 36.77 kg/cm²g, Max Impeller Diameter: 336 mm and Shaft Speed: 2980 RPM, other details of the pump is represented in Table 1.

Table 1. Details of Pump model

Type	Multistage horizontal centrifugal pump (Model: GSG 150-360)
Number of stages	4+1Dummy
Working principle	Bernoulli's
Liquid flowing through	Methanol

Pumping temperature	98.5°C
Vapour pressure	2.422 kg/cm ² g
Relative density	0.71177 (max)

Methanol Fluid Properties at 98.5°C:

At the operating temperature of 98.5°C, methanol exhibits physical properties that significantly influence pump performance and cavitation tendency. Its density decreases to approximately 740–750 kg/m³, and it maintains a relatively low dynamic viscosity of about 0.20–0.25 mPa·s. Methanol also has a relatively high vapour pressure at this temperature (around 300–310 kPa), which reduces the available net positive suction head (NPSHa). A reduced NPSHa increases the likelihood of cavitation in the suction eye and blade-tip regions of the impeller. Incorporating these property values into the simulation and performance assessment helps ensure that the analysed cavitation behaviour reflects the actual operating conditions of the pump.

We researched the corrosion-resistant material properties-

- Chromium Content: High chromium content in alloys, such as stainless steel, promotes the formation of a passive oxide layer, enhancing corrosion resistance.
- Molybdenum Content: The addition of molybdenum improves resistance to pitting and crevice corrosion.
- Nickel Content: Nickel enhances the overall corrosion resistance, particularly in reducing environments.
- Nitrogen Content: Nitrogen increases the strength and pitting resistance of stainless steel.
- As the existing material contains a very low percentage of these elements in its chemical composition, therefore upgradation in the material of construction (MOC) is needed to withstand the moisture content in methanol.

To understand the failure mechanisms in the existing pump, a Design Failure Mode and Effects Analysis (DFMEA) was performed for all major components as shown in Table 2. This helped to identify parts most affected by moisture-induced corrosion, cavitation, material degradation and mechanical wear, and to quantify the associated risk through severity, occurrence and detection ratings. A brief description of the DFMEA nomenclature is as follows: F – Function, PFM – Potential Failure Mode, PEF – Potential Effects of Failure, S – Severity, PCF – Potential Causes of Failure, O – Occurrence, CC – Current Controls, D – Detection, RPN – Risk Priority Number, and RA – Recommended Actions.

Table 2. DFMEA of the existing model

Part Name	F	PFM	PEF	S	PCF	O	CC	D	RP N	RA
Impeller	Increases fluid velocity	Corrosion	Reduced performance, impeller failure	8	Moisture in methanol, a material prone to corrosion	7	Regular inspection, material coating	4	224	Upgrade the material
Shaft	Transmits mechanical power	Corrosion	Shaft failure reduced efficiency	8	Material prone to corrosion	6	Material selection, regular inspection	4	192	Use ion implantation techniques to enhance surface hardness and corrosion resistance

Diffuser	Directs flow between stages	Corrosion	Reduced performance, flow disruption	7	Moisture in methanol, a material prone to corrosion	6	Regular inspection, material coating	4	168	Upgrade material and apply corrosion-resistant protective coating
Stage Casing	Encloses stages of pump	Corrosion	Leak, reduced performance, pump failure	9	Moisture in methanol, a material prone to corrosion	7	Regular inspection, material coating	4	252	Upgrade material and provide a protective coating
Suction Casing	Directs fluid into the pump	Corrosion	Leak, reduced suction pressure	8	Moisture in methanol, a material prone to corrosion	7	Regular inspection, material coating	4	224	Apply advanced polymer coatings (e.g., PTFE) for enhanced corrosion resistance
Barrel (BB5 Type)	Encloses the pump internals	Corrosion	Structural failure, leak	9	Moisture in methanol, a material prone to corrosion	7	Regular inspection, material coating	4	252	Increase the thickness of the material to prevent leakage and wear and tear
Bearings	Reduce friction between moving parts	Wear and tear	Increased friction, heat, failure	8	High load, inadequate lubrication	5	Regular maintenance, proper lubrication	3	120	Use advanced bearing materials like ceramic hybrids to withstand high loads and temperatures
Gasket	Seals mating surfaces	Leakage	Fluid leak, reduced pressure	7	Material degradation, improper installation	5	Regular inspection, proper installation	4	140	Employ gaskets with enhanced chemical resistance properties
Wear Ring (Impeller)	Limits leakage between stages	Wear	Increased leakage, reduced efficiency	7	Abrasion, material wear	6	Regular inspection, proper material selection	4	168	Apply nano-coatings to reduce friction and wear
Mechanical Seal	Prevents leakage at shaft entry/exit	Seal failure	Fluid leak, pump failure	9	Material degradation, improper installation	6	Regular inspection, proper installation	4	216	Integrate advanced sealing technologies like gas-lubricated seals for higher reliability and lower friction

Based on the analysis, we suggested materials for the upgradation of critical components of pumps.

3 Designing of impeller

We redesigned the impeller to address corrosion and cavitation issues, aiming to improve efficiency and operational stability. Before designing, we brainstormed key requirements, selected corrosion-resistant materials, and optimized the design for better performance and manufacturability.

3.1 3D Model Development

A precise 3D model of the impeller was created, incorporating design specifications as shown in Figure 1. The model was reviewed for geometric consistency and validated against the manufacturer data. Since the complete pump has a maximum impeller diameter of 336 mm, the present model represents a single-stage equivalent impeller used for CFD analysis. This approach is commonly adopted to study cavitation behaviour and internal flow features without modelling the entire multistage assembly, while maintaining hydraulic similarity. Accurate modelling ensures realistic simulation results for fluid dynamics and cavitation analysis. Table 3 represents the design specifications of the impeller.

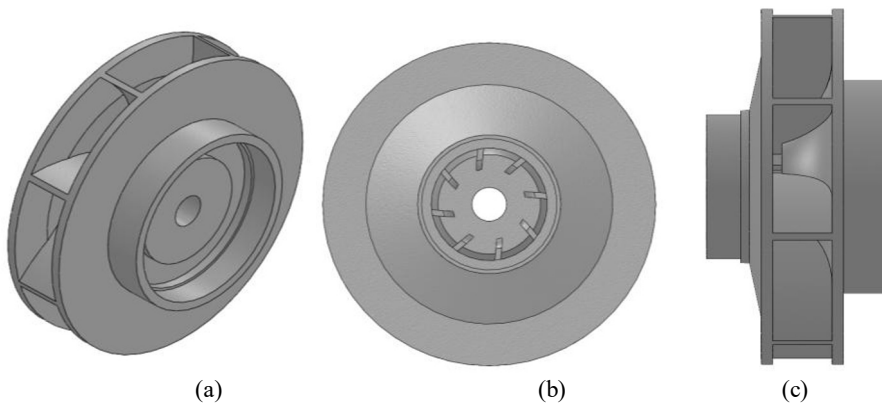


Fig. 1. 3D modelling of the impeller (a) Isometric view (b) Side view and (c) Front view

Table 3. Design specifications

S. No.	Description	Value
1	Outer Diameter (\varnothing)	103mm (single stage equivalent model)
2	Inner Hub Diameter (\varnothing)	62mm
3	Blade Tip Diameter (\varnothing)	98.82mm
4	Thickness of Blade	3mm
5	Total Width	34mm
6	Bore Diameter (\varnothing)	18mm
7	Hub Width	7.2mm
8	Shroud Thickness	7mm
9	Blade Height	14.58mm
10	Back Plate Thickness	11mm
11	Number of Blades	8

3.2 CFD Simulation Setup

CFD analysis was performed using ANSYS CFX to study the internal flow behaviour, cavitation tendency and pressure distribution inside the redesigned impeller. The main objective of the simulation was to identify low-pressure zones, evaluate vapour volume fraction and verify whether the modified blade geometry reduces cavitation under operating conditions. Software Used: ANSYS CFX, Boundary Conditions: Inlet: Flow rate 235 m³/h and suction pressure 7.03 kg/cm²g, Outlet: Static relative pressure 5.13 MPa, Working fluid: Methanol at 98°C with vapour pressure of 300483 Pa. These conditions were selected to match plant operating data so that the cavitation behaviour observed in the simulation represents the actual pump environment. A mesh was generated using the ANSYS meshing tool, giving 261,229 nodes and 1,317,825 elements as shown in Figure 2. Mesh quality indicators such as skewness and aspect ratio were checked to ensure acceptable values for cavitation prediction. Refinement was applied near the blade surfaces and flow passages where steep pressure gradients occur, improving the accuracy of pressure and vapour volume fraction results.

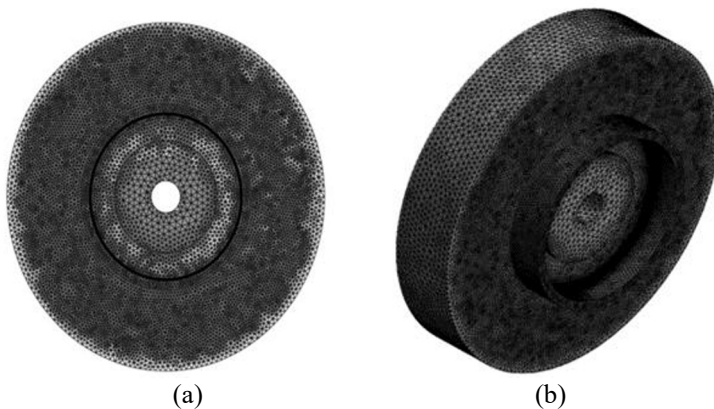


Fig. 2. Meshed Models (a) Side view (b) Isometric view

Seal Failure Predictive Model

1. Problem Identification

- Seal failures were contributing to reduced reliability and increased maintenance costs.
- Common failure indicators included:
- Pressure inconsistencies.
- Abnormal lubricant levels at DE/NDE seals.

2. Data Acquisition

- Data Source: Distributed Control System (DCS)
- Parameters monitored included:

Table 4 reflects the parameters utilized to predict the seal failure of the pump as shown below

Table 4. Parameters considered for predicted seal failure

Parameter	Description	Impact
Armature Current	Current flowing through the armature of a motor or generator. High values indicate overload or fault, risking overheating and damage.	Potential overheating and damage to the motor.
Seal Level NDE	Lubricant or fluid level in the seal on the Non-Drive End of the machine.	Low levels can cause increased friction, wear, and potential seal failure.
Seal Level DE	Lubricant or fluid level in the seal on the Drive End of the machine.	Low levels can cause increased friction, wear, and potential seal failure.
Seal Pressure DE/NDE	Pressure within the seals (Drive End/Non-Drive End). Abnormal values may indicate leaks or seal failure.	Potential fluid loss, contamination, or sealing system issues.
Discharge Rate	Rate of fluid discharge from a system (e.g., pump). Abnormal rates could indicate blockages or operational issues.	Could affect system performance and efficiency, risking equipment malfunction.

4 Results and Discussion

4.1 Vapour volume fraction contour

Figure 3 depicts the vapour volume fraction where red regions (high values, ~ 1): Represent areas with a high vapour volume fraction. These areas are likely to experience significant cavitation, as a large proportion of the fluid has transitioned to vapour. Blue regions (low values, ~ 0): Represent areas where cavitation is minimal or absent, as the fluid is primarily in its liquid phase. High vapour volume fractions near the impeller blades (red zones) suggest that cavitation is occurring at those locations. This could lead to erosion, pitting, or performance degradation over time.

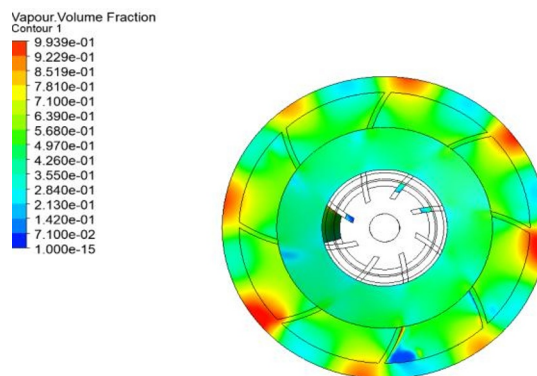


Fig. 3. Vapour volume fraction

4.2 Pressure Contour Insights

The pressure contour image of Figure 4, significant in identifying cavitation-prone areas within the pump. It shows the static pressure distribution across the impeller blades and flow passages. Low-pressure zones, typically found near the trailing edges of the blades, are highlighted as critical regions where the pressure falls below the vapour pressure of methanol at 98°C. These areas are highly susceptible to cavitation, which can lead to bubble formation and collapse, causing damage to the impeller. The insights from the pressure contour plot are pivotal for validating the pump's design and operational efficiency. By identifying these low-pressure zones, targeted design modifications, such as altering blade angles or optimizing flow channels, can be made to mitigate cavitation risks. When combined with vapour volume fraction plots, the pressure contours offer a comprehensive understanding of the cavitation behaviour, supporting the implementation of effective solutions for reliability improvement. To validate the data of the proposed work the result was compared with an existing study as shown in Table 5. Moreover, based on the result data Figure 5 and 6 of flow rate, head and current have been plotted as shown.

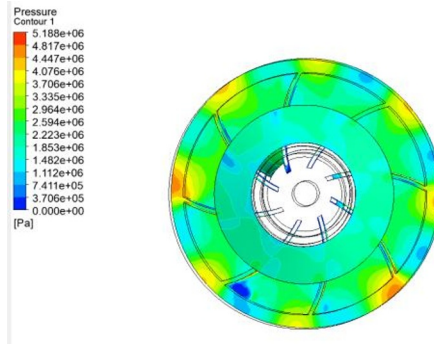


Fig.4. Pressure contours

Table 5. Results comparison

Parameter	Present study simulation data	Present study experimental data (Plant)	Comparison with Rajendran and Purushothaman [1]	Discussion
Flow Rate (m ³ /h)	Range: 195–280	Range: 195–280	Similar range considered (~200–300 m ³ /h)	Flow rate alignment is consistent across all data.
Suction Pressure (kg/cm ² g)	Simulated: 0.62–2.05 kg/cm ² g	Measured: 0.62–2.05 kg/cm ² g	Similar: ~0.65–2.00 kg/cm ² g	Suction pressure trends match well across all data sources.
Head (m)	715–736 (derived from contours and setup)	Measured: 715.87–736.37	Slightly higher: ~720–740 m	Head values are within range; minor variations are due to pump design factors.

Cavitation Indicators	Vapour volume fraction contour shows zones of cavitation initiation	Not explicitly provided (needs inspection)	Highlights cavitation zones at impeller blade tips	Simulation aligns with cavitation-prone zones described in research.
RPM	2980 (specified setup)	2980 (plant operation)	2950–3000 (research setup)	RPM consistency ensures comparable results.
Mass Flow Rate (kg/s)	89.1	89.1	~88.5–90 (derived from fluid properties)	Mass flow rate consistency validates model accuracy.
Cavitation Region	Near blade leading edge and low-pressure zones observed in vapour fraction	No data	Observed at blade leading edges (similar findings)	Matches research paper; cavitation zones validated in low-pressure regions.
Pressure Drop	Low-pressure regions: -2.8×10^5 to -3.1×10^5 Pa	Consistent with head losses: ~715–736 m	Low-pressure drop near blade exits	Matches trends; research pressure profiles validate simulation contours.

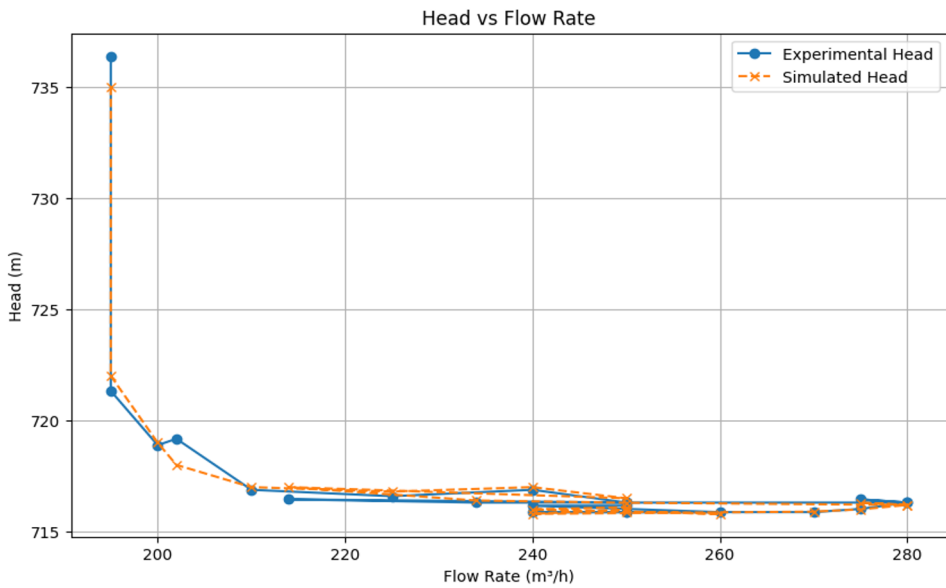


Fig.5. Graph between head and flow rate

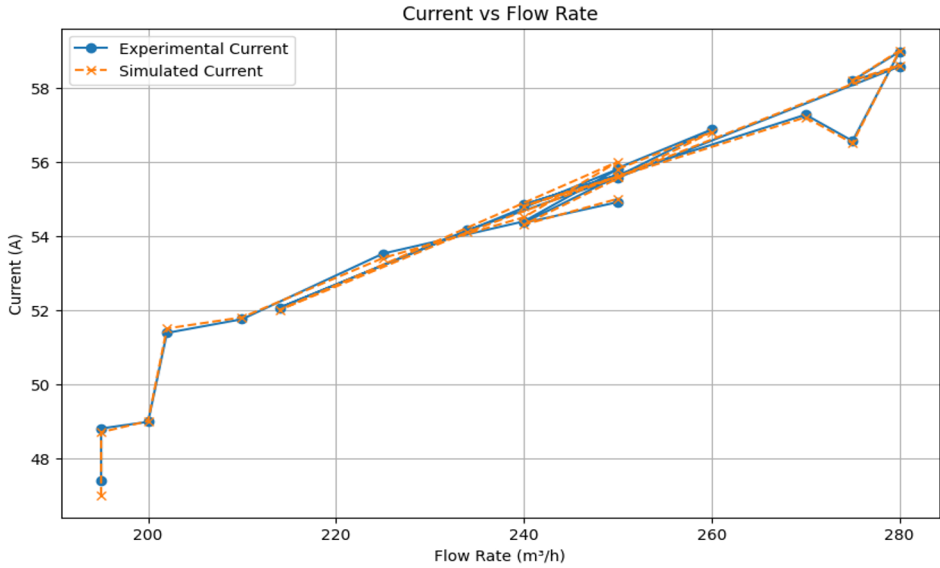


Fig.6. Graph between current and flow rate

Duplex stainless steel reduced surface roughness and improved cavitation resistance. Improved head stability and reduced power consumption compared to ASTM A216 GR WCB

5 Seal Failure Predictive Model Results- Correlation matrix

A correlation matrix shows the correlation between multiple variables. It's a way to visually represent the relationships between different features in your dataset. Each cell in the matrix represents the correlation between two variables represented in Figure 7.

Interpreting the Matrix:

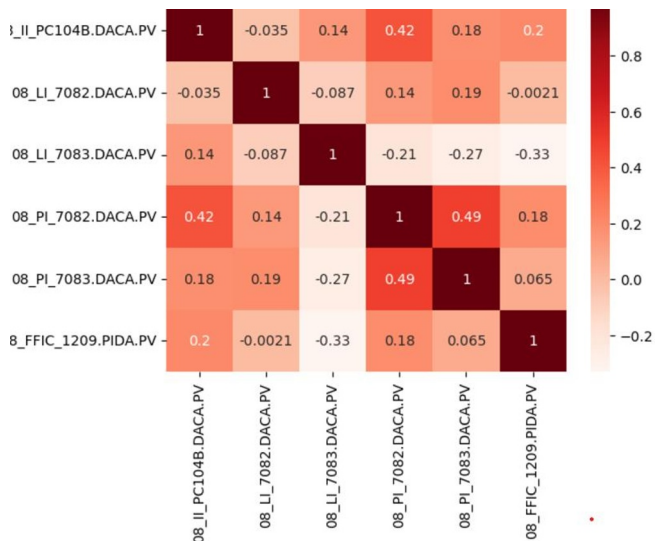


Fig.7. Correlation matrix

To interpret the correlation matrix, look for the following:

- Strong Positive Correlation: Values close to +1 (darker red in the heatmap) indicate a strong positive linear relationship. For example, if the correlation between "Armature Current" and "Seal Pressure DE" is high, it means that as armature current increases, seal pressure DE also tends to increase.
 - Strong Negative Correlation: Values close to -1 (lighter red or white in the heatmap) indicate a strong negative linear relationship. For example, if the correlation between "Seal Level DE" and "Discharge Rate" is strongly negative, it means that as seal level DE increases, the discharge rate tends to decrease.
 - Weak or No Correlation: Values close to 0 (light red or white) suggest a weak or no linear relationship between the variables.
1. Model Accuracy:
 - Achieved over 99% accuracy in predicting seal failures.
 - High recall ensured critical failure cases were detected.
 2. Operational Benefits:
 - Reduced unplanned maintenance events.
 - Real-time monitoring significantly improved response time to anomalies.

Conclusions

This research effectively addresses the reliability challenges of methanol pumps in the oil and petrochemical industries through a combination of material upgrades, operational optimizations, and advanced monitoring technologies. By transitioning to duplex stainless steel, the study significantly reduced corrosion and cavitation risks, enhancing the durability and lifespan of the pumps. ANSYS simulations provided critical insights into flow dynamics, enabling targeted design improvements and operational adjustments that resulted in more stable performance and reduced energy consumption. The integration of IoT-based sensors and a predictive maintenance model, utilizing machine learning algorithms, facilitated real-time monitoring and early detection of anomalies, thereby reducing unplanned maintenance events and extending maintenance intervals. These comprehensive efforts culminated in improved pump performance, increased operational efficiency, and a robust framework for addressing similar challenges in other industrial applications, contributing to long-term operational excellence and sustainability.

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