POLITEKNIK MALAYSIA
TUANKU SYED SIRAJUDDIN

TROUBLESHOOTING AND MAINTENANCE FOR MECHANICAL COMPONENTS

Understanding Centrifugal Pumps:
From Fundamentals to Industrial Applications



Mohd Zahri bin Jaafar
Muhamad Haziq bin Abd Manap
Mohd Hafidz bin Zakaria

First Edition
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POLITEKNIK TUANKU SYED SIRAJUDDIN
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PREFACE

Centrifugal pumps are the unsung heroes of modern industry. From circulating cooling water in massive power plants to transporting crude oil across continents and supplying clean drinking water to municipalities, these dynamic machines are the beating heart of countless industrial processes. Their reliable operation is not merely a matter of convenience; it is a critical requirement for production efficiency, environmental safety, and, in specialized fields like medical engineering, even human survival.

This book, "Centrifugal Pump: Quick Reference for Technician and Student," is designed as a practical, accessible, and comprehensive guide for those who operate, maintain, troubleshoot, and study these vital fluid-handling systems. Our primary goal is to bridge the gap between theoretical engineering principles and the harsh, practical realities of the workshop and the plant floor.

We have intentionally structured this book to be a quick reference. Chapter 1 establishes the foundational knowledge of pump types, principles, and components. Chapter 2 dives into performance curves, hydraulic calculations, and the critical concept of cavitation. Chapter 3 provides a hands-on approach to routine maintenance, dismantling, inspection, and precision alignment. Finally, Chapter 4 bridges theory and reality by analyzing nine real-world industrial case studies, followed by a comprehensive FAQ section addressing common operational queries.

Whether you are a seasoned maintenance technician seeking a quick troubleshooting guide on the night shift, or an engineering student striving to connect classroom theory with practical application, this book is crafted for you. We hope it serves as a valuable tool in your professional toolkit, helping you keep the pumps turning efficiently, safely, and reliably.

PTSS, Oktober 2026
Mohd Zahri bin Jaafar
Muhamad Haziq bin Abd Manap
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CHAPTER 1: FUNDAMENTALS OF INDUSTRIAL CENTRIFUGAL PUMPS

Introduction to Pumps

A pump is fundamentally a machine designed for the **purpose of transferring quantities of fluids and/or gases from one place to another**. These devices are essential components in a vast array of industrial processes and applications. They are critical to the daily operation of manufacturing plants, commercial buildings, and municipalities. Pumps range widely in size, from fractions of a horsepower to several thousand horsepower, catering to diverse needs.

Functions of Pumps in Industry

Pumps serve vital functions across numerous industries:

- **Transfer of Fluids and Gases**: They move liquids and gases from one location to another within a system.
- **Cooling and Lubrication Services**: Pumps are integral to cooling systems, where their failure can lead to equipment overheating and catastrophic damage, and in lubrication systems, where inadequate performance can destroy machinery.
- **Motive Force in Hydraulic Systems**: They provide the necessary power for hydraulic systems.
- **Water and Wastewater Management**: Municipalities extensively use pumps for water and wastewater transfer and treatment, as well as for land drainage.
- **Industrial Processes**: They are widely used in processes such as boiler feeding, oil production, irrigation, marine applications, and chemical processing.

🔎 **Did You Know?** Pumps account for approximately **27% of the electricity used by industrial systems** in the manufacturing sector.

Basic Pumping Principle

Pumps add energy to a fluid, but they do so in different ways based on their classification. The fundamental principle involves converting mechanical energy into fluid energy, which is commonly measured in terms of **head**. Head is typically expressed in feet or meters, representing the height of a fluid column with an equivalent amount of potential energy. This unit is convenient as it allows centrifugal pumps to be evaluated across various system fluids, as head remains constant for a given flow rate despite variations in fluid density and discharge pressure.

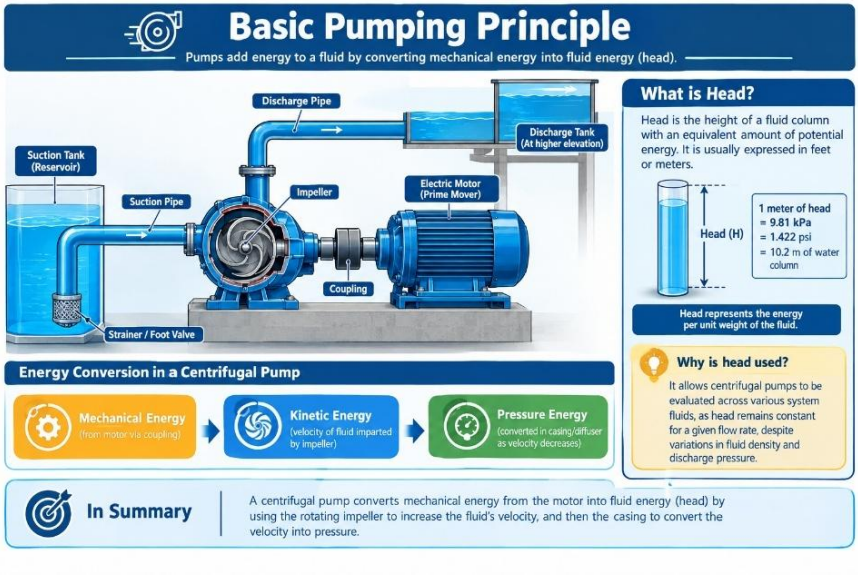


Figure 1: Basic Pumping Principle

Centrifugal Pump Operating Principle

A centrifugal pump fundamentally operates by using a **spinning impeller to add kinetic energy to a fluid**. As the fluid exits the impeller, it enters a **diffuser or volute**, which is a chamber designed to slow down the fluid. This deceleration converts the fluid's kinetic energy into potential energy, manifesting as an **increase in pressure**.

Centrifugal Force Analogy: Imagine swinging a half-filled bucket of water on a rope in a vertical plane. The centrifugal forces keep the water in the bucket, even when it's upside down, by pushing it against the bottom. If the bucket had holes, the water would be continuously pushed out, analogous to a pump's action. The faster the bucket spins, the greater the centrifugal force and the higher the pressure imparted to the liquid.

A centrifugal pump's **flow/pressure relationship** is described by a performance curve, which plots the flow rate against head (pressure). Understanding this relationship is crucial for proper pump sizing and efficient system design.

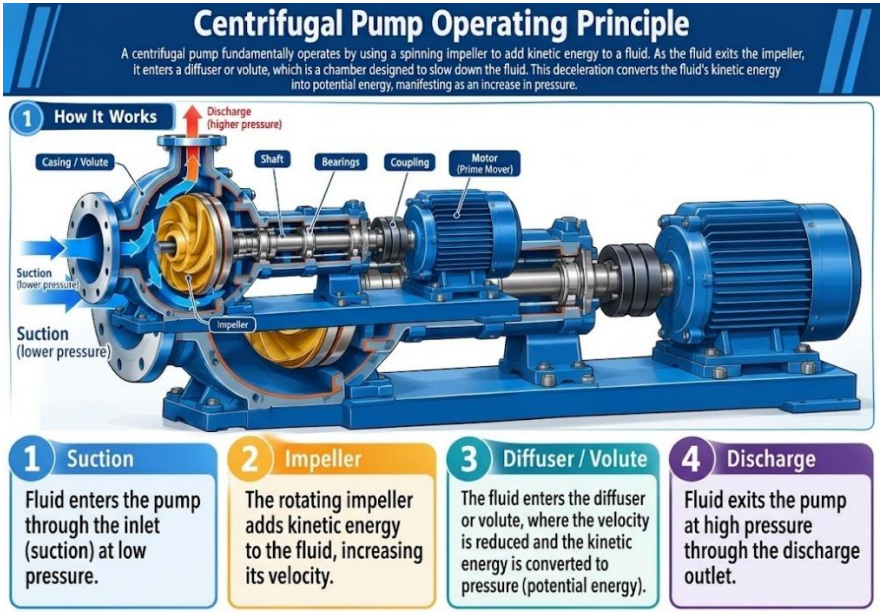


Figure 2: Centrifugal Pump Operating Principle

Energy Conversion in a Centrifugal Pump

The energy conversion in a centrifugal pump follows a two-stage process:

1. **Impeller Action**: The rotating impeller's vanes impart mechanical work to the fluid, forcing it into a circular movement. This action presses the fluid out of the impeller, resulting in increased pressure and velocity.

2. **Casing/Volute/Diffuser Action**: The pump casing, specifically the volute or diffuser, guides the fluid from the impeller. Its expanding cross-sectional area gradually reduces the fluid's velocity, converting the kinetic energy into static pressure. The fluid is then discharged from the pump at this increased static pressure.

Main Components of a Centrifugal Pump

- **Impeller**: The **rotating part** of a centrifugal pump. It consists of vanes attached to a hub, and its primary function is to **impart velocity to the fluid**, thereby increasing its kinetic energy. Impellers can be classified as closed (blades enclosed between two disks), semi-open (circular plate attached to one side of the blade), or open (blades only attached to a hub).
- **Casing**: The **stationary pressure boundary** of the pump that surrounds the impeller. Its primary function is to **collect the fluid discharged by the impeller** and **convert the fluid's velocity into static pressure** before it exits the pump.
- **Shaft**: The rotating component that **connects the impeller to the prime mover** (e.g., an electric motor). It transfers the mechanical power required to drive the impeller.
- **Bearings**: Components that **support the rotating shaft**, allowing it to rotate smoothly while minimizing friction and supporting axial and radial loads. Common types include rolling-element (ball or roller) and plain bearings.
- **Mechanical Seal**: A device used to **prevent fluid leakage** between the rotating shaft and the stationary casing, while also keeping contaminants out. Mechanical seals are generally more effective than packing for superior sealing but are also more complex to install and maintain.
- **Coupling**: A component that **connects the pump shaft to the motor shaft**, transmitting power and ensuring proper alignment between the two rotating elements.
- **Wear Ring**: A replaceable sacrificial component installed in the pump casing and/or on the impeller to **maintain a tight clearance** between rotating and stationary parts. Using wear rings significantly **reduces the cost of pump maintenance** by protecting the actual impeller or casing material from wear.

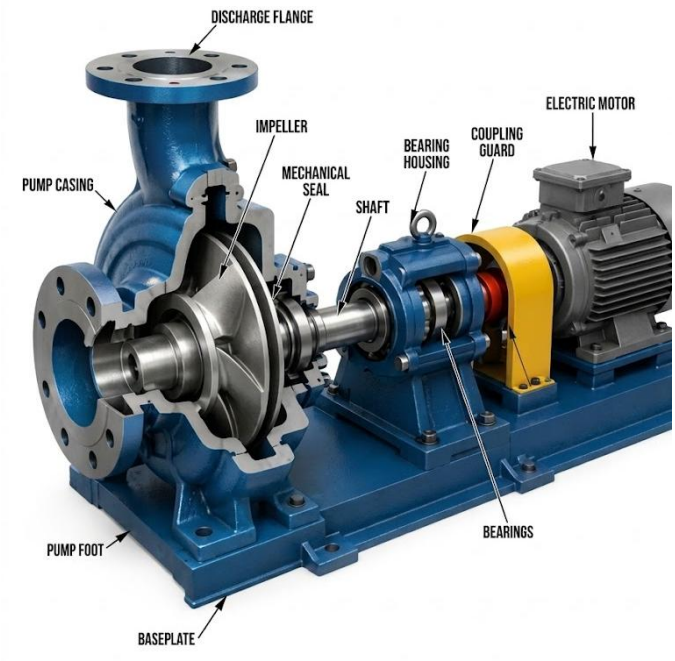


Figure 3: Main Components of a Centrifugal Pump

💡 **Engineering Tip** Proper **motor/pump alignment** is critical. Misalignment can cause excessive wear on bearings, seals, and couplings, leading to premature pump failure.

Classification of Pumps

Pumps are broadly classified into two main categories based on their operating principle:

- **Dynamic Pumps**: These pumps **add kinetic energy to a fluid using a spinning impeller and then convert this kinetic energy to pressure**. Dynamic pumps include:

- **Centrifugal Pumps**: Utilise centrifugal force generated by a rotating impeller to move fluid.
- **Axial Flow Pumps**: Impellers push the liquid in a direction parallel to the pump shaft.
- **Mixed Flow Pumps**: Combine elements of both centrifugal and axial flow, generating head through a combination of centrifugal force and vane action.
- **Liquid Ring Pumps**: Another type of rotodynamic pump that utilizes centrifugal force.

- **Positive Displacement Pumps**: These pumps **pressurize fluid by squeezing it directly with a collapsing volume action**. They deliver a fixed amount of fluid for each revolution or cycle.
    - **Reciprocating Pumps**: Such as piston, plunger, and diaphragm pumps, which use a back-and-forth motion.
    - **Rotary Pumps**: Such as screw, sliding vane, rotary lobe, gear, and circumferential piston pumps. Positive displacement pumps are generally used in **low-flow, high-head applications** and are more effective with **high-viscosity fluids**. They are also well-suited for applications requiring precise flow control due to their metered-flow nature.

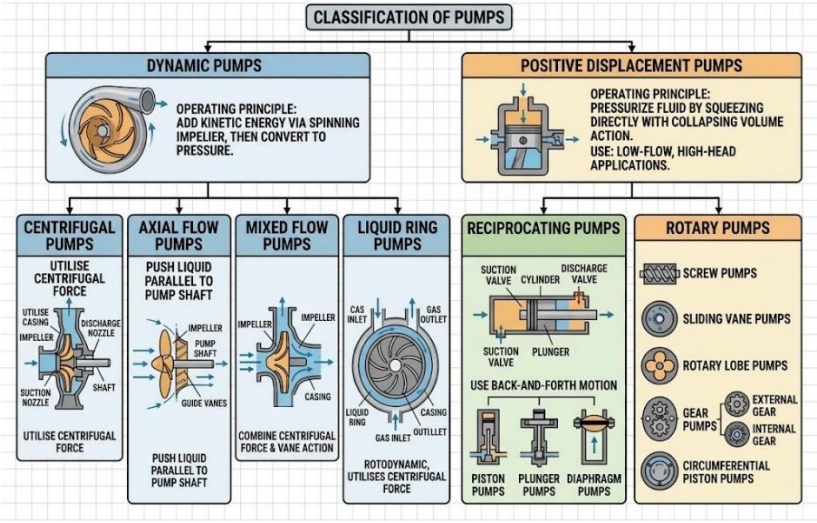


Figure 4: Classification of Pumps

Types of Centrifugal Pumps

Centrifugal pumps can be categorised in several ways:

- **Radial Flow Pumps**: The fluid flows predominantly radially outward from the impeller. Head is generated mainly by centrifugal force.
- **Mixed Flow Pumps**: Combine elements of both radial and axial flow. Head is generated by both centrifugal force and the lift of the impeller vanes on the fluid.
- **Axial Flow Pumps (Propeller Pumps)**: The impeller pushes the liquid in a direction parallel to the pump shaft. These impellers resemble propellers, and almost all the head is generated by vane action rather than centrifugal force. In mixed flow impellers, head contributions from both vane action and centrifugal force are comparable.

- **Single-Stage Pumps**: Contain only one impeller within the pump casing.
- **Multistage Pumps**: Incorporate **multiple impellers in a series** within the same casing to achieve higher heads than a single impeller can provide.
    - **Inline Multistage**: Impellers are arranged in line, with each impeller discharging into the suction of the next.
    - **Opposed Multistage**: Impellers are mounted back-to-back, balancing the axial thrust generated by opposing impellers.
    - **Double Suction**: Fluid enters the impeller from both sides simultaneously. These are used for greater flow rates and often have superior efficiencies, with hydraulic axial forces largely balanced due to symmetry.

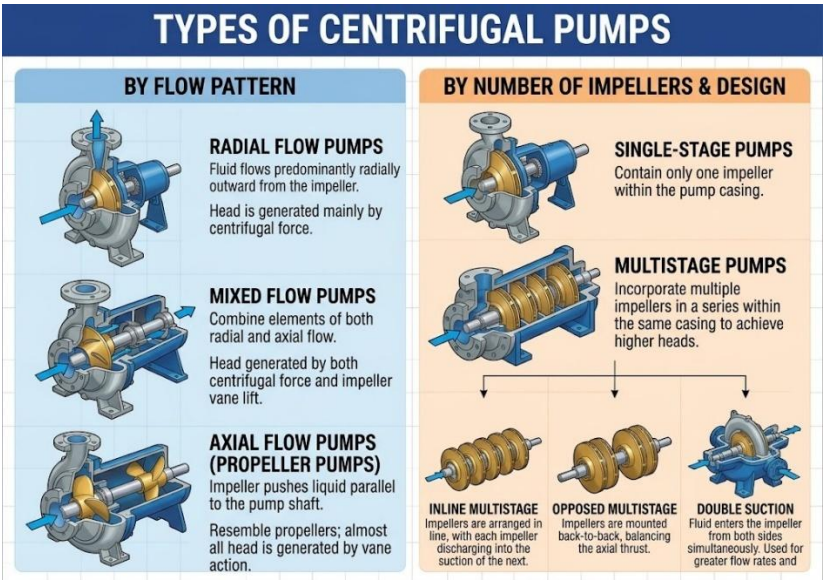


Figure 5: Types of Centrifugal Pumps

Advantages and Limitations of Centrifugal Pumps

Centrifugal pumps are widely used due to several advantages, but they also have limitations.

Advantages:

- **Simplicity and Cost-Effectiveness**: Generally simpler in design and less expensive to manufacture than positive displacement pumps.
- **Smooth Flow**: Provide smooth, non-pulsating fluid delivery.
- **Broad Operating Range**: Can operate under a wide range of conditions.
- **Flow Regulation**: Can regulate flow by throttling the discharge valve without damaging the pump.
- **Versatility**: Capable of handling a wide variety of fluids, including those with suspended solids.
- **Compactness**: Often more compact for a given flow rate than other pump types.
- **Low Maintenance**: Fewer moving parts lead to less wear and simpler maintenance routines.

Limitations:

- **Not Self-Priming**: Most centrifugal pumps are not self-priming and require their casings to be filled with liquid before starting to prevent gas binding.
- **Sensitive to Viscosity Changes**: Performance can degrade significantly when pumping highly viscous fluids.
- **Limited Head per Stage**: Each stage provides a limited head, requiring multistage configurations for high-pressure applications.
- **Cavitation Risk**: Susceptible to cavitation, especially with insufficient Net Positive Suction Head (NPSH), which can cause noise, vibration, and damage.

- **Efficiency Drop at Off-Design Conditions**: Efficiency drops considerably when operating away from the best efficiency point.
- **Internal Recirculation**: Operating at **low flow rates can cause internal recirculation**, leading to damaging vortices and accelerated wear. This can result in increased noise, vibrations, and sometimes, an unstable head-capacity curve.
- **Non-uniform Approach Flow**: An uneven velocity distribution at the inlet can lead to **flow separation at the inlet**, which can reduce efficiency and promote excessive vibrations.
- **Gas Binding**: A condition where the pump casing fills with gases or vapors, preventing the impeller from contacting enough fluid to function correctly.

 **Industrial Insight** Operating centrifugal pumps far from their Best Efficiency Point (BEP) significantly reduces efficiency and reliability, leading to increased energy consumption and maintenance costs.

Industrial Applications of Centrifugal Pumps

Centrifugal pumps are ubiquitous across industrial sectors due to their versatility and efficiency in handling various fluids. Some key applications include:

- **Water and Wastewater**: Pumping of potable water, sewage, and industrial wastewater in municipal and industrial treatment plants.
- **Oil and Gas**: Transferring crude oil, refined products, and natural gas liquids in pipelines, refineries, and offshore platforms.
- **Chemical Processing**: Moving corrosive, abrasive, or hazardous chemicals in various manufacturing processes.
- **Power Generation**: Circulating cooling water, boiler feed water, and condensate in thermal and nuclear power plants.

- **HVAC Systems**: Circulating chilled and hot water for heating, ventilation, and air conditioning in commercial and industrial buildings.
- **Agriculture**: Irrigation and drainage systems.
- **Food and Beverage**: Handling liquids like milk, juices, and various process water streams, often requiring hygienic designs.
- **Pharmaceutical Industry**: Employed in processes requiring hygienic and cleanable fluid transfer.
- **Mining**: Mine de-watering and dredge pumps for handling abrasive materials like gravel and waste.

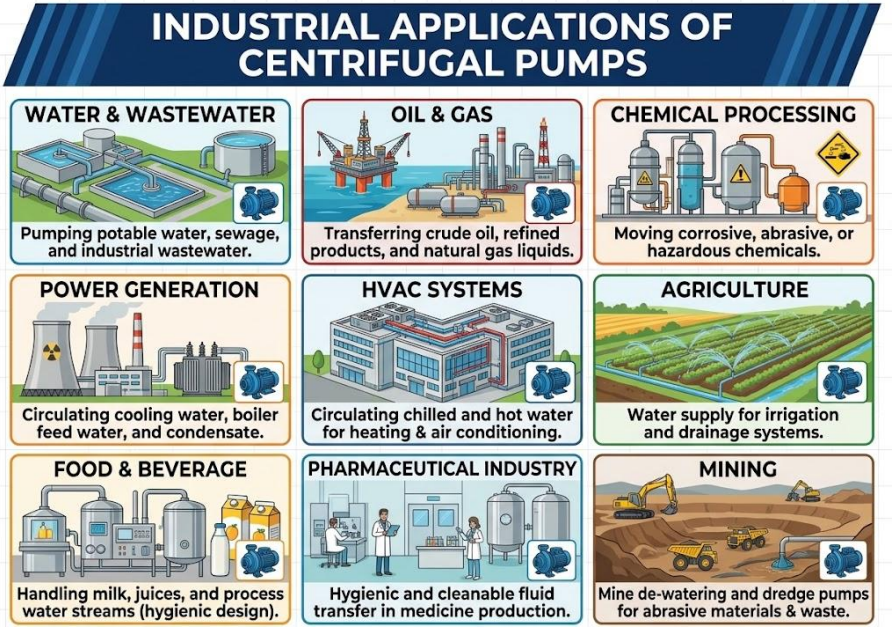


Figure 6: Industrial Applications of Centrifugal Pumps

CHAPTER 2 — PUMP TERMINOLOGY, PERFORMANCE AND CHARACTERISTICS

Introduction to Pump Performance

Pump performance defines the relationship between the volume of fluid transferred by a centrifugal pump and the pressure (head) generated, power consumed, and efficiency achieved under specific rotational speeds.

Unlike positive displacement pumps, which deliver a fixed volume per revolution regardless of backpressure, a centrifugal pump is a dynamic machine whose discharge flow rate varies inversely with system resistance.

Basic Pump Terminology

- Capacity / Flow Rate (Q): The useful volume of liquid discharged by the pump per unit of time, typically measured in m^3/h, L/s, or US Gallons Per Minute (GPM).
- Pressure (p): The force exerted by the fluid per unit area, measured in bar, kPa, or psi. While pressure depends directly on fluid specific gravity (SG), the head generated by a pump remains constant regardless of fluid density.
- Head (H): The height of a liquid column that corresponds to the specific energy imparted to the fluid by the pump. Head is commonly measured in metres (m) or feet (ft).
- Suction Head (Hs): The total energy head available at the suction nozzle of the pump, taking into account static suction height, suction tank pressure, and suction piping friction losses.
- Discharge Head (Hd): The total energy head present at the pump discharge nozzle, incorporating static discharge lift, surface pressure, and discharge line friction losses.
- Static Head (Hstat): The net vertical elevation difference between the liquid level of the suction supply source and the final discharge point.

- Friction Head (Hf): The equivalent head loss caused by fluid friction against pipe walls, valves, elbows, and fittings during flow.
- Total Dynamic Head (TDH or H): The total algebraic energy difference developed by the pump between its suction and discharge nozzles.

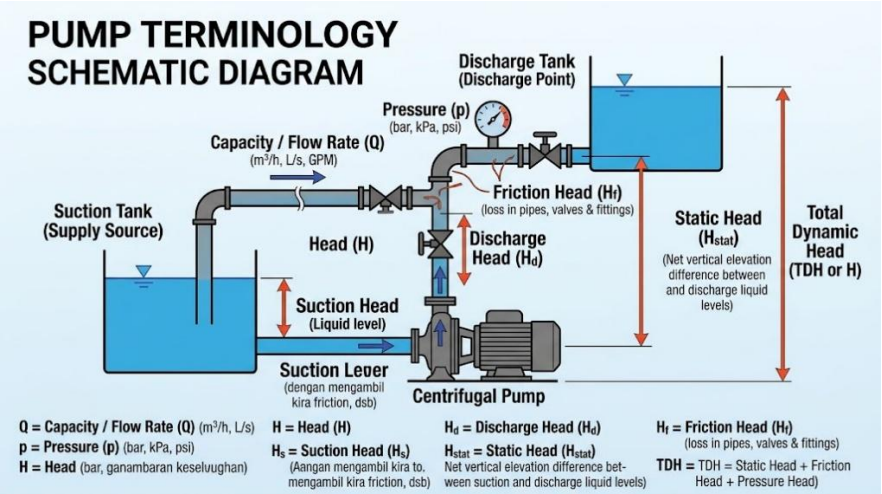


Figure 7: Pump Terminology

$TDH = Hd - Hs$

More completely:

$H = Hd - Hs$

$H = (pd - ps) / (\rho g) + (zd - zs) + (cd^2 - cs^2) / (2g)$

Where:

H = Total pump head (m)

Hd = Discharge head (m)

Hs = Suction head (m)

pd = Discharge pressure (Pa)

ps = Suction pressure (Pa)

ρ = Fluid density (kg/m³)
g = Gravitational acceleration (m/s²)
zd = Discharge elevation (m)
zs = Suction elevation (m)
cd = Discharge velocity (m/s)
cs = Suction velocity (m/s)

Pump Power

Energy transfer in centrifugal pumps involves three main power metrics:

1. Hydraulic (Water) Power (Pu or Pwhp)

   Hydraulic power is the actual useful power imparted directly to the fluid.

   For SI units:
   Pu = ρ × g × Q × H

   Where:
   Pu = Hydraulic power (W)
   ρ = Fluid density (kg/m³)
   g = Gravitational acceleration (m/s²)
   Q = Flow rate (m³/s)
   H = Pump head (m)
   If Q is given in m³/h and the required answer is in kW:
   Pu (kW) = (ρ × g × Q × H) / 3,600,000

   For clean water, where ρ ≈ 1000 kg/m³:
   Pu (kW) = (9.81 × Q × H) / 3600

   For US customary units:
   Pwhp = [Q (GPM) × H (ft) × SG] / 3960

Where:
Pwhp = Hydraulic power (hp)
Q = Flow rate (GPM)
H = Pump head (ft)
SG = Specific gravity of the liquid

2. Brake Horsepower / Shaft Power (Pbhp or P)

   Brake horsepower is the total mechanical power delivered by the driver to the pump shaft.

   Pbhp = Phydraulic / ηpump

   Where:
   Pbhp = Brake horsepower or shaft power
   Phydraulic = Hydraulic power
   ηpump = Pump efficiency
   If power is required in kW:
   Pshaft = Pw / ηpump

3. Driver Electrical Power (Pelec)

   Driver electrical power is the total electrical power drawn from the electrical supply by the motor.

   Pelec = Pshaft / ηmotor

   Therefore:
   Pelec = Pw / (ηpump × ηmotor)

   Where:
   Pelec = Electrical input power
   Pshaft = Pump shaft power

ηpump = Pump efficiency
ηmotor = Motor efficiency

Pump Efficiency

Overall pump efficiency (η) measures how effectively mechanical shaft input is converted into hydraulic fluid power.

The overall pump efficiency is composed of three internal efficiency components:
$\eta = \eta h \times \eta m \times \eta v$

Where:
η = Overall pump efficiency
ηh = Hydraulic efficiency
ηm = Mechanical efficiency
ηv = Volumetric efficiency

• Hydraulic Efficiency (ηh): Accounts for fluid friction losses along impeller vanes and casing channels, as well as shock and recirculation losses.

• Mechanical Efficiency (ηm): Accounts for mechanical friction losses in bearings, mechanical seals, and wear rings.

• Volumetric Efficiency (ηv): Accounts for internal fluid leakage recirculating from the high-pressure discharge back to the low-pressure suction eye through wear ring clearances.

The volumetric efficiency is:
$\eta v = Q / (Q + QL)$

Where:
Q = Useful pump flow rate
QL = Internal leakage flow rate

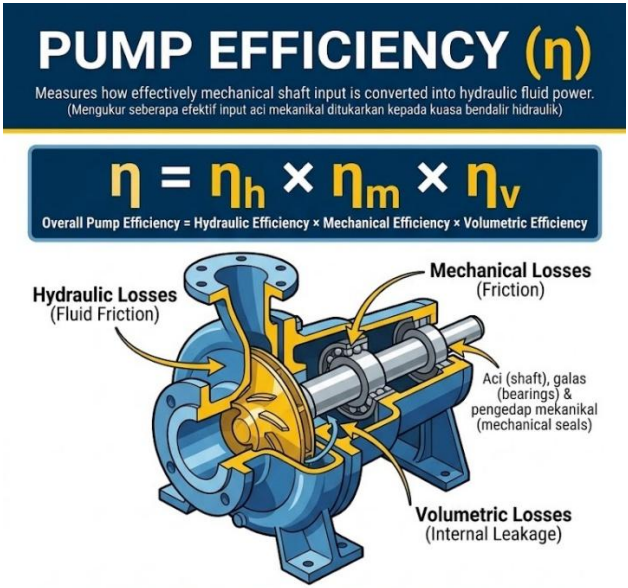


Figure 8: Pump Efficiency

Basic Pump Formula

The following basic formulae are used to calculate pump performance and power requirements.

1. Total Dynamic Head
   TDH = Hstat + Hf

   Where:
   TDH = Total Dynamic Head
   Hstat = Static head
   Hf = Friction head

   Alternatively:
   TDH = Hd – Hs

2. Hydraulic Power

   For general SI units:
   $Pw = (\rho \times g \times Q \times H) / 3{,}600{,}000$
   Where Q is in m^3/h and H is in metres.

   For clean water:
   $Pw = (9.81 \times Q \times H) / 3600$

   Where:
   Pw = Hydraulic power (kW)
   Q = Flow rate (m^3/h)
   H = Pump head (m)

3. Shaft Power / Brake Horsepower

   $Pshaft = Pw / \eta pump$

   Where:
   Pshaft = Shaft power (kW)
   Pw = Hydraulic power (kW)
   $\eta pump$ = Pump efficiency in decimal form

4. Pump Efficiency

   $\eta pump = (Pw / Pshaft) \times 100\%$

   For example, if $\eta pump = 0.72$:
   $\eta pump = 0.72 \times 100\%$
   $\eta pump = 72\%$

5. Brake Horsepower in US Customary Units

BHP (hp) = [Q (GPM) × H (ft) × SG] / [3960 × ηpump]

Where:
Q = Flow rate (GPM)
H = Pump head (ft)
SG = Specific gravity
ηpump = Pump efficiency in decimal form

Pump Arrangement

1. Single Pump Operation

A single pump operates individually against the system head curve. The operating point is established at the exact intersection of the pump H-Q curve and the system curve.

Operating Point:
Hpump(Q) = Hsystem(Q)

2. Pumps in Series

When pumps are connected in series, the same volumetric flow rate passes sequentially through each pump. The heads developed by each pump are added together.

Flow rate:
Qtotal = Q1 = Q2 = ... = Qn

Total head:
Htotal = H1 + H2 + ... + Hn

For two identical pumps:
$Q_{total} = Q_1 = Q_2$
$H_{total} = H_1 + H_2$

Therefore, series operation is mainly used when a higher total head is required.

3. Pumps in Parallel

When pumps operate in parallel, all pumps share common suction and discharge headers.

Each pump experiences approximately the same differential head, while the individual flow rates are added together.

Total head:
$H_{total} = H_1 = H_2 = \ldots = H_n$

Total flow:
$Q_{total} = Q_1 + Q_2 + \ldots + Q_n$

For two identical pumps:
$H_{total} = H_1 = H_2$
$Q_{total} = Q_1 + Q_2$

Therefore, parallel operation is mainly used when a higher total flow capacity is required.

4. Summary of Pump Arrangement:

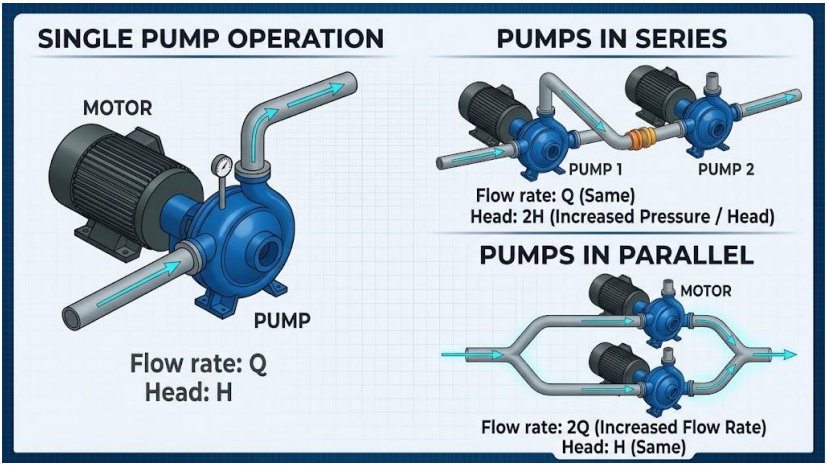


Figure 9: Summary of Pump Arrangement

5. Applications of Series and Parallel Pumps

Series Applications:

- Long-distance pipelines
- High-pressure boiler feedwater booster systems
- Deep-mine dewatering

Parallel Applications:

- Municipal water distribution
- Cooling tower circulation
- Plant processes with wide variations in daily liquid demand

Net Positive Suction Head (NPSH) And Cavitation

1. What is NPSH?

   Net Positive Suction Head (NPSH) is the measure of absolute fluid energy/pressure available or required at the suction nozzle of a centrifugal pump, above the liquid's vapor pressure at the pumping temperature.

   • It ensures that liquid entering the impeller eye remains in a stable liquid state without flashing into vapor.

2. Understanding Cavitation

   Cavitation occurs when the local static pressure inside the suction eye of the impeller falls below the vapor pressure of the liquid being pumped.
   Condition:
   $P < Pvp$

   Where:
   P = Local absolute static pressure
   Pvp = Vapor pressure of the liquid at the pumping temperature

   The liquid partially vaporizes to form small vapor bubbles. As these bubbles travel downstream into regions of higher pressure, they collapse (implode) violently against the impeller vanes. The consequences of cavitation are:

   - Severe noise, often described as a crackling sound similar to pumping gravel, accompanied by high vibration.
   - Mechanical damage, pitting, and material erosion on impeller blades.
   - Sudden drop in developed head, flow rate, and pump efficiency.

3. NPSHA vs. NPSHR

3.1 NPSHA — Net Positive Suction Head Available

NPSHA is the actual energy head provided by the piping system and suction tank setup to the pump inlet. It is determined by the system geometry, fluid properties, atmospheric or vessel pressure, and piping friction losses. For an open suction tank, the basic equation is:

$$NPSHA = (Pa / \rho g) \pm hs - hfs - (Pvp / \rho g)$$

Where:
NPSHA = Net Positive Suction Head Available (m)
Pa = Absolute pressure on the surface of the liquid (Pa)
ρ = Fluid density (kg/m^3)
g = Gravitational acceleration (m/s^2)
hs = Static suction head (m)
hfs = Total friction and entrance losses in the suction piping (m)
Pvp = Vapor pressure of the liquid at the pumping temperature (Pa)

Interpretation of hs:

- Positive hs = Flooded suction, where the liquid level is above the pump suction.
- Negative hs = Suction lift, where the pump is located above the liquid level.

Important:

All pressure terms in the NPSHA equation must be expressed as absolute pressure.

3.2 NPSHR — Net Positive Suction Head Required

NPSHR is the minimum energy head required at the pump suction nozzle to prevent excessive performance degradation caused by cavitation. NPSHR is normally determined experimentally by pump manufacturers during factory performance testing. A commonly used definition is NPSH3. NPSH3 is the NPSH condition at which the pump's total developed head has dropped by approximately 3% due to cavitation. The NPSHR value varies with pump design, impeller geometry, rotational speed, and flow rate.

3.3 The Golden Rule for Cavitation-Free Operation

To maintain reliable and cavitation-free operation across the required process flow range, the system NPSHA should exceed the pump's NPSHR.

Basic condition:
NPSHA > NPSHR

Where:
NPSHA = Net Positive Suction Head Available
NPSHR = Net Positive Suction Head Required

- Safety Margin:

A suitable engineering safety margin should be maintained between NPSHA and NPSHR.

For example:

NPSHA ≥ NPSHR + Safety Margin

The actual safety margin should be selected according to the pump manufacturer's recommendations, operating conditions, fluid properties, and applicable engineering standards.

3.4 Engineering Methods to Increase NPSHA and Eliminate Cavitation

If a pump is cavitating in the field, several design or operational changes can be made to increase NPSHA or reduce the pump's NPSHR requirement.

- Raise Suction Liquid Level / Elevation (hs)

Raise the supply vessel or lower the pump elevation to increase the static suction head.
Effect:
Higher suction liquid level → Higher hs → Higher NPSHA → Lower risk of cavitation

- Reduce Suction Pipe Friction Losses (hfs)

Increase suction pipe diameter, shorten the piping length, and eliminate unnecessary elbows, valves, fittings, and other restrictions.
Effect:
Lower suction friction loss → Lower hfs → Higher NPSHA

- Lower Fluid Temperature / Vapor Pressure (Pvp)

Cooling the liquid decreases its vapor pressure.
Effect:
Lower Pvp → Higher NPSHA → Lower risk of cavitation

- Pressurize the Suction Tank (Pa)

Increase the gas-space pressure in an enclosed suction vessel.
Effect:
Higher Pa → Higher NPSHA

3.5 Reduce Flow Rate or Pump Speed

Reducing the flow rate or pump rotational speed can reduce the NPSHR requirement, depending on the pump characteristics.

For example, reducing pump RPM using a Variable Speed Drive (VSD) can move the pump to a lower flow condition and may reduce NPSHR.

However, throttling should be applied carefully because changing the operating point also changes the pump flow, head, efficiency, and system conditions.

Effect:

Lower flow / lower speed → Generally lower NPSHR → Lower risk of cavitation

Pump Characteristic Curves

Industrial manufacturers publish four primary characteristic curves plotted against flow rate (Q) at a constant rotational speed.

1. Head vs Flow Rate (H-Q)

   The H-Q curve shows how pump head generally decreases as flow rate increases.

2. Efficiency vs Flow Rate (η-Q)

   The η-Q curve shows how pump efficiency changes with flow rate. The curve normally reaches its maximum at the Best Efficiency Point (BEP).

3. Power vs Flow Rate (P-Q)

   The P-Q curve shows the power consumed by the pump over different operating flow rates.

4. NPSHR vs Flow Rate (NPSHR-Q)

   The NPSHR-Q curve shows the Net Positive Suction Head Required by the pump at different flow rates.

   NPSHR represents the minimum suction head requirement associated with avoiding unacceptable cavitation effects.

Pump Curves for Series and Parallel Operation

Series Curve Construction:

At every given flow rate (Q), add the heads developed by the individual pumps vertically.

Htotal = H1 + H2

Parallel Curve Construction:

At every given head (H), add the flow rates of the individual pumps horizontally.

Qtotal = Q1 + Q2

For two identical pumps:

- Series:

Qtotal = Qsingle
Htotal = 2Hsingle

- Parallel:

Htotal = Hsingle
Qtotal = 2Qsingle

Important:

The equations above describe the theoretical combination of pump curves. The actual operating flow must still be determined from the intersection between the combined pump curve and the system curve.

System Curve and Operating Point

A System Head Curve represents the total head required by the piping network at any given flow rate.

For a simplified system:
$H_{system} = H_{static} + kQ^2$

Where:
H_{system} = Total system head
H_{static} = Static head
k = System resistance coefficient
Q = Flow rate

The actual operating duty point is the exact intersection where:
$H_{pump}(Q) = H_{system}(Q)$

At this point, the head produced by the pump is equal to the head required by the system.

Best Efficiency Point (BEP)

The Best Efficiency Point (BEP) is the operating capacity where the pump converts shaft power to hydraulic energy with maximum efficiency.

At or near BEP:

1. Fluid incidence conditions are closer to the design condition of the impeller, reducing flow separation and hydraulic losses.

2. Radial thrust loads on the pump shaft and bearings are generally lower, helping to improve mechanical seal and bearing operating life.

   Operating a pump significantly away from BEP can increase vibration, recirculation, hydraulic losses, and mechanical loading.

Pump Affinity Laws

The performance of geometrically similar centrifugal pumps at different speeds (N) or impeller diameters (D) can be estimated using the Pump Affinity Laws.

A. Effect of Pump Speed

For a change in pump speed from N1 to N2 while the impeller diameter remains constant:

Flow rate:

$$Q2 / Q1 = N2 / N1$$

Therefore:

$$Q2 = Q1 \times (N2 / N1)$$

Head:

$$H2 / H1 = (N2 / N1)^2$$

Therefore:

$$H2 = H1 \times (N2 / N1)^2$$

Power:

$$P2 / P1 = (N2 / N1)^3$$

Therefore:

$$P2 = P1 \times (N2 / N1)^3$$

Summary:
$Q \propto N$
$H \propto N^2$
$P \propto N^3$

This means that a relatively small increase in pump speed can produce a much larger increase in power requirement.

B. Effect of Impeller Diameter

For a change in impeller diameter from D1 to D2 while the rotational speed remains constant:

Flow rate:
$Q2 / Q1 = D2 / D1$

Therefore:
$Q2 = Q1 \times (D2 / D1)$

Head:
$H2 / H1 = (D2 / D1)^2$

Therefore:
$H2 = H1 \times (D2 / D1)^2$

Power:
$P2 / P1 = (D2 / D1)^3$

Therefore:
$P2 = P1 \times (D2 / D1)^3$

Summary:

$Q \propto D$

$H \propto D^2$

$P \propto D^3$

Note:

The affinity laws are approximations and are most appropriate for geometrically similar operating conditions. For actual impeller trimming, the manufacturer's performance curves should be used whenever available.

WORKED EXAMPLE 1: Calculation of TDH, Hydraulic Power and Shaft Power

Problem:
A centrifugal pump is used to transfer clean water from a lower tank to an upper tank.

Given:
Static Head, Hstat = 18 m
Friction Head, Hf = 6 m
Target flow rate, Q = 90 m^3/h
Pump efficiency, $\eta pump$ = 72% = 0.72
Gravitational acceleration, g = 9.81 m/s^2
Water density, ρ = 1000 kg/m^3

Calculate:
a) Total Dynamic Head (TDH)
b) Hydraulic Power (Pw) in kW
c) Shaft Power / Brake Horsepower (BHP) in kW

Solution:
a) Calculate Total Dynamic Head
TDH = Hstat + Hf
TDH = 18 + 6
TDH = 24 m

Therefore:
TDH = 24 m

b) Calculate Hydraulic Power

For clean water:
$Pw = (9.81 \times Q \times H) / 3600$
Substitute:
$Pw = (9.81 \times 90 \times 24) / 3600$
$Pw = 21{,}189.6 / 3600$
$Pw = 5.89$ kW

Therefore:
$Pw \approx 5.89$ kW

c) Calculate Shaft Power / BHP
$Pshaft = Pw / \eta pump$
$Pshaft = 5.89 / 0.72$
$Pshaft = 8.18$ kW

Therefore:
$Pshaft \approx 8.18$ kW

Final Answers:
a) TDH = 24 m
b) Hydraulic Power = 5.89 kW
c) Shaft Power = 8.18 kW

WORKED EXAMPLE 2: Pump Affinity Laws — Effect of Speed Change

Problem:

A centrifugal pump operates at a speed of:
N1 = 1450 RPM

At this speed, the pump delivers:
Q1 = 60 m^3/h
H1 = 25 m
P1 = 5.5 kW

If the pump speed is increased to:
N2 = 1740 RPM

using a Variable Speed Drive (VSD), calculate:
a) New flow rate (Q2)
b) New head (H2)
c) New power consumption (P2)

Solution:

First, calculate the speed ratio:
N2 / N1 = 1740 / 1450
N2 / N1 = 1.20
a) New Flow Rate

Using:
Q2 / Q1 = N2 / N1

Therefore:
Q2 = Q1 × (N2 / N1)

$Q2 = 60 \times 1.20$
$Q2 = 72\ m^3/h$
Therefore:
$Q2 = 72\ m^3/h$

b) New Head

Using:
$H2 / H1 = (N2 / N1)^2$

Therefore:
$H2 = H1 \times (N2 / N1)^2$
$H2 = 25 \times (1.20)^2$
$H2 = 25 \times 1.44$
$H2 = 36\ m$

Therefore:
$H2 = 36\ m$

c) New Power

Using:
$P2 / P1 = (N2 / N1)^3$

Therefore:
$P2 = P1 \times (N2 / N1)^3$
$P2 = 5.5 \times (1.20)^3$
$P2 = 5.5 \times 1.728$
$P2 = 9.50\ kW$

Therefore:
$P2 \approx 9.50\ kW$

Final Answers:
a) Q2 = 72 m^3/h
b) H2 = 36 m
c) P2 = 9.50 kW

Engineering Observation:
Increasing pump speed from 1450 RPM to 1740 RPM represents a 20% increase in speed.

However:
Flow increases by approximately 20%.
Head increases by approximately 44%.
Power increases by approximately 73%.
This demonstrates why pump speed changes must be carefully evaluated before implementation.

WORKED EXAMPLE 3: Pump Affinity Laws — Impeller Trimming

Problem:

A centrifugal pump has an original impeller diameter of:
$D1 = 200$ mm

At constant rotational speed, the pump delivers:
$Q1 = 80\ m^3/h$
$H1 = 30$ m

The engineer wants to reduce the pump head to:
$H2 = 24.3$ m

by trimming the impeller diameter.
Calculate:

a) New impeller diameter (D2)
b) New flow rate (Q2)

Solution:

a) Calculate the New Impeller Diameter

Using:
$H2 / H1 = (D2 / D1)^2$

Substitute:
$24.3 / 30 = (D2 / 200)^2$
$0.81 = (D2 / 200)^2$

Taking the square root:
$\sqrt{0.81} = D2 / 200$
$0.90 = D2 / 200$
Therefore:
$D2 = 200 \times 0.90$
$D2 = 180$ mm

Therefore:
$D2 = 180$ mm

b) Calculate the New Flow Rate

Using:
$Q2 / Q1 = D2 / D1$

Therefore:
$Q2 = Q1 \times (D2 / D1)$
$Q2 = 80 \times (180 / 200)$
$Q2 = 80 \times 0.90$
$Q2 = 72$ m³/h

Therefore:
$Q2 = 72$ m³/h

Final Answers:
a) New impeller diameter, $D2 = 180$ mm
b) New flow rate, $Q2 = 72$ m³/h

Engineering Note:
For actual impeller trimming, the affinity-law calculation should be treated as an estimate. The manufacturer's actual pump performance curves should be consulted before selecting the final trimmed diameter.

Question:
Why can't two identical pumps installed in parallel normally deliver exactly twice the flow rate in a friction-dominated piping system?

Engineering Answer:
When two pumps operate in parallel, the combined flow rate through the common piping system increases.

Pipe friction losses increase approximately with the square of flow rate:
$Hf \propto Q^2$

Therefore, as the total flow increases, the system head requirement increases rapidly.

The system curve becomes steeper, and the new operating point is determined by the intersection of the combined pump curve and the system curve.

As a result, the actual increase in flow is normally less than 100%.
Important:

The exact increase in flow cannot be assumed to be a fixed percentage such as 20–35%. It depends on the individual pump characteristic curve and the system resistance curve.

Step 1 — Locate the Required Flow Rate (Q)

Find the required process flow rate on the horizontal x-axis.

Step 2 — Read the Total Head (H)

Move vertically from the required flow rate until the line intersects the selected pump H-Q curve or impeller diameter curve.
Then read the corresponding head on the vertical y-axis.

Step 3 — Verify Pump Efficiency (η)

Check the efficiency curve at the operating point.
Determine whether the pump is operating reasonably close to its Best Efficiency Point (BEP).

Step 4 — Determine Power Requirement (P)

Check the P-Q curve to determine the required shaft power or brake horsepower.
The motor driver must be appropriately sized so that it does not become overloaded under the expected operating conditions.

Step 5 — Check NPSHR

Check the NPSHR curve at the required flow rate.
Compare the pump NPSHR with the available NPSHA from the system.
Basic condition:
NPSHA > NPSHR

A suitable engineering margin should be provided according to the pump manufacturer's recommendations and the application requirements.

CHAPTER 3 — PUMP MAINTENANCE, TROUBLESHOOTING AND WORKSHOP PRACTICE

Introduction to Pump Maintenance

Centrifugal pump maintenance aims to keep pumping machinery operating at peak efficiency, prevent unscheduled production downtime, and maximize the operational service life of all mechanical components. Effective maintenance significantly reduces total life-cycle costs and ensures plant operational safety. A key performance metric for pump operational reliability is **Mean Time Between Failure (MTBF)**.

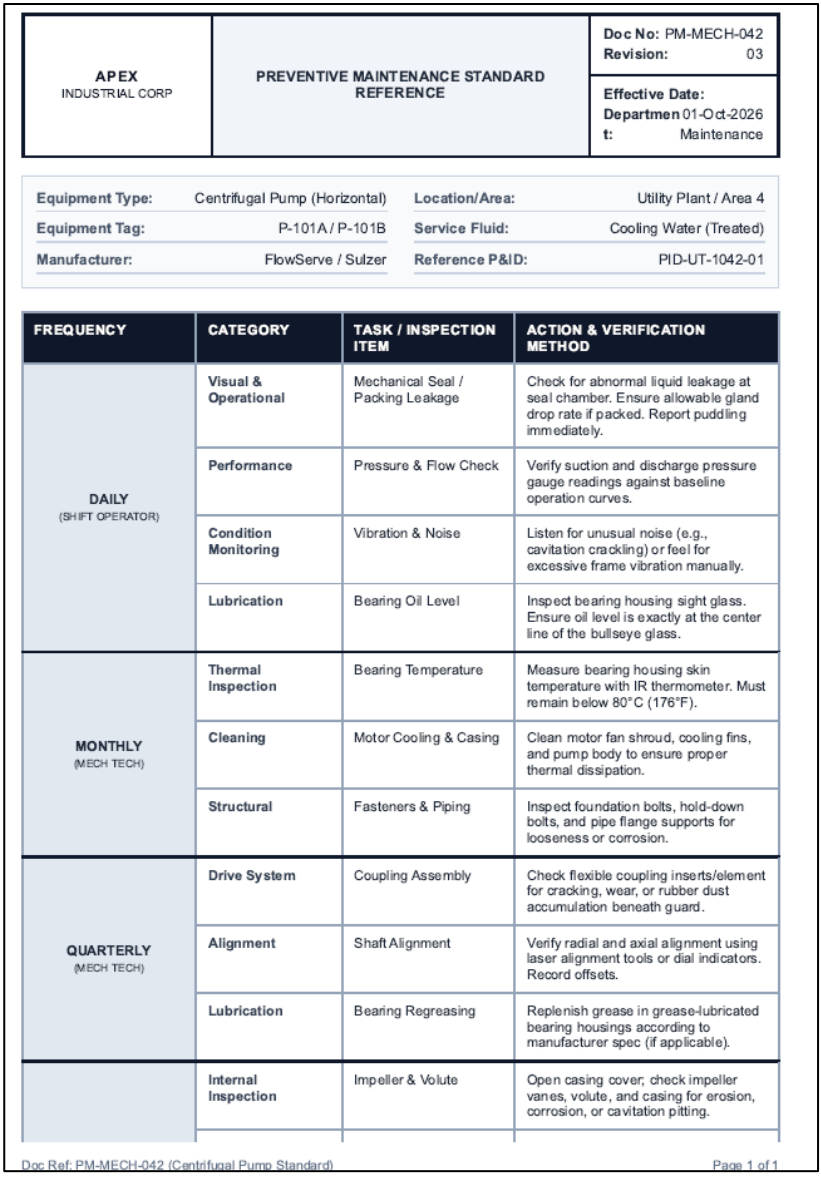
Types of Maintenance

1. **Preventive Maintenance (PM):** Scheduled, time-based maintenance tasks (such as periodic re-greasing, oil changes, gland packing adjustments, and belt tensioning) designed to prevent equipment degradation before failure occurs.

2. **Predictive Maintenance (PdM):** Condition-monitoring techniques (such as vibration analysis, infrared thermography, and oil sample analysis) used to detect early signs of mechanical degradation, allowing repairs to be planned before physical failure occurs.

3. **Corrective Maintenance (CM):** Unscheduled repair or replacement tasks performed after a pump failure or significant performance drop has already occurred.

4. **Condition-Based Maintenance (CBM):** Maintenance performed based on real-time operational parameters (such as elevated bearing temperatures or increased seal leakage rates) rather than strict calendar schedules.



APEX INDUSTRIAL CORP	PREVENTIVE MAINTENANCE STANDARD REFERENCE	Doc No: PM-MECH-042 Revision: 03 Effective Date: 01-Oct-2026 Department: Maintenance

Equipment Type:	Centrifugal Pump (Horizontal)	**Location/Area:**	Utility Plant / Area 4
Equipment Tag:	P-101A / P-101B	**Service Fluid:**	Cooling Water (Treated)
Manufacturer:	FlowServe / Sulzer	**Reference P&ID:**	PID-UT-1042-01

FREQUENCY	CATEGORY	TASK / INSPECTION ITEM	ACTION & VERIFICATION METHOD
DAILY (SHIFT OPERATOR)	**Visual & Operational**	Mechanical Seal / Packing Leakage	Check for abnormal liquid leakage at seal chamber. Ensure allowable gland drop rate if packed. Report puddling immediately.
	Performance	Pressure & Flow Check	Verify suction and discharge pressure gauge readings against baseline operation curves.
	Condition Monitoring	Vibration & Noise	Listen for unusual noise (e.g., cavitation crackling) or feel for excessive frame vibration manually.
	Lubrication	Bearing Oil Level	Inspect bearing housing sight glass. Ensure oil level is exactly at the center line of the bullseye glass.
MONTHLY (MECH TECH)	**Thermal Inspection**	Bearing Temperature	Measure bearing housing skin temperature with IR thermometer. Must remain below 80°C (176°F).
	Cleaning	Motor Cooling & Casing	Clean motor fan shroud, cooling fins, and pump body to ensure proper thermal dissipation.
	Structural	Fasteners & Piping	Inspect foundation bolts, hold-down bolts, and pipe flange supports for looseness or corrosion.
QUARTERLY (MECH TECH)	**Drive System**	Coupling Assembly	Check flexible coupling inserts/element for cracking, wear, or rubber dust accumulation beneath guard.
	Alignment	Shaft Alignment	Verify radial and axial alignment using laser alignment tools or dial indicators. Record offsets.
	Lubrication	Bearing Regreasing	Replenish grease in grease-lubricated bearing housings according to manufacturer spec (if applicable).
	Internal Inspection	Impeller & Volute	Open casing cover; check impeller vanes, volute, and casing for erosion, corrosion, or cavitation pitting.

Doc Ref: PM-MECH-042 (Centrifugal Pump Standard) Page 1 of 1

Figure 10: Example of Preventive Maintenance Reference

NORTHERN REFINERY ARAU PLANT FACILITY	STANDARD OPERATING PROCEDURE PREDICTIVE MAINTENANCE (PDM)	DOC #: SOP-PDM-901 REV #: 002 DATE : 23-SEP-2026 CLASS : RESTRICTED

1.0 EQUIPMENT IDENTIFICATION

EQUIPMENT TYPE	Horizontal Centrifugal Pump	**ASSET TAG (KKS)**	10-PU-4401 A/B
CRITICALITY	VITAL (Production Bottleneck)	**RATED SPEED**	2950 RPM (50 Hz)
MANUFACTURER	Ebara / KSB	**FLUID MEDIUM**	Hydrocarbon Condensate

2.0 DIAGNOSTIC PARAMETERS & ACTION LIMITS

TECHNOLOGY	TARGET COMPONENT / PARAMETER	THRESHOLD LIMIT VALUE (TLV)	INTERVAL
VIBRATION ANALYSIS	**Bearing Housing (DE & NDE)** ISO 10816-3 Standard	**Normal:** < 2.8 mm/s RMS **ALERT** > 4.5 mm/s RMS (Analyze FFT spectrum) **ALARM** > 7.1 mm/s RMS (Trip equipment)	**30 DAYS**
INFRARED THERMOGRAPHY	**Motor Stator & Pump Bearings**	**Normal:** Baseline (Ambient + 25°C max) **ALERT** > 70°C Absolute or ΔT > 15°C between ends **ALARM** > 90°C Absolute (Risk of bearing seizure)	**90 DAYS**
TRIBOLOGY (OIL ANALYSIS)	**Bearing Lubricating Oil** ISO 4406 Cleanliness	**ALERT** Viscosity change > 10%, Water > 300 ppm **ALARM** High Fe/Cu ppm, Water > 1000 ppm (Emulsified)	**180 DAYS**
ULTRASOUND	**Acoustic Friction Signature**	**ALERT** +8 dB increase from baseline (Lack of lube) **ALARM** +16 dB increase from baseline (Micro-spalling)	**30 DAYS**

3.0 CONDITION RESPONSE MATRIX

LEVEL	CONDITION ASSESSMENT	MANDATORY PROTOCOL
LEVEL 1 (NORMAL)	All mechanical and electrical signatures are stable and within acceptable OEM tolerances.	No action required. Log data into CMMS system and continue scheduled operational monitoring.
LEVEL 2 (ALERT)	Degradation detected. Parameter has crossed warning limits but equipment is fully functional.	1. Halve the monitoring interval (e.g., from 30 days to 14 days). 2. Raise proactive Work Order. 3. Verify spare parts availability (seals, bearings).
LEVEL 3 (ALARM)	Severe anomaly. High risk of catastrophic mechanical failure or loss of containment.	1. Immediately transition load to Standby Pump. 2. Isolate and tag out (LOTO) affected unit. 3. Convene RCFA (Root Cause Failure Analysis) team.

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CBM ENGINEER	**MAINTENANCE SUPERINTENDENT**	**PLANT OPERATIONS MANAGER**

Figure 11: Example of PdM Standard Operating Procedure

Routine Pump Inspection

Daily and weekly routine inspections focus on monitoring six critical operational parameters:

- **Pressure:** Inspect suction and discharge pressure gauges to ensure the pump is operating on its intended system curve.
- **Flow:** Verify that fluid delivery meets process demand and that strainers or suction lines are clear of blockages.
- **Temperature:** Monitor bearing housing and stuffing box/seal chamber temperatures. Normal bearing housing temperature should generally remain below 70 degrees C (158 degrees F).
- **Vibration:** Detect abnormal vibration patterns on the pump casing, bearing frames, and motor baseplates.
- **Noise:** Listen for abnormal mechanical rubbing, bearing growl, or crackling sounds (resembling pumping gravel) that indicate cavitation.
- **Leakage:**
    - *Gland Packing:* Controlled leakage is required for cooling and lubrication (typical rate: 2 to 60 drops per minute).
    - *Mechanical Seal:* Must operate with zero visible liquid leakage during normal operation.

Common Failures of Centrifugal Pump

Table 1: Common Failures of Centrifugal Pumps

Failure Mode	Possible Root Causes
No Flow	Pump not primed, incorrect motor rotation direction, closed suction valve, blocked suction strainer or pipe.
Low Flow	Low motor RPM, clogged impeller passages, worn wear rings (excessive internal clearance), entrained air.
Low Discharge Pressure	Damaged or eroded impeller, incorrect impeller diameter, blown casing gasket.
Excessive Power Consumption	Bent shaft, liquid viscosity higher than design, mechanical binding, severe misalignment.
Excessive Vibration	Shaft misalignment, unbalanced rotor, damaged bearings, piping strain on casing.
Excessive Noise	Cavitation, internal mechanical rubbing between rotating and stationary parts, worn bearings.
Overheating	Operating below minimum continuous flow rate, over-greased or under-lubricated bearings, tight packing.
Mechanical Seal Leakage	Abrasive particles between seal faces, incorrect seal installation, dry running condition.

Failure Mode	Possible Root Causes
Bearing Failure	Lubricant contamination (water/dirt), shaft misalignment, excessive radial or axial thrust loads.
Impeller Damage	Cavitation pitting erosion, chemical corrosion, impact from solid foreign objects.
Cavitation	System NPSHA is lower than pump NPSHR, suction filter blocked, elevated liquid pumping temperature.

Pump Failure Diagnosis

Systematic diagnosis requires a logical step-by-step approach without making hasty assumptions:

1. Confirm the physical symptom (e.g., unusual noise, elevated vibration, pressure drop).
2. Review historical maintenance logs and baseline operational records.
3. Determine whether the root problem originates from **internal pump mechanics** or **external system conditions** (e.g., piping strain, valve positions, electrical supply issues).

Troubleshooting Methodology

Follow this logical troubleshooting workflow: Identify Symptom -> Gather Operational Data -> Analyze Root Causes -> Implement Corrective Action -> Test & Validate Operation

Pump Troubleshooting Decision Tree

A basic decision tree structure for fluid flow issues:

- **Is the pump shaft rotating?**
    - *No:* Check motor power supply, overload relays, or check for mechanical binding.
    - *Yes:* Inspect suction and discharge pressure gauge readings.
- **Is discharge pressure present, but there is no flow?**
    - *Yes:* Closed discharge valve or stuck non-return (check) valve.
    - *No:* Pump has lost prime (air-bound) or motor is running in reverse.

Root Cause Analysis (RCA)

Root Cause Analysis techniques prevent failure recurrence:

1. **5 Why Analysis:** Iteratively asking "Why" five times to drill down to the fundamental cause.
    - Example:
        1. Why did the bearing fail? -> The bearing overheated.
        2. Why did it overheat? -> Lack of lubrication.
        3. Why was lubricant low? -> Oil seal leaked out.
        4. Why did the oil seal leak? -> Excessive shaft vibration from misalignment.
        5. Why was there misalignment? -> Shaft alignment procedure was skipped during the last overhaul.

2. **Fishbone Diagram (Ishikawa / Cause-and-Effect Diagram):** Categorizing potential failure causes using the **4M** framework:

   - **Man:** Inadequate training, improper installation techniques.
   - **Machine:** Component fatigue, shaft deflection, bearing wear.
   - **Material:** Incorrect metallurgy for corrosive service.
   - **Method:** Lack of standard operating procedures (SOPs), improper LOTO (Lockout/Tagout) execution.

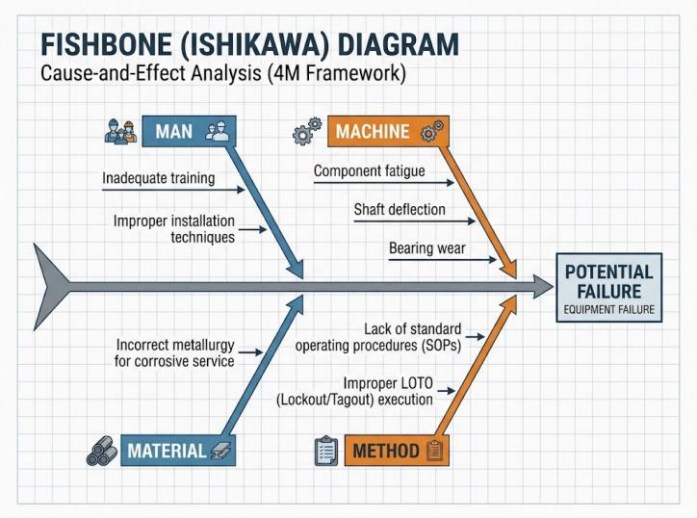


Figure 12: 4M Fishbone Diagram for Equipment Failure Analysis

Centrifugal Pump Dismantling for Maintenance

1. Safety Precautions

- Wear full Personal Protective Equipment (PPE): safety boots, gloves, eye protection, and hard hat.
- Isolate, depressurize, drain, and flush hazardous liquids from the pump casing and piping.

2. Lockout/Tagout (LOTO)

- Isolate the electrical power supply at the main circuit breaker.
- Apply a safety padlock and warning tag stating "DANGER - DO NOT OPERATE" prior to performing mechanical work.



Figure 13: Lockout Tagout Safety Steps

3. Manufacturer's Instruction Manual

- Consult the manufacturer's instruction manual for exploded views, cross-sectional drawings, running clearances, and bolt torque specifications.

4. Pump Identification and Documentation

- Record nameplate data, including model number, serial number, rated flow rate, total head, and impeller diameter.

5. Tools and Equipment Required

- Hand tools: open-end/ring spanners, socket sets, screwdrivers, soft-faced mallets.
- Mechanical pullers (bearing puller, wheel puller, hydraulic press).
- Precision measuring instruments: vernier calipers, micrometers, feeler gauges, dial indicators, torque wrench.



Figure 14: Industrial Centrifugal Pump Maintenance and Overhaul

6. Dismantling Sequence

- Remove the casing drain plug to empty residual fluid.
- Disconnect the coupling spacer element (for back-pull-out designs).

- Unbolt casing studs and carefully extract the rotating element assembly.
- Remove the impeller nut, impeller, shaft sleeve, mechanical seal, and bearing frame.



Figure 15: Disassembling and Servicing of An Industrial Pump

7. Dismantling Sequence List

1. Isolate Electrical Power (LOTO)
2. Drain Pump Casing & Flush System
3. Disconnect Coupling & Guard
4. Remove Casing Main Studs/Bolts
5. Extract Back-Pull-Out Assembly
6. Remove Impeller Nut & Impeller
7. Remove Mechanical Seal / Packing Gland
8. Disassemble Bearing Housing & Remove Bearings

Inspection of Pump Components

- **Impeller:** Inspect for cavitation pitting, vane erosion, corrosion, cracks, or hub damage.



Figure 16: Damaged and Oxidized Pump Impeller

- **Shaft:** Inspect for bend/runout using a dial indicator and check for scoring along sleeve contact surfaces.



Figure 17: Damaged Industrial Shaft with Visible Fracturing and Wear

- **Bearings:** Inspect for pitting, discoloration from heat, flaking, cage damage, or excessive play.
- **Mechanical Seal:** Inspect seal faces (carbon vs. silicon carbide) for flatness, chipping, cracking, or uneven wear patterns.



Figure 18: Annotated Exploded View of An Industrial Mechanical Seal Assembly

- **Casing:** Inspect volute walls for erosion, pitting, and cut-water (volute tongue) damage.
- **Wear Rings:** Measure diametral clearance between the impeller hub and casing wear ring.

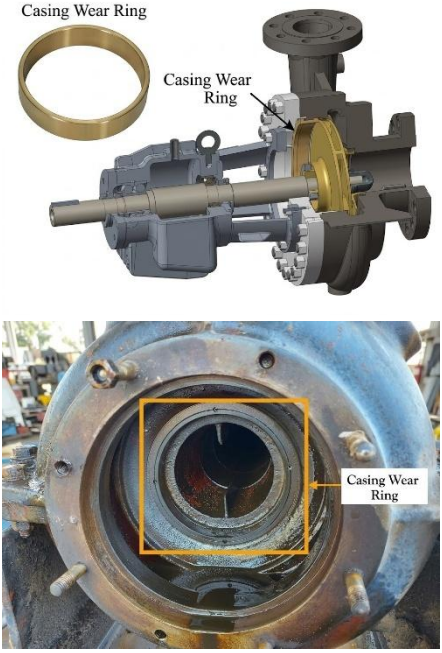


Figure 19: Installation Position of The Casing Wear Ring

- **Coupling:** Inspect rubber inserts/elastomers for wear, cracking, or hardening.

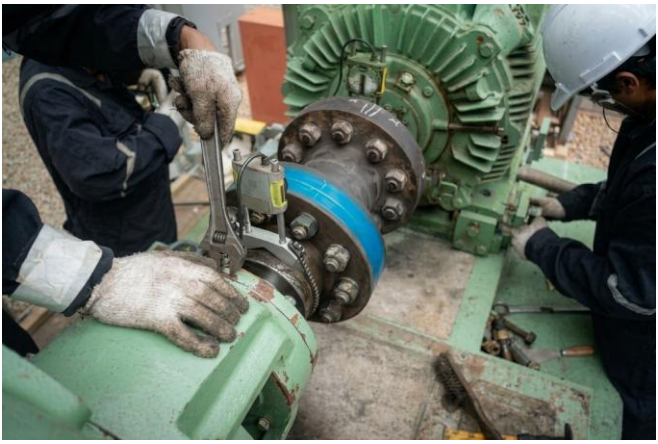


Figure 20: Performing Coupling Alignment on An Industrial Motor-Pump

Measurement and Inspection Tools

- **Vernier Caliper:** Measures general dimensions, shaft diameters, and sleeve lengths.
- **Micrometer (Inside/Outside):** Measures impeller hub outer diameter and wear ring inner diameter to a precision of 0.01 mm.
- **Feeler Gauge:** Measures flat gap clearances between flat-style wear rings or coupling gaps.
- **Dial Indicator:** Measures shaft bend/runout (Total Indicated Runout - TIR) and coupling misalignment.
- **Torque Wrench:** Ensures casing bolts, impeller nuts, and coupling bolts are tightened to specified torque values.

Repair and Replacement of Components

1. **Restoring Wear Ring Clearances:** When diametral wear ring clearance exceeds double the original design value, replace the wear rings or machine custom replacement rings on a lathe.
2. **Shaft Sleeve Replacement:** Replace scored or grooved shaft sleeves to protect mechanical seals and packing.
3. **Shaft Straightening Warning:** Shafts with a runout exceeding 0.05 mm (0.002 inches) must be straightened using a press or replaced. Avoid excessive hammer blows that can cause stress risers or micro-cracks.
4. **Impeller Balancing:** Dynamic or static balancing must be performed on trimmed or repaired impellers to minimize vibration.

Centrifugal Pump Assembly and Testing

1. Assembly Preparation

- Clean all metal components using approved solvent cleaners.
- Replace all O-rings, casing gaskets, and mechanical seal elastomers with new items.

2. Assembly Sequence

- Install bearings onto shaft -> Install mechanical seal -> Fit shaft assembly into bearing housing -> Mount impeller and lock nut -> Install rotating assembly into casing.

3. Mechanical Seal Installation

- Apply a light film of soapy water or elastomer lubricant to O-rings. Never touch polished mechanical seal faces with dirty hands or greasy rags.

4. Bearing Installation

- Heat bearings using an induction heater or oil bath to approximately 100 degrees C to 120 degrees C (212 degrees F to 248 degrees F) before sliding onto the shaft seat. Never apply direct hammer force to the outer bearing race.



Figure 21: Bearing Pre-Heating Process Using an Induction Heating System

5. Impeller Installation

- Ensure the drive key is securely fitted in the shaft keyway. Tighten and lock the impeller nut using its locking washer or setscrew.

6. Casing Assembly

- Tighten casing bolts in a crisscross (star) pattern using a torque wrench to ensure uniform gasket compression.

7. Coupling Installation

- Reinstall coupling hubs onto pump and driver shafts with proper key fit.

Shaft and Coupling Alignment

Precision alignment between the pump shaft and motor shaft is critical to prevent premature seal and bearing failures:

1. **Types of Misalignments:**
    - **Parallel (Radial) Misalignment:** Offset between the centerline axes of the two shafts.
    - **Angular Misalignment:** Angle formed between the two shaft centerlines at the coupling point.
2. **Alignment Methods:**
    - **Rim and Face Method (Dial Indicators):** Dial indicators measure radial (rim) and axial (face) Total Indicated Runout (TIR) through 360-degree rotation.
    - **Laser Alignment Tool:** High-precision optical alignment using laser transmitters and sensors.
3. **Soft Foot Inspection:**
    - Verify that all four motor feet rest flat on the baseplate frame before adding shim packs.

Post-Assembly Inspection

- Rotate the pump shaft by hand to ensure free rotation without binding or rubbing.
- Check axial endplay (float) of the shaft.
- Verify mechanical seal flush piping connections are installed correctly.

Pump Testing

1. **Leakage Test:** Fill the pump casing with liquid and apply pressure to confirm casing gasket and seal integrity.
2. **Rotation Test:** Briefly jog the motor to verify that shaft rotation matches the directional arrow on the casing.
3. **Pressure Test:** Monitor suction and discharge pressure readings upon startup.
4. **Flow Test:** Confirm delivered flow rate matches design specification.
5. **Vibration Test:** Measure overall vibration velocity (mm/s RMS) on bearing housings.
6. **Temperature Monitoring:** Continuously monitor bearing temperatures during the initial 1-hour run-in period.

Maintenance and Test Report

All maintenance activities, measured clearances (wear ring gap, shaft TIR, alignment data), and performance test results must be recorded on a **Maintenance Report Sheet** and updated in the facility's **Computerized Maintenance Management System (CMMS)**.

🔧 Workshop Activity

Title: Overhaul, Inspection, Alignment, and Reassembly of an End-Suction Centrifugal Pump. **Objective:** Students will master pump dismantling, internal clearance measurement, component inspection, and shaft alignment techniques. **Procedure:**

1. Perform LOTO electrical isolation on the workshop test pump rig.
2. Unbolt casing studs and remove the rotating element assembly.

3. Measure wear ring clearances using an outside micrometer and feeler gauge. Record readings.
4. Measure shaft runout (TIR) using a dial indicator and V-blocks.
5. Reassemble the pump and perform shaft alignment using dial indicators until TIR is below 0.05 mm.
6. Complete a comprehensive overhaul report.

⚠️ Safety Alert

- **ELECTRICAL HAZARD:** Never begin mechanical repair work before verifying LOTO isolation with a calibrated voltage tester!
- **TRAPPED PRESSURE:** Always ensure suction and discharge valves are fully closed and the casing drain plug is opened to vent trapped pressure before loosening casing bolts!

📝 Maintenance Checklist (Routine Inspection)

A centrifugal pump checklist should include key elements such as:

- [ ] Check suction and discharge pressure gauge readings.
- [ ] Inspect bearing housing oil level and clarity (or re-grease schedule).
- [ ] Inspect gland packing drip rate (2 to 60 drops/min) or mechanical seal condition.
- [ ] Check bearing housing operating temperature (must remain below 70 degrees C).
- [ ] Check pump and driver for abnormal noise or vibration.
- [ ] Verify motor electrical current (Amperes) is within rated nameplate limits.
- The following is an example of an industry checklist.

Table 2: Routine Inspection Checklist - Centrifugal Pump

Plant / Location:	Water Treatment Plant / Area 2	**Equipment Tag ID:**	P-101A (Duty Pump)
Equipment Name:	End-Suction Centrifugal Water Pump	**Operating Status:**	[ ] Running [ ] Standby [ ] Tripped
Inspection Date & Time:	____/____/2026 ___:___ AM/PM	**Inspector Name & ID:**	_____

Table 3: Section 1 - Pre-Inspection Safety & Environment Check

Safety Item	Status	Remarks / Action Required	Initial
1. Area Cleanliness & Housekeeping (No oil/water spill on floor)	[ ] Pass [ ] Fail		
2. Coupling Guard Fitted & Securely Bolted	[ ] Pass [ ] Fail		
3. Electrical Junction Box Closed & Cable Glands Tight	[ ] Pass [ ] Fail		
4. LOTO Status (If under maintenance, tags verified)	[ ] Pass [ ] Fail		

Table 4: Section 2 - Operating Parameters & Quantitative Measurements

Parameter Inspected	Standard / Normal Range	Actual Value	Unit	Status	Remarks
Suction Pressure (Ps)	1.5 – 2.5	_____	bar	[ ]P [ ]F	Positive pressure, no vacuum drop
Discharge Pressure (Pd)	5.0 – 6.5	_____	bar	[ ]P [ ]F	Within design duty point
Differential Pressure / TDH	3.0 – 4.5	_____	bar	[ ]P [ ]F	Pd - Ps
Flow Rate (Capacity - Q)	80 – 100	_____	m^3/h	[ ]P [ ]F	Process demand flow
Motor Current (I)	18 – 24 (Max: 28)	_____	Amp	[ ]P [ ]F	Below nameplate Full Load Amps
Bearing Housing Temp - DE	40 – 65 (Max: 70)	_____	°C	[ ]P [ ]F	Drive End bearing frame
Bearing Housing Temp - NDE	40 – 65 (Max: 70)	_____	°C	[ ]P [ ]F	Non-Drive End bearing frame
Stuffing Box / Seal Temp	35 – 55 (Max: 65)	_____	°C	[ ]P [ ]F	Mechanical seal chamber
Bearing Oil Level & Clarity	1/2 to 2/3 Sight Glass	_____	Visual	[ ]P [ ]F	Clean oil, no water contamination
Mechanical Seal Drip Rate	0 (Zero visible leak)	_____	drops/min	[ ]P [ ]F	Gland packing: 2 - 60 drops/min
Vibration Velocity (DE / NDE)	< 2.8 (ISO 10816)	_____	mm/s RMS	[ ]P [ ]F	Overall vibration amplitude
Noise Level & Acoustics	< 85 dBA (No crackle)	_____	dBA / Visual	[ ]P [ ]F	No cavitation or metallic rubbing
Suction Strainer Diff. Pressure	< 0.3	_____	bar	[ ]P [ ]F	Clean strainer if > 0.5 bar

Table 5: Section 3 - Visual & Mechanical Integrity Checklist

Inspection Item	Condition	Action Required?	Technician Notes
1. Baseplate & Foundation Bolts (Tight, no cracks, grout intact)	[ ] OK [ ] Defect	[ ] Yes [ ] No	
2. Piping Flange Joints & Gaskets (No liquid weeping or steam leak)	[ ] OK [ ] Defect	[ ] Yes [ ] No	
3. Seal Flush Tubing & Cooling Water Line (Unobstructed flow)	[ ] OK [ ] Defect	[ ] Yes [ ] No	
4. Oil Sight Glass & Breather Cap (Clean breather, no water in oil)	[ ] OK [ ] Defect	[ ] Yes [ ] No	
5. Motor Fan Cover & Cooling Fins (Free of dust buildup / debris)	[ ] OK [ ] Defect	[ ] Yes [ ] No	

Table 6: Section 4 - Abnormalities Observed & Immediate Action Taken

Details of Abnormality Found (if any): _____
Immediate Corrective Action Taken / Work Order Created (WO No): _____
Overall Equipment Status: [ ] NORMAL (Fit for service) [ ] MONITOR (Requires follow-up) [ ] SHUTDOWN / CRITICAL

Table 7: Section 5 - Inspection Verification & Authorization

Inspected By (Technician / Inspector)	Reviewed & Verified By (Maintenance Supervisor)
Signature: _____	Signature: _____
Name: _____	Name: _____
Date & Time: ____/____/2026 ___:___	Date & Time: ____/____/2026 ___:___

🛠️ Technician's Note

- *Bearing Installation Tip:* Never strike bearing balls or cages with a steel hammer! Always press on the inner ring when fitting onto a shaft, or use an induction heater for smooth thermal expansion.
- *Mechanical Seal Tip:* Most premature mechanical seal failures are caused by microscopic dirt on the seal faces during assembly or severe shaft misalignment. Maintain an ultra-clean work area!

CHAPTER 4 — INDUSTRIAL CASE STUDIES AND FAQ

SECTION A: INDUSTRIAL CASE STUDIES & RESEARCH ON CENTRIFUGAL PUMPS

Case Study 1: Catastrophic Slurry Pump Casing Fracture at KGHM Polska Miedź S.A. (Poland)

- **1. Industrial Background & Importance:**
  At the KGHM Polska Miedź S.A. Hydrotechnical Unit in Rudna, Poland, high-power multi-stage slurry pumps (630 kW and 800 kW) form the backbone of the copper flotation waste transport system. Because these pumps handle massive volumes of abrasive mining tailings, any unexpected pump failure halts the entire copper production line, incurring severe financial losses.

- **2. Problem Encountered & Failure Mode:**
  Three heavy-duty split-case centrifugal slurry pumps suffered sudden, catastrophic fracturing of their gray cast iron outer housings (ASTM A48 Class 35) during operation and pressure leak testing.

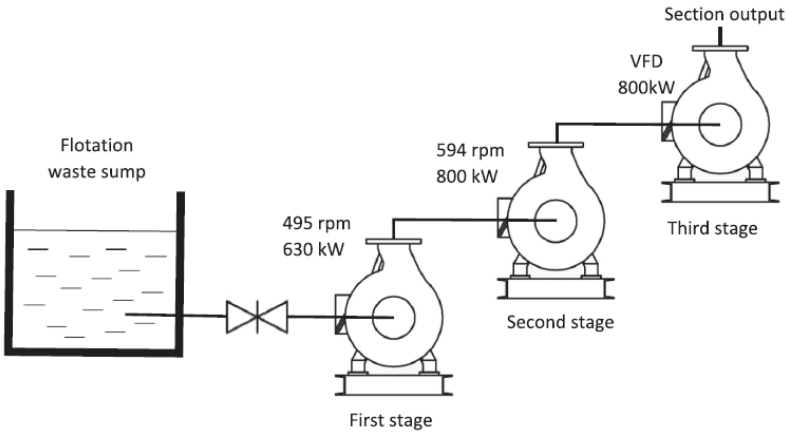


Figure 22: Pumping Section Scheme



Figure 23: Pump Failure – Large Crack Across Pump Housing

- **3. Investigation & Engineering Analysis:**
  - **Material Testing:** Static tensile testing revealed that the actual ultimate tensile strength of the fractured housings had dropped dramatically to between 25% and 46% of the required 241 MPa standard.
  - **Microstructure Analysis (SEM):** Scanning electron microscopy uncovered severe casting defects, including coarse cementite, phosphorus eutectics (steatite), and gas porosities, which acted as internal stress risers and crack initiators.
  - **Vibration Analysis:** Vibration measurements identified a low-frequency "beat phenomenon" (<2 Hz) caused by dynamic interference between adjacent pump stages, creating fluctuating cyclic stress loads on the casings.
  - **Finite Element Modeling (FEM):** FEM simulations confirmed that the combination of reduced material strength, bolt pre-tensioning, and cyclic vibration caused stress concentrations exceeding the material's yield limit.
- **4. Solution & Corrective Actions:**
  - Upgraded the housing material specification from gray cast iron to cast stainless steel (ASTM A743 CA6NM).
  - Implemented strict foundry quality control, utilizing commercial chemical inoculants to eliminate porosities and coarse cementite phases during casting.
  - Adjusted pump rotational speeds via Variable Frequency Drives (VFDs) to decouple operating frequencies and eliminate destructive beat interference.

- **5. Key Takeaways:**
  Never assume a manufactured component meets specification without material testing! Material casting defects combined with low-frequency hydraulic vibrations can cause catastrophic mechanical failure, even if overall vibration levels seem acceptable.

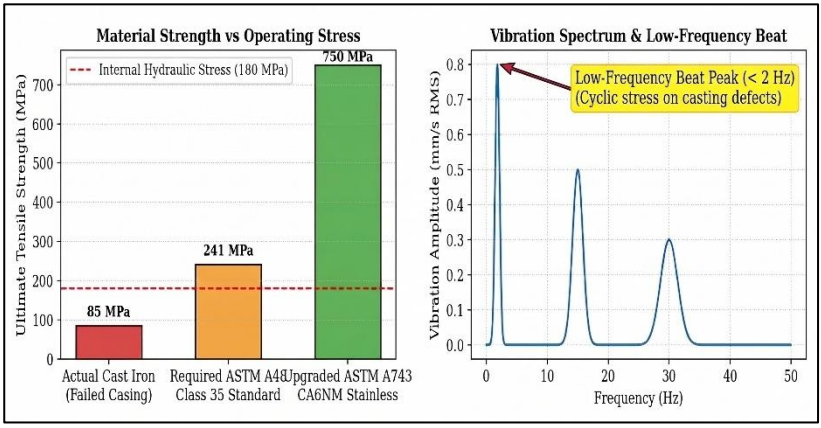


Figure 24: Casing Fracture & Low-Frequency Vibration

- **Reference:**
  Wróbel, J., Pietrusiak, D., Rozmus, R., Roicki, R., Zarzycki, B., & Stefanek, P. (2025). Failure analysis and guidelines for further exploitation of centrifugal slurry pumps used for copper flotation waste transport: A case study. *Engineering Failure Analysis*, 174, 109479. https://doi.org/10.1016/j.engfailanal.2025.109479

Case Study 2: Severe Sediment Erosion of Double-Suction Impellers at the Jingtai Yellow River Irrigation Project (China)

- **1. Industrial Background & Importance:**
  The Jingtai Yellow River Irrigation Project (JYRIP) in Gansu Province, China, is a multi-stage, high-lift pumping scheme that lifts water from the Yellow River to irrigate arid agricultural land bordering the

Tengger Desert. Double-suction centrifugal pumps are used due to their high flow capacity and reliability.

- **2. Problem Encountered & Failure Mode:**
  Pumping raw Yellow River water containing extremely high sand concentrations (up to 61,547 PPM during the rainy season) caused severe sediment erosion wear on ductile iron (QT600-3) impellers. After 3,000 to 5,000 operating hours, water delivery dropped by 8% to 20%, total head dropped by up to 18.87%, and pump efficiency collapsed by up to 26.3%, costing over 100 million RMB annually in component replacements.

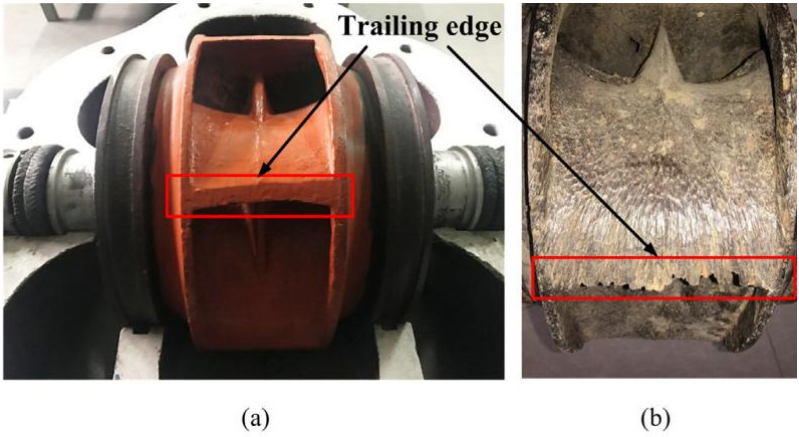


Figure 25: Comparison of Impeller Surfaces Before and After Eroded: (A) Before Eroded; (B) Eroded Surfaces After Running 5000 Hours.

- **3. Investigation & Engineering Analysis:**

  - **SEM Analysis:** Scanning electron microscopy revealed a distinct wear transition: impact erosion damage occurred near the blade leading edge (LE), whereas cutting and grooving wear dominated near the trailing edge (TE).

- **Numerical Simulation:** Computational Fluid Dynamics (CFD) using the Eulerian-Lagrangian approach and the McLaury erosion model confirmed that sand particle concentration and particle size (mean diameter of 25 μm) were the primary drivers of metal erosion, whereas particle shape factor had a minor impact.

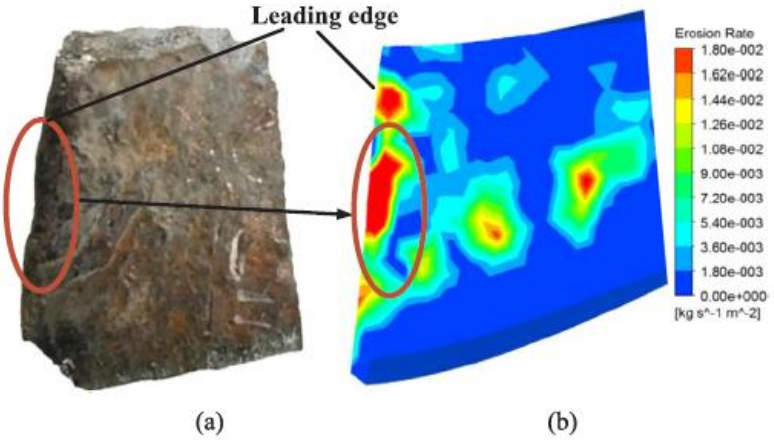


Figure 26: Comparison of Numerical Predictions with Actual Erosion Wear on LE. (A) Observation Results (B) Simulation Results

- **4. Solution & Corrective Actions:**

- Optimized impeller blade hydraulic profiles (anti-wear blade profile design) to minimize localized particle impact angles.

- Applied hard-facing protective coatings and scheduled high-load pumping operations outside the heavy rainy season.

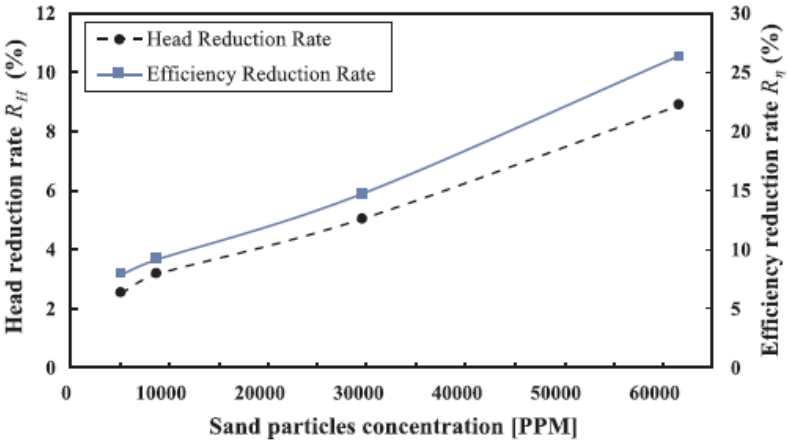


Figure 27: Head and Efficiency Reduction Rate with Different Particle Concentration

- **5. Key Takeaways:**
  When pumping fluids containing suspended solids, erosion wear changes the physical shape of the impeller, causing severe hydraulic head and efficiency loss. Engineers must analyze particle size and concentration to select anti-wear materials and specialized blade geometry.

- **Reference:**
  Shen, Z., Chu, W., Li, X., & Dong, W. (2019). Sediment erosion in the impeller of a double-suction centrifugal pump – A case study of the Jingtai Yellow River Irrigation Project, China. *Wear*, 422–423, 269–279. https://doi.org/10.1016/j.wear.2018.12.016

Case Study 3: Proactive Mechanical Seal Reuse & Maintenance Cost Reduction at an Oil Multinational Company (Nigeria)

- **1. Industrial Background & Importance:**
  At an oil multinational processing facility in Rivers State, Nigeria, centrifugal pumps transport crude oil and refined hydrocarbons. Mechanical seals are the most vulnerable component, failing between 26 and 54 times a year due to sand and sediment erosion in the processed fluid.

- **2. Problem Encountered & Failure Mode:**
  A traditional "run-to-failure" maintenance approach resulted in excessive corrective maintenance costs (1.42 million Naira per seal replacement) and frequent, unplanned production halts.

- **3. Investigation & Engineering Analysis:**

  - **Qualitative FMECA:** Failure Mode, Effects, and Criticality Analysis identified the mechanical seal, impeller, and shaft as the top three critical components, with the mechanical seal having the lowest availability (98.38%).

  - **Operational Analysis:** Field investigations revealed that seal failure was primarily caused by sand particles grinding between mating faces. However, if seals were removed *before* total face destruction, they could be cleaned of debris and safely reused.

- **4. Solution & Corrective Actions:**

  - Implemented a proactive maintenance schedule where pumps were switched to standby units at predetermined intervals (5, 8, or 11 days depending on fluid sand levels: high, medium, or low).

  - Mechanical seals were pulled, cleaned of abrasive debris, inspected, and reinstalled to complete a second operating cycle (running an additional 4.5 to 9 days).

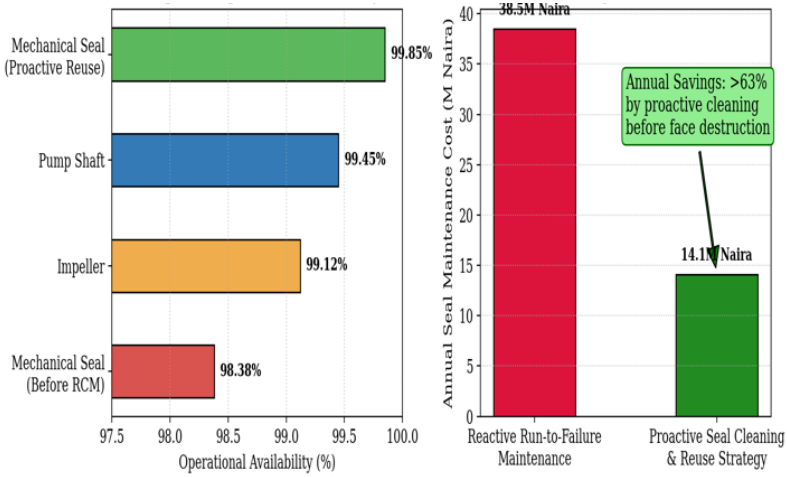


Figure 28: Component Operational and Annual Cost Saving

- **5. Economic Impact:**
  This proactive seal-cleaning strategy reduced annual mechanical seal maintenance expenditures by 13.6 million to 24.4 million Naira. Maintenance engineering is not just about replacing broken parts—it is about managing component life cycles to maximize plant profitability.

- **Reference:**
  Saturday, E. G., & Abbey, R. (2025). Development of a maintenance strategy for centrifugal pumps. *European Journal of Science, Innovation and Technology*, 5(1), 143–152.

Case Study 4: Reliability-Centered Maintenance (RCM) on LPG Multi-Stage Barrel Pumps at a Refinery (Nigeria)

- **1. Industrial Background & Importance:**
  In a petroleum refinery in Rivers State, Nigeria, 19-stage vertical barrel centrifugal pumps transfer Liquefied Petroleum Gas (LPG). Because LPG has extremely low viscosity, pump reliability is vital for refinery safety and continuous production.

- **2. Problem Encountered & Failure Mode:**
  Unstructured, reactive maintenance practices over a 10-year period led to high spare parts consumption and excessive maintenance labor costs.

- **3. Investigation & Engineering Analysis:**

  - **RCM & FMECA Application:** Applied FMECA and Decision Logic Tree Analysis (LTA) across 10 years of historical failure logs.

  - **Criticality Ranking:** Identified the electric motor (highest Mean Time To Repair [MTTR] of 58 hours) and the mechanical seal (highest failure rate of 8.06×10^{-4} failures/hour) as the most critical failure bottlenecks.

- **4. Solution & Corrective Actions:**

  - Replaced reactive maintenance with a structured RCM strategy combining condition-based predictive monitoring and time-based preventive maintenance tasks.

  - Optimized spare part inventory management for seals, shafts, and impellers.

- **5. Economic Impact:**
  The RCM strategy reduced mechanical seal spare part costs by **19.88%** and slashed labor costs across critical components: impellers

(-50%), motors (-33%), shafts (-25%), and mechanical seals (-25%). The industry must appreciate that systematic RCM tools directly translate to massive labor and capital savings.

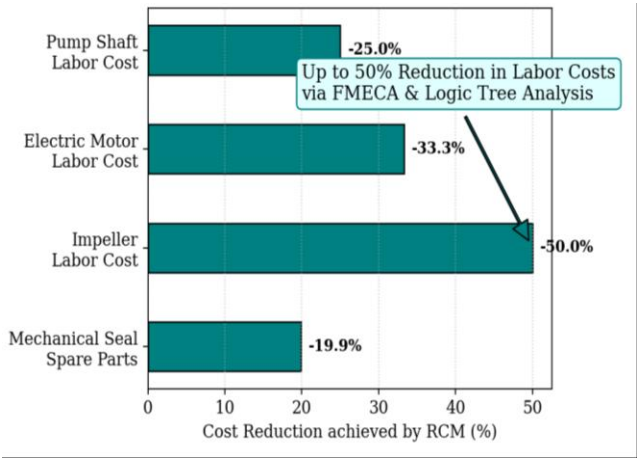


Figure 29: Cost Optimization for LPG Barrel Pumps (Refinery)

- **Reference:**
  Funmilayo, A. T., & Saturday, E. G. (2023). Cost effective maintenance strategy for centrifugal pumps using reliability centered maintenance. *International Journal of Frontiers in Engineering and Technology Research*, 5(2), 1–11. https://doi.org/10.53294/ijfetr.2023.5.2.0031

Case Study 5: Centrifugal Pump Reliability Improvement in a South African Pulp and Paper Mill

- **1. Industrial Background & Importance:**
  South Africa is one of the world's leading pulp and paper producers, relying on hundreds of centrifugal pumps to handle corrosive liquors, abrasive wood pulp slurries, and process water.

- **2. Problem Encountered & Failure Mode:**
  Centrifugal pumps designed for a 30-year operational lifespan were suffering premature, unexpected breakdowns within an average of just 4.5 years, costing millions of Rands in lost revenue.

- **3. Investigation & Engineering Analysis:**

  - **Data Triangulation:** Combined maintenance personnel questionnaires, literature benchmarks, and physical repair shop operational logs.

  - **Pareto Failure Analysis:** Pareto charting identified mechanical seal failure as the single largest contributor to pump breakdowns, followed by impeller damage, foreign debris ingress, and bearing seizure.

  - **Root Cause Findings:** Over 80% of breakdowns stemmed from human and installation errors: shaft misalignment, un-supported baseplates, improper seal flush arrangements, lack of bearing lubrication, and reactive "breakdown maintenance" practices.

- **4. Solution & Corrective Actions:**

  - Recommended transitioning from corrective/scheduled maintenance to Machine Learning-assisted strategy selection (Analytic Hierarchy Process - AHP).

  - Mandated formal condition monitoring training (vibration signals and smart sensors) for plant technicians.

- **5. Key Takeaways:**
  Premature pump failures are rarely caused by manufacturing defects—they are mostly caused by poor installation, shaft misalignment, improper lubrication, and bad maintenance habits.

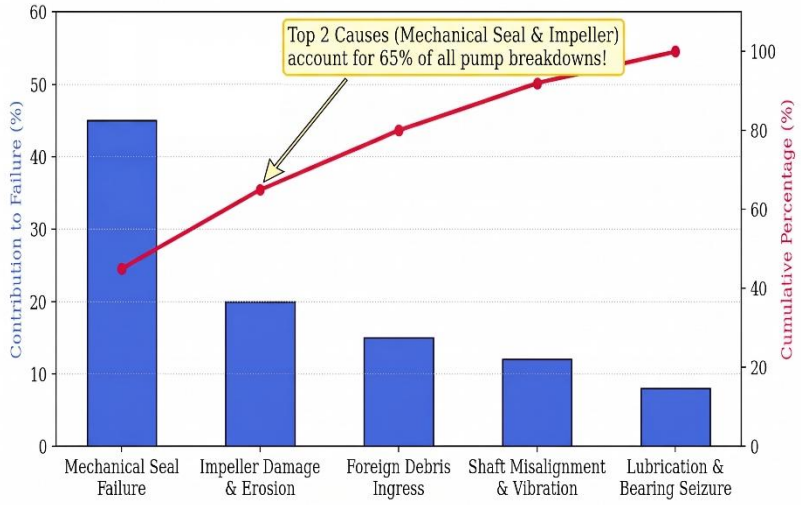


Figure 30: Contribution to Failure and Cumulative Percentage

- **Reference:**
  Shabane, N., Makhanya, B. B. S., & Pretorius, J.-H. (2024). Centrifugal pump reliability improvement in the pulp and paper industry. In *Proceedings of the 14th Annual International Conference on Industrial Engineering and Operations Management* (pp. 12-14). IEOM Society International.

Case Study 6: Predictive Maintenance via Vibration Analysis in a Paper Pulp Manufacturing Facility

- **1. Industrial Background & Importance:**
  In a paper pulp production plant, centrifugal pumps operate continuously across critical production units, including the Water Treatment Unit and the Brownstock Processing Unit.
- **2. Problem Encountered & Failure Mode:**
  Uncoordinated inspection intervals caused unexpected machinery breakdowns, leading to costly production line halts.
- **3. Investigation & Engineering Analysis:**
  - **Parameter Categorization:** Grouped factory pumps based on three key operational variables: priority level, operational age, and workload.
  - **Vibration Spectrum Monitoring:** Measured triaxial bearing vibration amplitudes to establish a direct correlation between vibration growth and mechanical wear.
- **4. Solution & Corrective Actions:**
  - Established customized predictive vibration inspection intervals based on pump group risk: **7 days** (high workload/critical), **15 days** (medium), and **30 days** (low workload).

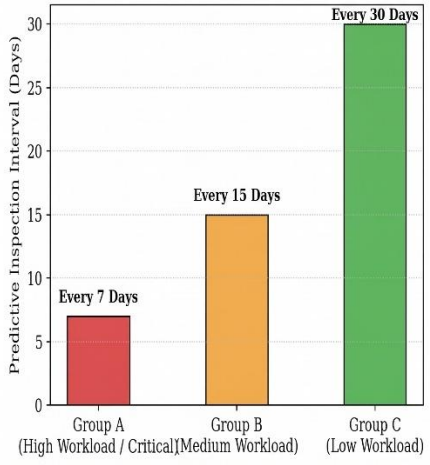


Figure 31: Vibration Monitoring Inspection Matrix

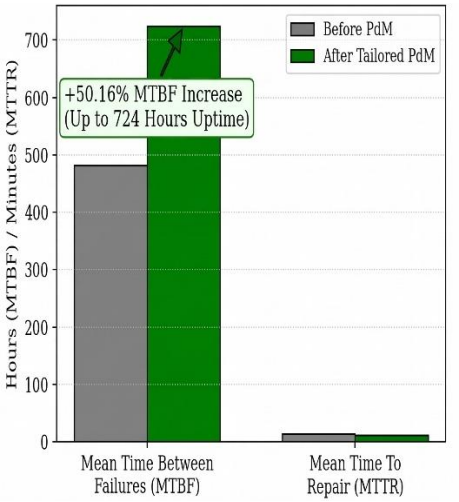


Figure 32: Reliability Improvement Metrics

- **5. Results:**
  - **Water Treatment Unit:** Mean Time Between Failures (MTBF) increased by **50.16%** (reaching 724 hours).
  - **Brownstock Unit:** Mean Time To Repair (MTTR) dropped by **13.19%** (down to 12.02 minutes).
  - *Lesson:* Fixed "calendar-based" maintenance is inefficient. Tailoring predictive vibration inspection frequency to workload and machine criticality dramatically improves reliability.
- **Reference:**
  Polhong, W., & Rungkitakarnpanich, J. (2017). Predictive maintenance for centrifugal pumps in pulp industry. *Journal of Applied Science and Emerging Technology*, 16(3), 625–632. https://doi.org/10.14416/j.kmutnb.2017.11.017

Case Study 7: Integrated Reliability Enhancement of Methanol Pumps at a Petrochemical Facility

- **1. Industrial Background & Importance:**
  Multistage centrifugal methanol pumps (Sulzer Model GSG 150-360) are used in oil and petrochemical refineries to handle volatile methanol fluid.

- **2. Problem Encountered & Failure Mode:**
  Traces of moisture in methanol accelerated internal corrosion, impeller cavitation erosion, and mechanical seal degradation, creating high Design FMEA Risk Priority Numbers (RPN = 224 for impellers, 252 for casings).

- **3. Investigation & Engineering Analysis:**

  - **Metallurgical Analysis:** ASTM A216 Gr. WCB cast steel casing/impeller material lacked pitting resistance against moist methanol.

  - **ANSYS CFD Modeling:** CFD simulations mapped high vapor volume fraction zones at impeller blade tips, identifying localized cavitation hotspots.

- **4. Solution & Corrective Actions:**

  - **Material Upgrade:** Upgraded material of construction (MOC) from cast steel to **Duplex Stainless Steel**, reducing corrosion-related degradation by 35% to 40%.

  - **Impeller Redesign:** SolidWorks/ANSYS optimized blade tip geometry, reducing vapor volume fraction by ~18% and improving head stability by 3% to 5%.

  - **Predictive DCS AI Model:** Developed a machine learning classification model trained on real-time Distributed Control System

(DCS) data (armature current, seal pressure, lubricant level), achieving over 99% seal failure prediction accuracy.

- **5. Results**
  Component RPNs dropped by 30% to 40%, and unplanned maintenance events fell by 20% to 25%. Modern pump engineering combines materials science, fluid simulation (CFD), and digital AI analytics!

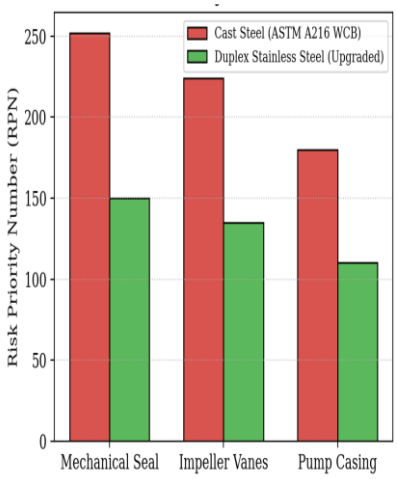


Figure 33: FMEA Risk Priority Number Reduction

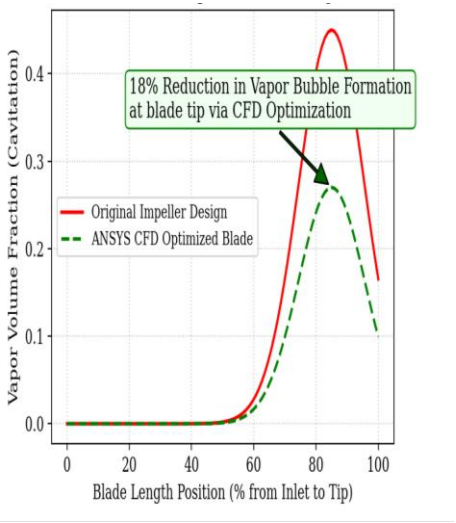


Figure 34: CFD Cavitation Vapor Fraction Along Blade

- **Reference:**
  Modi, K., & Jain, P. (2024). Integrated reliability enhancement of methanol pumps through material optimization, cavitation analysis, and predictive maintenance. *E3S Web of Conferences*, 500, 01042. https://doi.org/10.1051/e3sconf/202450001042

Case Study 8: Early Cavitation Detection & BEP Determination Using Acoustic Emission at Saudi Aramco & David Brown Textron

- **1. Industrial Background & Importance:**
  Conducted by Saudi Aramco Oil Co. and David Brown Textron, this research evaluated condition monitoring techniques on a 60 kW industrial centrifugal pump.

- **2. Problem Encountered & Failure Mode:**
  Conventional cavitation detection relies on detecting a **3% head drop**, which occurs ONLY AFTER cavitation bubbles have already formed, collapsed, and eroded internal metal components.

- **3. Investigation & Engineering Analysis:**

  - Mounted high-frequency Acoustic Emission (AE) sensors (20 kHz to 1 MHz) on the pump casing, suction flange, and discharge flange during NPSH and performance testing.

  - **Incipient Cavitation Finding:** AE RMS signal levels spiked dramatically at high NPSH values (7.3 m to 11 m), picking up high-frequency stress waves from initial bubble formation **long before any pressure drop occurred**.

  - **BEP Identification Finding:** AE RMS activity dropped to its absolute global minimum at a flow rate of 94.5 m^3/h, which perfectly matched the manufacturer's Best Efficiency Point (BEP) where fluid turbulence is lowest.

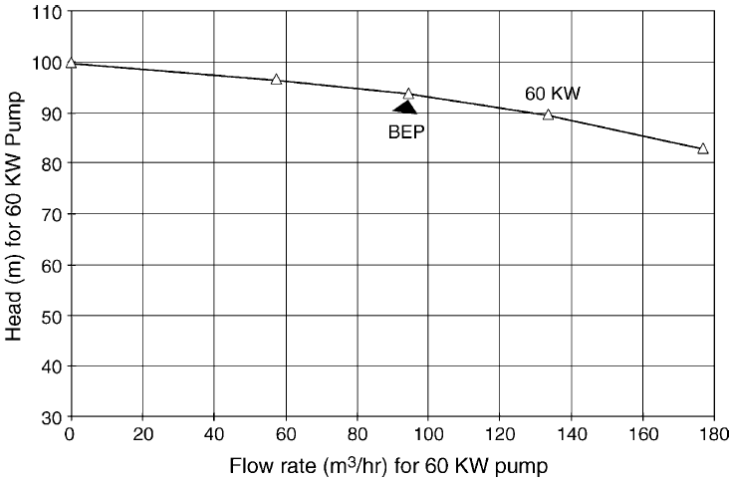


Figure 35: Performance Test Result of the 60 Kw Centrifugal Pump

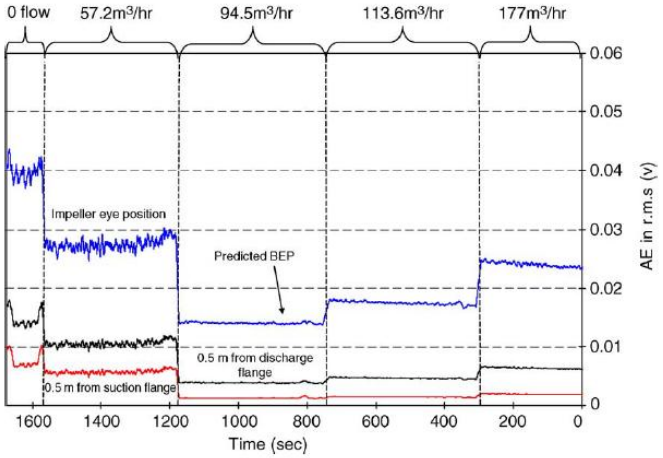


Figure 36: AE r.m.s. Levels Associated with The Performance Test

- **4. Solution & Practical Application:**
  - Demonstrated that AE monitoring allows plant engineers to detect *incipient* (early-stage) cavitation and verify a pump's exact BEP in real time without dismantling equipment.
- **5. Key Takeaways:**
  Acoustic Emission monitoring can "hear" microscopic cavitation bubbles bursting before traditional pressure gauges or human ears notice anything wrong!
- **Reference:**
  Alfayez, L., Mba, D., & Dyson, G. (2005). The application of acoustic emission for detecting incipient cavitation and the best efficiency point of a 60 kW centrifugal pump: Case study. *NDT & E International*, 38(5), 354–358. https://doi.org/10.1016/j.ndteint.2004.10.002

Case Study 9: Emergency Cardiopulmonary Bypass Centrifugal Pump Failure During Robotic Surgery (Shizuoka General Hospital, Japan)

- **1. Industrial & Medical Background & Importance:**
  At Shizuoka General Hospital in Japan, a specialized medical centrifugal pump was driving the Cardiopulmonary Bypass (CPB) machine, artificially pumping blood to sustain a 38-year-old patient's brain and organs during robot-assisted cardiac surgery.

- **2. Problem Encountered & Emergency Crisis:**
  Forty-seven minutes into surgery, an electronic circuit board malfunction depleted the CPB battery, causing a sudden, total shutdown of the main centrifugal pump and suction devices during open-heart manipulation.

- **3. Investigation & Emergency Protocol:**

  - Native cardiac contraction was stopped under aortic cross-clamping, so manual hand-cranking was immediately initiated by surgical staff.

  - Bringing in a backup CPB machine was impossible due to severe space constraints in the robotic operating room.

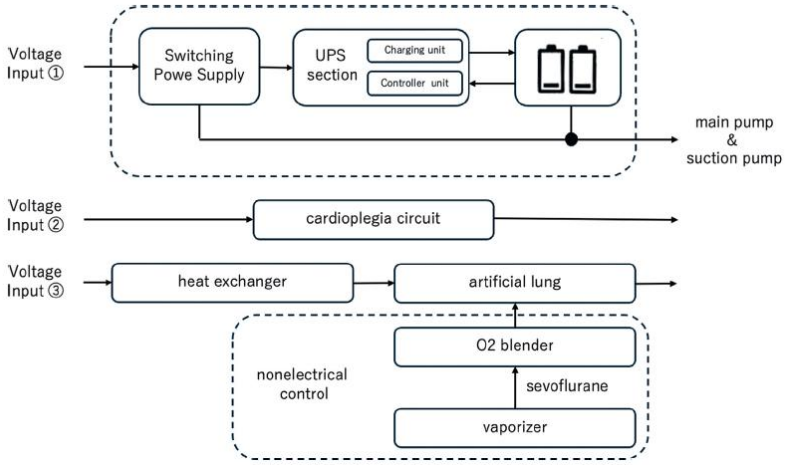


Figure 37: The Block Diagram for Emergency CPB Failure Management in Robotic Mitral Valve Repair

- **4. Solution & Emergency Engineering Actions:**

  - **Systemic Hypothermia:** Immediately cooled the patient to 25 °C and applied head ice packs to reduce cerebral metabolic demand and prevent brain damage during low flow.

  - **Pump Exchange:** Clamped arterial/venous lines and reconnected the circulatory circuit to an alternative Extracorporeal Membrane Oxygenation (ECMO) centrifugal pump within 2 minutes of circulatory arrest.

  - Completed the robotic valve repair concurrently during the pump exchange.

- **5. Results:**
  The patient recovered completely with zero neurological complications. *Centrifugal pumps aren't just for oil and water—they save human lives!* Mechanical and biomedical engineers must design robust

fail-safe protocols and rapid emergency procedures for critical pumping applications.

- **Reference:**
  Osumi, H., Kaminaka, R., Koh, N., & Atsumi, K. (2025). Management of emergency cardiopulmonary bypass failure during robot-assisted mitral valve repair: Successful recovery with hypothermia and centrifugal pump exchange. *Journal of Cardiothoracic and Vascular Anesthesia*, 39(12), 3498–3500. https://doi.org/10.1053/j.jvca.2025.08.012

SECTION B — FREQUENTLY ASKED QUESTIONS

Q1: Why does a centrifugal pump require priming before startup?

A centrifugal pump cannot displace air or gas effectively because the density of air is extremely low compared to liquid. If the pump casing and suction line are filled with air, the rotating impeller cannot generate sufficient suction pressure drop to pull liquid up into the impeller eye6384. Priming fills the casing and suction line completely with liquid, venting all trapped air.

Q2: What happens when a centrifugal pump runs dry?

Running dry deprives internal close-running parts (such as mechanical seals, wear rings, and internal bushings) of liquid lubrication and cooling. This leads to rapid frictional heating, thermal shock, mechanical seal face destruction, wear ring galling, and catastrophic pump seizure within seconds.

Q3: What is the difference between NPSHA and NPSHR?

NPSHA (Net Positive Suction Head Available) is the absolute pressure head available at the pump suction nozzle, determined entirely by the suction piping geometry, static liquid height, friction losses, and liquid vapor pressure. NPSHR (Net Positive Suction Head Required) is the minimum suction pressure head required at the impeller eye, determined by the pump manufacturer through testing, to prevent cavitation.

Q4: What causes cavitation in a centrifugal pump?

Cavitation occurs when the local static pressure inside the suction eye of the impeller falls below the liquid's vapor pressure at the operating temperature ($P < P_{vp}$). Liquid vaporizes into tiny vapor bubbles, which then travel downstream into higher pressure regions and implode violently, sending destructive shock waves against impeller metal surfaces.

Q5: What is the Best Efficiency Point (BEP)?

The Best Efficiency Point (BEP) is the specific flow rate and head on a pump's characteristic curve where the pump converts mechanical shaft power into hydraulic fluid power with maximum efficiency. At BEP, hydraulic losses, internal turbulence, and radial thrust loads on the shaft and bearings are minimized.

Q6: Why do pumps vibrate excessively?

Excessive pump vibration is typically caused by shaft/coupling misalignment, rotor unbalance, worn or damaged rolling element bearings, operating away from BEP (inducing hydraulic recirculation), cavitation, bent shafts, or loose foundation anchor bolts.

Q7: Why does a mechanical seal leak?

Mechanical seal leaks occur due to face wear or scratching caused by abrasive particles, thermal distress from dry running, improper seal installation, excessive shaft deflection/whip, chemical degradation of elastomers, or loss of spring compression.

Q8: Why is pump discharge flow lower than expected?

Lower flow can be caused by low motor RPM, incorrect direction of impeller rotation, increased internal wear ring clearances (leakage), partial clogging of the impeller passages or suction strainer, or higher system static head than designed.

Q9: Why are pumps connected in series?

Pumps are connected in series (discharge of Pump 1 connected to suction of Pump 2) to increase the Total Dynamic Head ($H_{total} = H_1 + H_2$) while maintaining a constant flow rate ($Q_{total} = Q_1 = Q_2$). This is ideal for steep, high-friction piping systems.

Q10: Why are pumps connected in parallel?

Pumps are connected in parallel (sharing common suction and discharge headers) to increase total volumetric flow capacity ($Q_{total} = Q_1 + Q_2$) while developing the same head ($H_{total} = H_1 = H_2$). This is ideal for flat, static-head dominant systems.

Q11: How often should a centrifugal pump be routinely inspected?

Routine visual and quantitative checks (pressure, temperature, oil level, vibration, leakage) should be conducted daily or weekly. Detailed predictive analysis (oil sampling, vibration spectrum, thermography) is typically performed monthly or quarterly.

Q12: What pre-start checks should be conducted before starting a pump?

Pre-start checks include: verifying LOTO removal, checking oil levels/clarity, confirming suction/discharge valve positions (suction wide open), checking shaft free rotation by hand, verifying seal flush water supply, confirming correct motor rotation direction, and ensuring priming/venting is complete.

Q13: What is the function of wear rings in a centrifugal pump?

Wear rings provide a small, renewable running clearance between the rotating impeller and stationary casing. They restrict high-pressure fluid from leaking back to the suction eye, protecting the main casing and impeller from permanent wear.

Q14: How does impeller trimming affect pump performance?

Reducing the outer diameter of an impeller reduces flow rate ($Q \propto D$), total head ($H \propto D^2$), and brake horsepower ($P \propto D^3$) according to the Affinity Laws. It allows a pump to be custom-sized to match reduced process demands without throttling.

Q15: Why should you never throttle the suction valve of a centrifugal pump?

Throttling the suction valve increases suction line friction losses, drastically reducing NPSHA. This starves the impeller eye, inducing severe cavitation, vibration, performance loss, and potential mechanical failure.

Q16: What is "soft foot" and how does it affect pump alignment?

Soft foot occurs when one or more feet of a pump or motor driver do not rest flat on the baseplate frame. Tightening anchor bolts on a soft foot distorts the machine casing, bending the frame and introducing artificial shaft misalignment and high vibration.

Q17: What is the purpose of a mechanical seal flush plan?

A seal flush plan introduces clean, cool fluid into the seal chamber to lubricate and cool the seal faces, remove frictional heat, prevent solids from settling, and maintain seal chamber pressure above fluid vapor pressure.

Q18: What is internal recirculation in a centrifugal pump?

Internal recirculation is a reverse, turbulent fluid flow phenomenon that occurs at the suction eye or discharge tips of an impeller when operating at low flow rates (below BEP). It creates intense hydraulic noise, severe pressure pulsations, and cavitation-like vane erosion.

Q19: What causes shaft sleeve scoring under gland packing?

Shaft sleeve scoring is caused by overtightening gland nuts (preventing required cooling leakage), dirty/abrasive fluid entering the stuffing box, or using incorrect/hard packing material without proper seal cage flush liquid.

Q20: How does entrained air affect centrifugal pump operation?

Entrained air or gas collects in the low-pressure suction eye of the impeller. Air pockets reduce developed head and capacity, cause erratic discharge pressure pulsations, and can lead to total loss of prime (air-locking).

Q21: What is the preferred lubrication level for grease-lubricated ball bearings?

Grease-lubricated rolling element bearing housings should be filled to approximately one-third (33%) of their void capacity. Over-filling causes grease churning, extreme operating temperatures, and accelerated bearing degradation.

Q22: What is Total Dynamic Head (TDH)?

Total Dynamic Head (TDH) is the net energy head developed by the pump between its suction and discharge nozzles. It equals the sum of static head difference (Hstat) plus all friction head losses (Hf) in the suction and discharge piping system (TDH = Hstat + Hf).

Q23: What causes axial thrust in a single-suction centrifugal pump?

Axial thrust is caused by unequal hydraulic pressure distributions acting on the front and back shrouds of a single-suction impeller. High discharge pressure acts on the back shroud, creating a net force pointing toward the suction eye.

Q24: How do balancing holes reduce axial thrust?

Balancing holes drilled through the impeller back shroud connect the high-pressure chamber behind the impeller to the low-pressure suction eye. This relieves pressure behind the back shroud, balancing axial forces acting on the thrust bearing.

Q25: What is the difference between packing gland cooling leakage and mechanical seal leakage?

Gland packing requires a controlled continuous drip rate (2 to 60 drops per minute) to cool and lubricate the packing rings against the rotating shaft. A mechanical seal relies on a microscopic liquid film between lapped faces and should exhibit zero visible liquid leakage during normal operation.

Q26: Why should you avoid operating a pump against a completely closed discharge valve for long periods?

Operating against shut-off converts all input driver energy into fluid heat and turbulence inside the casing. The liquid inside the pump rapidly overheats and boils, causing thermal expansion, internal component binding, seal destruction, and potential casing explosion.

Q27: How does fluid viscosity affect centrifugal pump performance?

Pumping viscous fluids increases disk friction, blade passage resistance, and internal hydraulic losses. This causes a significant reduction in pump flow rate, developed head, and efficiency, while drastically increasing brake horsepower demand.

Q28: What is Total Indicated Runout (TIR)?

Total Indicated Runout (TIR) is the total maximum variation measured by a dial indicator during one complete 360-degree rotation of a shaft or coupling hub. It measures radial eccentricity or axial bend.

Q29: What causes oil whirl in hydrodynamic sleeve bearings?

Oil whirl is an unstable fluid-dynamic self-excitation in sleeve bearings where the rotating shaft rides on a circulating oil wedge, causing the shaft centerline to orbit at approximately 42% to 48% of running speed.

Q30: What is the purpose of an automatic minimum flow recirculation valve (ARC valve)?

An ARC valve automatically ensures that a minimum continuous flow rate passes through the pump during low-process demand periods. It prevents overheating, hydraulic instability, and severe recirculation damage when discharge lines are closed.

Q31: How does a Variable Frequency Drive (VFD) save energy in pumping systems?

A VFD controls pump flow rate by adjusting motor rotational speed (N) rather than dissipating excess head across a throttled control valve. Power demand drops with the cube of speed ($P \propto N^3$), resulting in massive electrical energy savings at reduced flow demands.

Q32: What is "piping strain" and how is it detected?

Piping strain occurs when misaligned process piping is forcefully bolted to pump casing flanges, imposing heavy external forces and bending moments on the pump. It is detected by placing dial indicators on pump coupling hubs while unbolting piping flanges; any movement over 0.05 mm indicates piping strain.

Q33: Why must rolling element bearings be heated during installation on a shaft?

Heating bearings (using induction heaters to ~100–120 °C) thermally expands the inner bearing ring. This allows the bearing to slide smoothly onto the shaft seat without using excessive force, preventing race scoring and ball damage.

Q34: What causes graphitization in cast-iron pump casings?

Graphitization is a form of galvanic corrosion where iron is selectively leached out of cast iron in corrosive or saline water, leaving behind a soft, porous matrix of graphite. It weakens casing structures and accelerates erosion near high-velocity volute tongues.

Q35: What is the function of a volute casing?

The volute casing is a spiral-shaped housing with an expanding cross-sectional area. Its function is to collect high-velocity liquid leaving the impeller outer periphery and gradually reduce its kinetic velocity, converting kinetic energy into static pressure energy.

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