

THE CORROSION AND EROSION OF CENTRIFUGAL PUMPS IN A MARINE ENVIRONMENT : CAUSES, EFFECTS AND MITIGATION

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ABSTRACT

Centrifugal pumps are a sub-class of dynamic axisymmetric work-absorbing turbo machinery. These are used to transport fluids by the conversion of rotational kinetic energy to the hydrodynamic energy of the fluid flow. The rotational energy typically comes from an engine or electric motor. The fluid enters the pump impeller along or near the rotating axis and is accelerated by the impeller, flowing radially outward into a diffuser or volute chamber from where it exits.

To ensure long and trouble free operation in a media, it is of utmost importance to have knowledge about corrosion, erosion and the effect it can have on the product and the system in the operating environment. A significant proportion of material damage and subsequent component failure caused by corrosion and erosion can be eliminated by selecting the optimum material for a given application.

The corrosiveness of a liquid on metals is mainly dependent on:

Oxygen, chloride and/or sulphide content.

Temperature.

pH - value.

Erosion is the wear and tear of the pump internal parts by suspended solid particles contained in the fluid being pumped. The most affected parts are: wear rings, shaft sleeves, packing, mechanical seal faces, lip seals, the pump casting, and the impeller.

The fresh and sea water in present ships are used as cooling water for marine engines. Therefore, corrosion damage in seawater system is a frequent occurrence. In particular, in the impeller of pump, the performance and material span due to the corrosion and cavitation erosion has adverse effects.

Thus, this report describes the causes and effects of corrosion and erosion of sea water operating centrifugal pumps, and the way these can be alleviated.

Keywords: *Cavitation, Corrosion, Erosion, Galvanic Effects, Sea Water.*

INTRODUCTION

True centrifugal pumps were not developed until the late 17th century, when Denis Papin built one using straight vanes. The curved vane was introduced by British inventor John Appold in 1851.

Like most pumps, a centrifugal pump converts rotational energy, often from a motor, to energy in a moving fluid. A portion of the energy goes into kinetic energy of the fluid. Fluid enters axially through eye of the casing, is caught up in the impeller blades, and is whirled tangentially and radially outward until it leaves through all circumferential parts of the impeller into the diffuser part of the casing. The fluid gains both velocity and pressure while passing through the impeller. The doughnut-shaped diffuser, or scroll, section of the casing decelerates the flow and further increases the pressure.

Centrifugal pumps are the type most commonly used in marine industries. These pumps consist of an impeller which transfers energy from a prime mover to the fluid, causing it to flow. By impeding this flow, an increase in pressure or head can be developed. This is done by surrounding the impeller with a casing in the form of a volute which takes the flow from the impeller to discharge by means of a cutwater. Many pumps use diffusers to control the flow from the impeller.

In the simplest form, as shown in Figure 1, the components of a centrifugal pump consist of an impeller, a shaft to support and transfer rotational energy to the impeller, a casing to direct fluid into the impeller as well as to collect fluid emerging from the impeller.

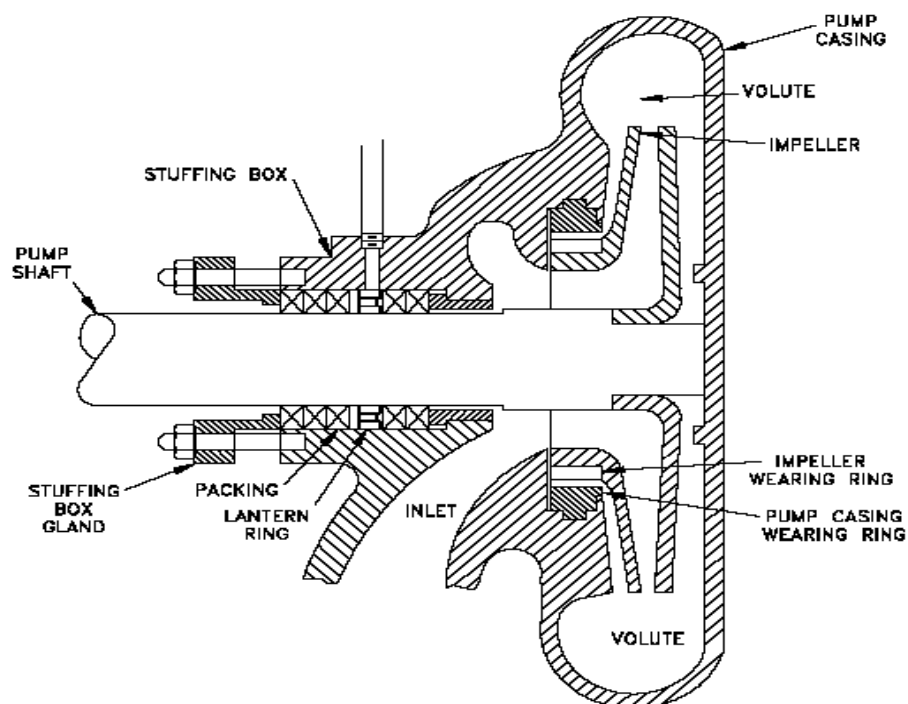


Fig. 1: The basic components of a centrifugal pump.

From the description of the pump components and operating principle, it is relatively easy to imagine just some of the simple dynamic mechanical forces that will be active within such a machine. Radial forces generated by components rotating at speed and axial thrust from the reaction of the impeller with the fluid are but a few that challenge the pump components and especially the shaft.

The pump shaft already carries many of the force burdens inherent to pump operating principle but when we consider that it is also responsible the transmission of all rotational torque energy required to operate the pump, it is no surprise that broken shafts are a frequent cause of immediate pump failure. The centrifugal pump is a machine designed and expected to efficiently convert rotational kinetic energy into fluid motion. Less dramatic than immediate failure, but perhaps more important is the gradual loss of pumping efficiency.

Selecting the right pump type and sizing it correctly are critical components to the success of any pump application. Equally important is selecting construction materials. The initial cost of these materials is normally the first consideration. Operational costs, replacement costs and longevity of service and repair costs will, however, determine the actual cost of the pump during its lifetime.

Standard pump part materials (such as cast irons, bronzes and low-carbon steels) are typically the least expensive first cost, and the most readily available for replacement. However, these materials can become more expensive if they cause premature failure and unexpected service and replacement.

The premature failure occurs in most of the sea water operated centrifugal pumps due to :-

- **Corrosion** - inside the pump caused by the fluid properties
- **Erosion** - wear of the impeller can be worsened by suspended solids
- **Cavitation** - the net positive suction head (NPSH) of the system is too low for the selected pump.

Corrosion is a natural process, which converts a refined metal to a more chemically-stable form, such as its oxide, hydroxide or sulphide. It is the gradual destruction of materials (usually metals) by chemical and/or electrochemical reaction with their environment.

Erosion - Abrasive wear - is the mechanical removal of metal from the cutting or abrading action of solids carried in suspension in the pumped liquid.

Cavitation - which can normally occur with high-suction energy pumps and the erosion causes by the cavitation is the removal of metal as a result of high, localized stresses produced in the metal surface from the collapse (implosion) of cavitation vapor bubbles in higher pressure regions of the impeller inlet.

It is, however, important to understand the various types of corrosion in a sea water operating centrifugal pump and factors affecting the corrosion rate in order to select the appropriate materials. It can be quite difficult to choose a material to withstand multiple factors, such as corrosion in addition to erosion and/or cavitation. Therefore, researchers focused on these three issues.

A. CORROSION

Corrosion is the destructive attack of a metal by chemical or electrochemical reaction with its environment. Following are some of the different types of corrosion causes on the centrifugal pumps.

1. Pitting Corrosion
2. Inter granular Corrosion
3. Crevice Corrosion
4. Microbial Corrosion
5. High Temperature Corrosion
6. Erosion – Corrosion
7. Galvanic Corrosion
8. Selective Corrosion

1. Pitting Corrosion :

Typical examples of pitting corrosion can be seen on aluminium and stainless steels in liquids containing chlorides, e.g. seawater. These materials are dependent on a thin surface oxide film for their corrosion protection. Mechanical damage or an inhomogeneous spot in the oxide film could be the starting point for corrosion attacks. The conditions in the pit are characterized by oxygen deficiency and low pH, which intensifies the attack and may also render it self-sustaining.

Certain conditions, such as low concentrations of oxygen or high concentrations of species such as chloride which complete as anions, can interfere with a given alloy's ability to reform a passivating film. In the worst case, almost all of the surface will remain protected, but tiny local fluctuations will degrade the oxide film in a few critical points. Corrosion at these points will be greatly amplified, and can cause *corrosion pits* of several types, depending upon conditions. Pitting remains among the most common and damaging forms of corrosion in passivated alloys, but it can be prevented by control of the alloy's environment.

Pitting results when a small hole, or cavity, forms in the metal, usually as a result of de-passivation of a small area. This area becomes anodic, while part of the remaining metal becomes cathodic, producing a localized galvanic reaction. The deterioration of this small

area penetrates the metal and can lead to failure. This form of corrosion is often difficult to detect due to the fact that it is usually relatively small and may be covered and hidden by corrosion-produced compounds. Figure 2 shows the pitting corrosion on a stainless steel stator housing operating in seawater.



Fig. 2: Pitting corrosion on a stainless steel stator housing operating in seawater.

2. Inter granular Corrosion :

Inter granular corrosion occurs between the grain boundaries inside a metal. This type of corrosion is well known for stainless steels which have been soaked for an excessive period of time at temperatures between 500 and 800 °C. At this temperature chromium will react with carbon at the grain boundaries and form carbides. This causes chromium depletion in the immediate vicinity of the grain boundaries. If the chromium content falls below 12 %, corrosion can easily start. Figure 3 shows inter-granular corrosion between the grain boundaries in a metal.

Special alloys, either with low carbon content or with added carbon "getters" such as titanium and niobium (in types 321 and 347, respectively), can prevent this effect, but the latter require special heat treatment after welding to prevent the similar phenomenon of "knife line attack". As its name implies, corrosion is limited to a very narrow zone adjacent to the weld, often only a few micrometers across, making it even less noticeable.

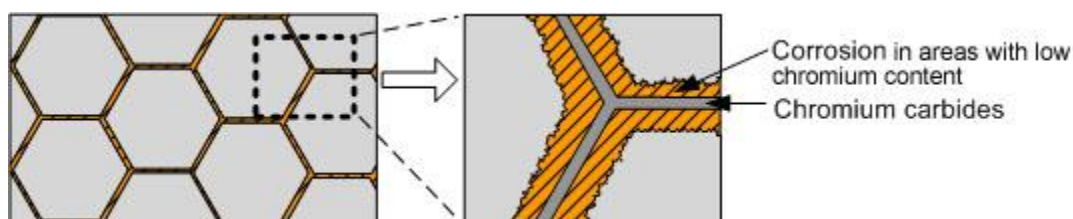


Fig. 3: Inter granular corrosion between the grain boundaries in a metal.

3. Crevice Corrosion :

Crevice corrosion is a localized form of corrosion occurring in confined spaces (crevices), to which the access of the working fluid from the environment is limited. Formation of a differential aeration cell leads to corrosion inside the crevices. Examples of crevices are gaps and contact areas between parts, under gaskets or seals, inside cracks and seams, spaces filled with deposits and under sludge piles. Figure 4 shows a crevice corrosion on a stainless steel nut exposed to seawater.



Fig. 4: Crevice corrosion on a stainless steel nut exposed to seawater.

Crevice corrosion is influenced by the crevice type (metal-metal, metal-nonmetal), crevice geometry (size, surface finish), and metallurgical and environmental factors. The susceptibility to crevice corrosion can be evaluated with ASTM standard procedures. A critical crevice corrosion temperature is commonly used to rank a material's resistance to crevice corrosion.

4. Microbial Corrosion :

Microbial corrosion or commonly known as microbiologically influenced corrosion (MIC), is a corrosion caused or promoted by micro organisms, usually chemoautotrophs. It can apply to both metallic and non-metallic materials, in the presence or absence of oxygen. Sulphate reducing bacteria are active in the absence of oxygen (anaerobic); they produce hydrogen sulfide causing sulfide stress cracking. In the presence of oxygen (aerobic), some bacteria may directly oxidize iron to iron oxides and hydroxides, other bacteria oxidize sulphur and produce sulphuric acid causing biogenic sulfide corrosion. Concentration cells can form in the deposits of corrosion products, leading to localized corrosion.

Affected areas can be treated using cathodic protection, using either sacrificial anodes or applying current to an inert anode to produce a calcareous deposit, which will help shield the metal from further attack.

5. High Temperature Corrosion :

High-temperature corrosion is chemical deterioration of a material (typically a metal) as a result of heating. This non-galvanic form of corrosion can occur when a metal is subjected to

a hot atmosphere containing oxygen, sulphur, or other compounds capable of oxidizing (or assisting the oxidation of) the material concerned.

6. Erosion – Corrosion :

When water flows at high velocities and oxygen erodes the corrosion products from the surface, erosion-corrosion is common. Generally localized to areas with turbulent flow, the attacks are even more severe when gas bubbles and solid particles are present.

In centrifugal pumps, the impeller is particularly susceptible to abrasion-corrosion (Figure 5). Although the casing can be damaged by this, the problem is usually secondary to that of the impeller. The diffuser-type casing with its many vanes is more susceptible to abrasion-corrosion than is the volute-type casing with only one vane - the casing tongue - as an obstruction to the line of flow.



Fig. 5: Erosion-corrosion of an impeller.

Wearing rings are also susceptible to abrasion-corrosion and should receive special consideration in material selection. The higher fluid velocities through the small clearance annulus can result in a high rate of wear, unless the proper material is selected.

Many times, the erosion-corrosion damage can be mistaken for cavitation damage. Cavitation can occur if the pump is not working in the correct area of the QH curve or does not have enough NPSH (net positive suction head). For a correctly applied pump the risk of cavitation is low. In such cases erosion- corrosion is most likely the cause of damage to the material.

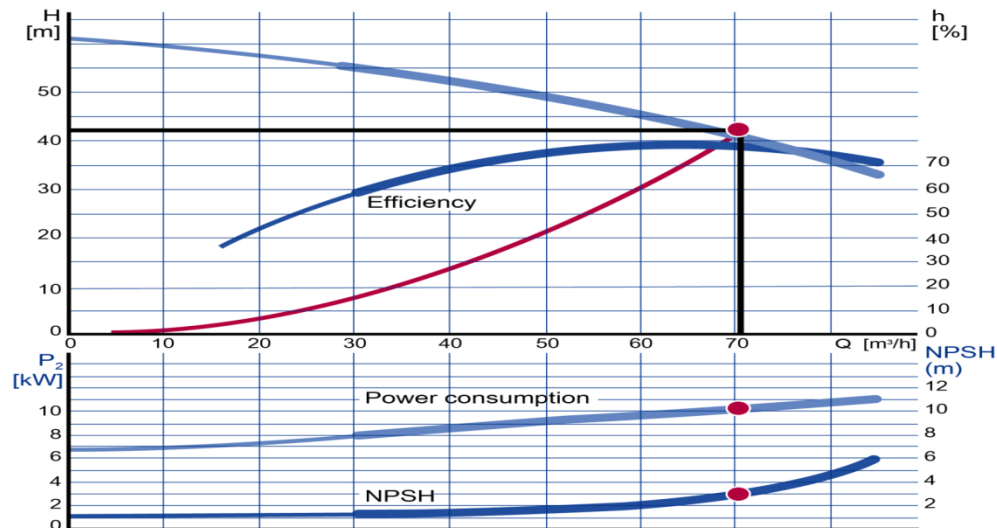


Fig. 6: Typical performance curves for a centrifugal pump.

The performance of a centrifugal pump is shown by a set of performance curves. The performance curves for a centrifugal pump are shown in Figure 6. Head, power consumption, efficiency and NPSH are shown as a function of the flow.

7. Galvanic Corrosion :



Fig. 7: Galvanic corrosion of eye bolt connected to a stainless

When two different metals are electrically connected and in contact with an electrolyte (liquid), they will form a galvanic cell where the more noble material is cathodic and the less noble anodic. The anodic material will corrode. A sample of galvanic corrosion is shown in Figure 7. The electro potentials of metals can be measured in different water solutions and listed in galvanic series, as for seawater (Figure 8).

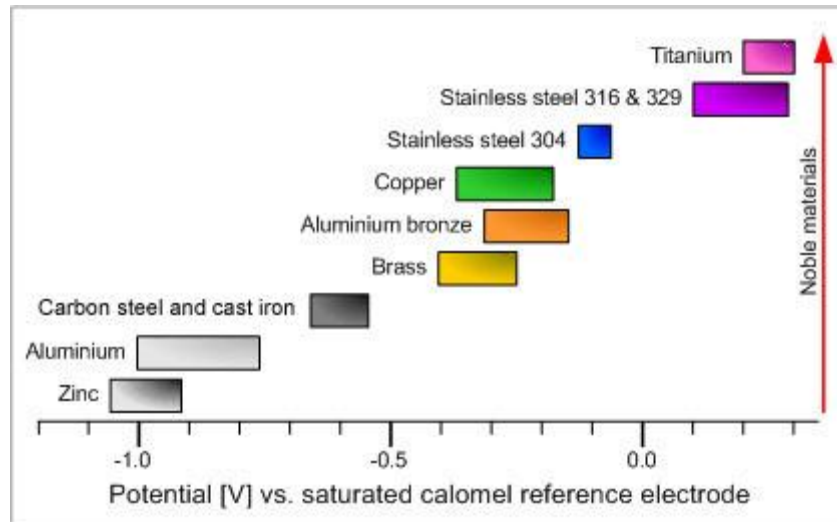


Fig. 8: Galvanic series for metals in sea water.

The corrosion rate depends on:

- The surface area ratio between cathode and anode (a bigger anode area compared to the cathode area reduces the galvanic effects, e.g. stainless steel fasteners on a cast iron pump).
- The magnitude of potential difference (compare aluminium bronze in contact with stainless steel and cast iron in contact with stainless steel).
- The conductivity of the electrolyte (liquid).

8. Selective Corrosion :

Selective corrosion occurs in metals in which the alloying elements are not uniformly distributed. Typical examples of this type of corrosion are:

- Dezincification of brass, whereby zinc is dissolved and leave behind a porous copper material.
- Graphitization of cast iron (Figure 9), whereby the iron is dissolved and leave behind a network of graphite of low mechanical strength.



Fig. 9: Graphitic corrosion of an impeller made of grey cast iron.

Common factors for corrosion:

Some of the most important parameters affecting the corrosion rate of metals are outlined below.

1.Oxidizing agents: The corrosion process is conditional on an anodic reaction and a cathodic reaction taking place simultaneously. The anodic reaction causes the metal to dissolve. An oxidizing agent must be present for the cathodic reaction, and the most common agents are dissolved oxygen or hydrogen ions. If the availability of oxidizing agents is restricted, the corrosion process will be inhibited or will cease entirely. The hydrogen concentration can easily be measured as pH-value. Oxygen is normally present in water, but not in sewage due to the oxygen consuming bacteria.

2.The electric conductivity of the electrolyte: Corrosion involves electrochemical reactions, and an increase in the electrical conductivity of the electrolyte will therefore increase the corrosion rate. In sea water the chloride content causes rapidly increased conductivity.

3.Temperature: An increase in temperature will generally cause an increase in the corrosion rate. A rule of thumb is that temperature increases of 10°C will double the corrosion rate.

4.Concentration: An increased concentration will normally increase the corrosion rate up to a maximum level. Higher concentration above this will not give higher corrosion rate, for example, a chloride concentration above approximately 1500 ppm will not increase the corrosion rate.

Corrosion control:

To make the use of steel and other metals practical in construction and manufacturing, some corrosion-protection practices must be employed. Otherwise, the life of steel and other metals will be limited, reducing efficiency and escalating the cost of maintenance. There are several

effective ways to stop corrosion:

1.Sacrificial metals: Steel can be protected by adjacent placement to a dissimilar metal. For example, if zinc or magnesium is placed in direct contact with steel, it protects the steel from corrosion. Usually, on board ships, this sacrificial anode is fitted in the suction filter of the sea line and in all the heat exchangers. Here, zinc and magnesium serve as sacrificial metals that not only protect the area of immediate contact, but also protect beyond the metal in each direction. They can function economically and efficiently without any maintenance during the operating period to control the corrosion. Furthermore, after installation there are no labor costs involved and no electrical supply is required.

2.Electrolytic system: This is one of the most commonly used systems to fight bio-fouling on ships. The electrolytic system consists of pairs of anodes, mostly copper and aluminum (or iron). The anodes are mounted in the sea chest or the strainer.

DC current is passed through the copper anodes, which produce ions that are carried with the seawater in the whole piping network (Figure 10). These copper ions in the seawater prevent marine organisms from settling down and multiplying on the surface of the pipes. The second anode is used to prevent corrosion of the metal surface. The iron anodes help in preventing layers of oxide films of the metals from breaking down by the corrosive agents (sulphur) of seawater. This system also gives protection to valves, condensers, engine cooling systems and ancillary equipment.



Fig. 10: Electrolytic system

A control panel measures and monitors the output of each of the anodes.

3.Chemical Dosing: Chemical dosing is also a common method which is used to prevent marine growth in piping network. Anti-fouling chemical such as ferrous chloride is used to dose sea water boxes. The chemical coats the pipe work with a protective ferrous layer to prevent corrosion.

4.Ultrasonic: High frequency waves are also used as a method to prevent marine growth in piping systems. Ultrasonic system is supposed to be known as one of the most highly effective methods to prevent bio-fouling. A reduction in bio-fouling of as much as 80% is claimed by this method

In the ultrasonic method, a wave generator produces and sends electrical impulses at high frequency. These waves are passed through a coaxial cable to transducers which are mounted externally to the sea chests or strainers. The transducers contain piezoelectric ceramic crystals, which when excited by electrical impulses, generate an ultrasonic beam. The main advantage of this system is that it is non-invasive and no parts are in contact with sea water. Moreover, no toxic substances are produced.

B. EROSION

Erosion - Abrasive wear - is the mechanical removal of metal from the cutting or abrading action of solids carried in suspension in the pumped liquid. The rate of wear for any material is dependent upon the following characteristics of the suspended solids:

1. Solid concentration
2. Solids size and mass
3. Solids shape (spherical, angular or sharp fractured surfaces)
4. Solids hardness
5. Relative velocity between solids and metal surface

The rate of wear is also dependent upon the materials selected for the rotation and stationary components of a centrifugal pump. Although metal hardness is not the sole criterion of resistance to abrasive wear, hardness does provide a convenient index in selecting ductile materials usually available for centrifugal pumps. Such an index is shown in Figure 11, where the abrasive wear-resistance ratio is shown as a function of Brinell hardness for various materials.

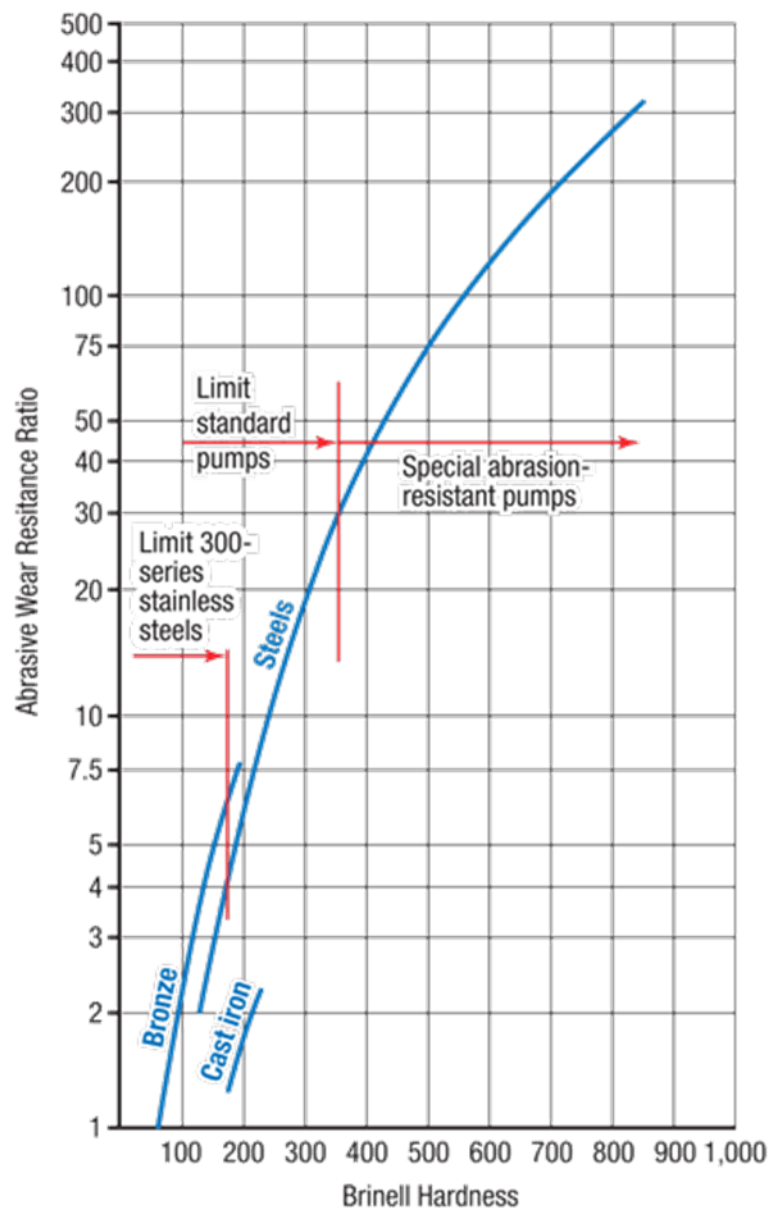


Fig. 11: Hardness Index

It should be noted that a brittle material, such as cast iron, exhibits a much lower ratio than either the steels or bronzes of the same hardness. The following tabulation can also be used as a guide in material selection, listed in order of increasing abrasive-wear resistance:

1. Cast iron
2. Bronze
3. Manganese bronze
4. Nickel-aluminum bronze
5. Cast steel
6. 300-series stainless steel
7. 400-series stainless steel



Fig. 12: Erosion damage of a pump.

The fluid being pumped is often not well defined. Terminology like river water, sea water, boiler feed water, condensate water, etc., is usually the only definition we have of the fluid being pumped. Any of these fluids can contain several concentrations of solids that cause erosion and wear inside a pump (Figure 12).

Common factors for erosion:

Some of the parameters affecting the erosion of metals are given below.

Solid particles : The sea-water circulating pumps of ships operating in waters that contain large quantities of silt and sand. A pump handling liquids which contain abrasives, will suffer erosion on all internal surfaces, including bearings and shaft seals. Materials inside the pump should be changed to more resistant materials. Materials such as carbon steel, high chrome iron, harden stainless steel, or hard coatings like ceramic or tungsten alloy are some of the most commonly used.

Fluid Velocity : Small impellers with high motor speeds may produce the necessary pump pressure. This type of combination produces high fluid velocities that will wear pump parts much faster than desirable. In addition the impeller suffers rapid wear due to high tip velocities. When a pump is disassembled and excessive wear is found, 95% of the time velocity fluid is to blame.

Turbulence: Uneven wear in parts is often due to turbulence. Bad piping designs or poorly sized valves can cause turbulence or uneven wear in pumps. Whenever possible, use straight

pipe sections before and after the pump. Uneven flow creates turbulent flow and excessive wear occurs.

It is not recommended to place an elbow at the suction of any pump (Figure 13). This will cause a turbulent flow into the pump. If elbows are needed on both sides of the pump, can be used long radius elbows with flow straighteners. It should have 10 pipes diameters before the first elbow on the suction piping (Example: If the pump has a 10 cm. diameter of suction nozzle, it should respect 100 cm. of straight pipe before the first elbow). Short radius elbows cause vibrations and pressure imbalances that lead to wear and maintenance on the pump.

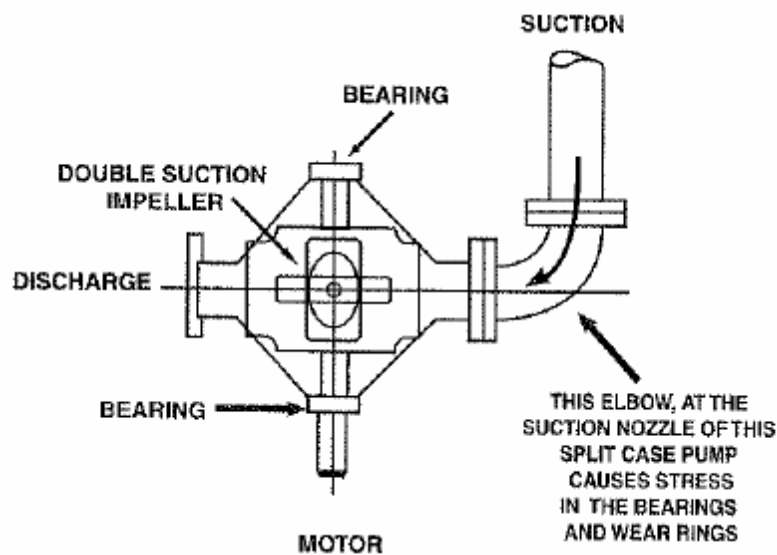


Fig. 13: Pump suction pipe.

A pipe size increase can be used in the discharge piping. This will reduce the fluid velocity and friction losses. An isolation valve with a low loss characteristic such as a gate valve should be placed after the increaser and check valve.

Throttling: A centrifugal pump should never be operated continuously at or near the shut off head. This normally happens when a tank or vessel is near the maximum capacity and an operator or level sensor starts closing the discharge valve while the pump is running. All this wasted energy is transferred to the fluid being pumped. This type of operation shortens the life of the pump and increases the downtime. This energy is converted into heat and vibration raising the fluid temperature. Some pump casings can dissipate the heat. Other casings contain heat switches that will trip-out and “shut off” the pump.

An intensive radial load is created when operating near the shut-off head and the shaft deflects about 60° from the cut-water. This concept is called shaft deflection. The pump will be noisy, will vibrate, and maintenance on seals, bearings, and shaft sleeves is expected.

C. CAVITATION

Centrifugal pumps are often victims of cavitation if the local pressure falls below the vapor pressure of a specific liquid. The pressure of the pump in feet of water is known as the Net Pressure Suction Head available (NPSHa) and this is the sum of atmospheric pressure (H_a), vertical distance from water surface to pump centerline ($\pm H_z$), friction in the pump (H_f), pump flow velocity (H_v) and vapor pressure of the water at ambient pressure (H_{vp}).

$$NPSHa = H_a + H_z - H_f + H_v - H_{vp}$$

If the NPSHa falls below the Net Pressure Suction Head required (NPSHr) damaging cavitation will occur, this is called suction cavitation. It can be caused by design, specific operating conditions or obstructions in the system. NPSHr is a value determined by the manufacturer through testing. The manufacturer may also determine Net Pressure Suction Head inception (NPSHi), this is the pressure required by the pump to suppress all cavitation. In between NPSHi and NPSHr non-damaging cavitation can occur.



Fig. 14: Cavitation damage in some pumps. Note the tag team effect caused by erosion and corrosion

Other ways a pump can experience cavitation is through recirculation and excessive discharge velocities. In recirculation, the relative velocity of two opposed flows of liquid is very high, thus causing cavitation.

Cavitation corrosion appears in areas where vapour bubbles are formed due to low pressure. When the bubbles implode on a surface the protective oxide is destroyed and eroded away and after that built up again. The process is repeated and characteristic deep holes of cavitation corrosion are formed on the surface. It can usually be seen on the trailing edge of impellers (Figure 14).

The impact of the impeller material on the life of a high-suction energy pump under cavitation conditions is shown in Table 1. As an example, changing from mild steel (reliability factor of 1.0) to stainless steel (reliability factor of 4.0) would increase the

impeller life from cavitation damage by a factor of four. Hard coatings, such as certain ceramics, can also increase the impeller life under cavitating conditions.

Table 1: Material Cavitation Life Factors.

Material	Life Factor
Nickel – Aluminium Bronze	8.0
Titanium	6.0
Bronze	4.0
300 – Series Stainless Steel	4.0
400 – Series Stainless Steel	3.0
Monel	2.0
Cast Iron	1.5
Brass, Gun Metal	1.2
Mild Steel	1.0

Cavitation can be detected and mitigated since the mechanisms behind cavitation are well understood and because cavitation generates a shock wave resulting in audible sounds and mechanical vibrations. This sound is usually observed as “crackling” or popping.

Simple ways to reduce cavitation in a pump system are –

- Increase pressure at the head.
- Reduce frictional piping losses and turbulence.
- Avoid operating pump in a heated condition.

CONCLUSION

Pumps are highly engineered machines which require close tolerances for proper performance. Therefore, the compatibility of a material with the pumpage is essential to the overall satisfaction of the pump user. A complete understanding of corrosion as it relates to the various pump components is vital in achieving the reliability expected today.

In summary, the following criteria should be considered in the selection of the material for a centrifugal pump impeller and/or casing:

1. Corrosion resistance
2. Abrasive-wear resistance
3. Cavitation resistance
4. Strength (primarily for the casings)
5. Casting and machining properties

6. Cost

For most water and other noncorrosive services, bronze satisfies these criteria for the impeller and thus is the most widely used impeller material for these services. Cast iron impellers should generally be used to a limited extent in small, low-cost pumps. As cast iron is inferior to bronze in corrosion, erosion and cavitation resistance; low initial cost would be the only justification for a cast iron impeller. Further, stainless steel impellers are widely used where bronze would not satisfy the requirements for corrosion, erosion and/or cavitation resistance. For the pump casing, cast iron is the generally preferred material in most water and waste water pumping applications.

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