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Design of Mechanical Oil Seal and Gasket

S. M. Muzakkir[a,*] and Satish Kumar [b]

[a] *Department of Mechanical Engineering, Jamia Millia Islamia, New Delhi, India*
[b] *Department of Mechanical Engineering, Indian Institute of Technology Delhi, India*
**Corresponding Author Email Id: smmuzakkir@jmi.ac.in,*
mez108659@mech.iitd.ac.in

ABSTRACT

The leakage of fluids in mechanical systems (hydraulic and lubricating systems) is undesirable and its direct consequences include industrial downtime, reduced product quality, environmental pollution, fire hazards etc. The prevention of leakage minimizes the equipment maintenance cost and prevents hazardous accidents. The seals are tribological elements that are used for closing the unintentional openings or gaps between the jointed members. They provide a physical barrier that produces a joint which prevents leakage and withhold fluid under pressure. The critical of the seal types are contact seal which operates with rubbing contact against its mating surface under positive pressure. The gaskets are used to provide sealing of mating flanges of a mechanical joint which does not involves any gross relative motion. Any improper selection or design of the seal and gasket may result in its failure in form of leakages, pressure losses, contamination or heat generation that causes reduced efficiencies, energy losses, degraded performance and possibly environmental pollution. The present paper describes the design of an oil seal and gasket.

Keywords: Leakage, Design, Tribological Considerations,

INTRODUCTION

The seals are required for closing the unintentional openings or gaps between two or more jointed members for producing a joint that can prevent leakage and withhold fluid under pressure by providing a physical barrier. Basic functions of seal are prevention of fluid leakage between two relatively moving machine components and prevention of entry of foreign particles, like dust or abrasive material into the operating medium. To fulfill these functions, a seal unit requires the following:

1. A sealing medium

An elastomer such as nitrile (resistant to fuels and oils), silicon (non-reactive, stable, and resistant to extreme environments and temperatures from -55 °C to +300 °C) and fluoro rubber (resistance to high temperatures and chemicals) is used as a sealing medium. The other important function of the elastomer is to bear the misalignment of the shaft and the vibrations.

2. A loading mechanism

A loading mechanism comprise of spring which is required to compensate for the wear of the seal during its use.

3. A casing

A casing provides an enclosure that contains seal and restricts its degrees of freedom

The size of seals varies from few millimeters (for micro-bearings) to few thousand millimeters (for canal locks) because of their wide range of applications, e.g. in motor industry, household appliances, power and pump industries, offshore applications, oil refining, automotive, aerospace, construction, agriculture, hydraulics and pneumatics industries. The construction of a typical commercial oil seal unit is shown in Fig.1

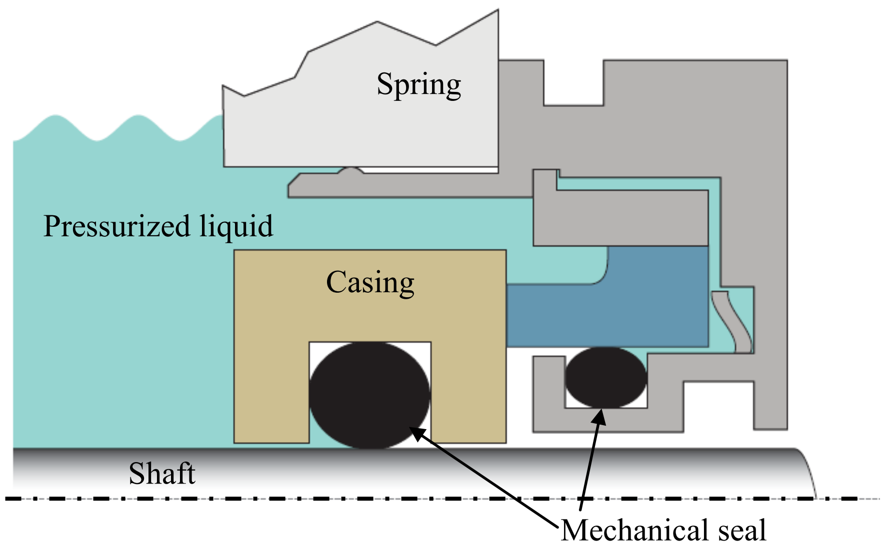


Fig 1 Construction of oil seal [1]

This seal unit consists of an elastomeric seal, circumferential spring, called garter spring, and metallic (carbon steel, aluminium or brass) casing. A press fit between casing and seal is recommended to avoid rotation of the seal material in the casing. To reduce the extent of press-fit casing-bore and seal outer diameters must be machined to the required tolerances and surface roughness. For proper functioning of the oil seals, the shafts should have a highly polished surface free from scratches and tool marks.

The seals may be classified into contact seals and clearance (non-contacting) seals. Contact seals bears against its mating surface under positive pressure whereas clearance seals operates with positive clearance (i.e. no rubbing contact). For both kinds of seals, knowledge of tribology is essential. The majority of the seal types are contact seals, operating with rubbing contact. Friction and wear can be held to a minimum by ensuring that the contact surface is adequately lubricated.

The flat gaskets for industry were first invented by Austrian Engineer Richard Klinger about 100 years ago using asbestos and rubber material. A gasket is a material or combination of materials clamped between two separable members of a mechanical joint. Its function is to affect a seal between the members (flanges) and maintain the seal for a prolonged period of time. The gasket must be capable of sealing the mating surfaces, impervious and resistant to the medium being sealed, and able to withstand the application temperature and pressure.

The relationship between a gasket and its mating flanges is dynamic in nature. The reasons for this are the deformations associated with internal pressure, vibration, external forces, and thermal expansion or contraction. These deformations are dynamic due to external disturbances. The performance of the gasket is affected by gasketing environment and is strongly dependent on the design of the flanges and fasteners. The figure 2 gives the nomenclature of a typical gasketed joint.

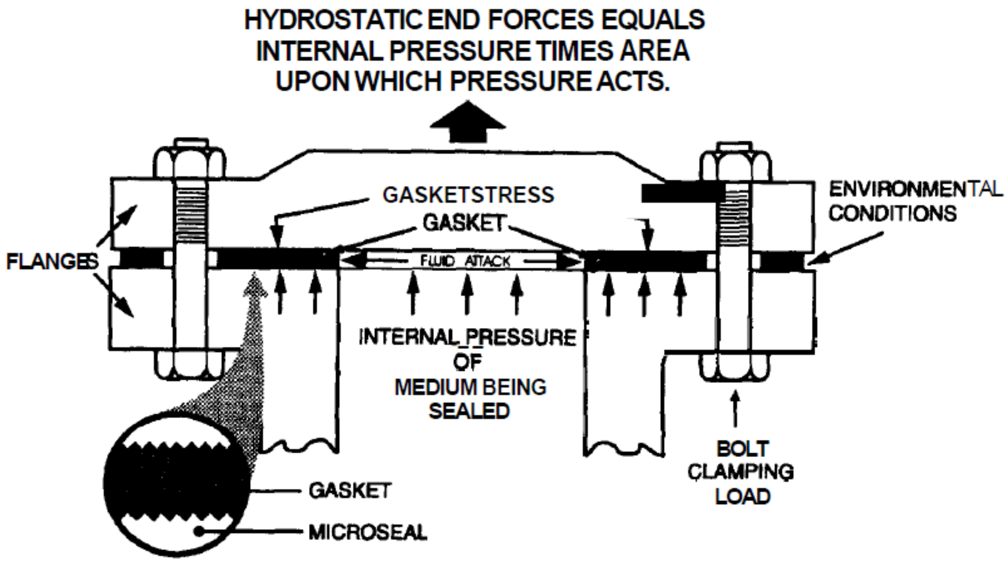


Figure 2 Nomenclature of a gasketed joint [5]

The design of a gasket requires consideration of the gasket and the joint together. The gasket may work or fail according to whether the joint is designed in accordance with the properties of the gasket. In order to ensure successful design and use of a gasket, the gasket must satisfy the following requirements: it must be heat and media resistance, it must ensure zero leakage through the gasket, it must ensure zero leakage over the gasket, it should be environmentally safe, it must accommodate surface finish conditions of flanges, be able to reduce and/or control port distortion, be able to reduce and/or control flange distortion, it must accommodate thermal expansion and contraction, it must possess adequate recovery, it must minimize torque loss, must not require any re-torque, it must transfer heat as desired, it must maintain close tolerance on compressed thickness-maintain shim thickness, it must provide acoustic or thermal isolation and must have anti-stick properties.

DESIGN OF MECHANICAL OIL SEAL

The seal is interposed between two machine elements that have relative motion between them constituting a tribo pair. Therefore, the design of a seal requires tribological considerations. Tribology is required for sustainability of the systems having relatively moving machine elements such as gears, cam & follower, bearings, seals, valves, etc. Decrease in the system performance due to aging depends on the rate of wear. Therefore, it is very important to understand the change in system with time and frame suitable maintenance schemes for that system. The various demands on a fluid seal are quite stringent and some are contradictory. The leakage must be low or effectively zero, but a contradictory demand is low friction and low wear rate.

Any improper selection or design of the seal may result in failure in form of leakages, pressure losses, contamination or heat generation that causes reduced efficiencies, energy losses, degraded performance and possibly environmental pollution. The failure costs are generally high as it includes down time costs also in addition to seal cost and disassembly & installation costs. As per mechanical design, the diameter of the sealing lip must be slightly less than the shaft diameter so that the seal is elastically deformed while being mounted on the shaft. The elastic deformation and spring action creates contact pressure between the sealing lip (small portion of the elastomer which makes mechanical contact over the surface of the rotating shaft) and the rotating shaft. Too large magnitude of the contact pressure causes excessive friction, resulting in high temperature and rapid wear of the sealing lip. On the other hand, excessive leakage happens due to too little contact pressure. An estimation of the correct contact pressure between the seal lip and the shaft is essential to reduce friction, increase seal life and getting good sealing.

In designing a seal, the thickness of oil film between seal faces play an important part in determining seal performance and seal life. If thickness of oil film too small it can be bridged by surface irregularities, producing high friction and rapid seal wear. If too thick, the meniscus will break down, producing a high leakage rate. In practice, the seal will not be perfect under dynamic conditions (i.e. it will not be zero–leakage without excessive preload pressure), and its performance will also depend on load, speed and fluid viscosity.

The prevailing failure mode of contacting seals is wear of seal material. Seal wear is dependent on the contact pressure and surface finish of the surface against which the seal rubs, this in turn being determined to a large extent by the production method. Wear can then be aggravated by lack of lubrication, shaft irregularities, excessive frictional heat, a seal compound which is too soft, etc. To reduce wear and avoid leakage, the sealing interface can be designed targeting almost nil to full hydrodynamic lubrication mechanism. On one hand, wear rate depends on the designed lubrication regime and is the lowest for hydrodynamic lubrication. However, on the other hand the rate of leakage strongly depends on the operating clearance (leakage gap) between the sealing surfaces. Therefore, tribological design of seal is a trade-off between wear rate and leakage rate. It is important to understand that even a modest degree of waviness or slight distortion may provide favorable lubrication or excessive leakage. Therefore a detailed study of these aspects is essential for sustainable seal operation.

For tribological design of seals, consideration of fluid surface tension must be accounted. The usual formula to calculate the pressure due to capillarity is

$$\Delta p = \gamma \left[\frac{1}{R_1} + \frac{1}{R_2}\right] \qquad (1)$$

where γ is the surface tension, R_1 and R_2 are the radii of the meniscus in mutually perpendicular planes.

In case of parallel plane surfaces, R_2 can be taken as infinity and R_1 as approximately h/2 where h is the separation of the surfaces. From equation (1) it can be said that higher surface tension is desirable to reduce leakage rate. For example, the contact angles of oil against synthetic rubber and steel under industrial conditions are found to be high, so that the sealed oil does not spread along the steel shaft and leakage rate is negligible if pressure difference across the sealing surfaces is lesser than Δp predicted from Eq. 1.

The surface tension is a function of temperature; therefore, increase in temperature will increase the leakage rate. In addition, wear rate also increases with increase in temperature; this means tribological design of seal must incorporate thermal analysis.

If the fluid pressure across the seal is over and above the required pressure to overcome the surface tension (Eq. 1), an estimate of the volume of the leakage may be made using the following formula:

$$\text{Flow/unit width} = \frac{1}{12\mu} h^3 \frac{dp}{dx} \qquad (2)$$

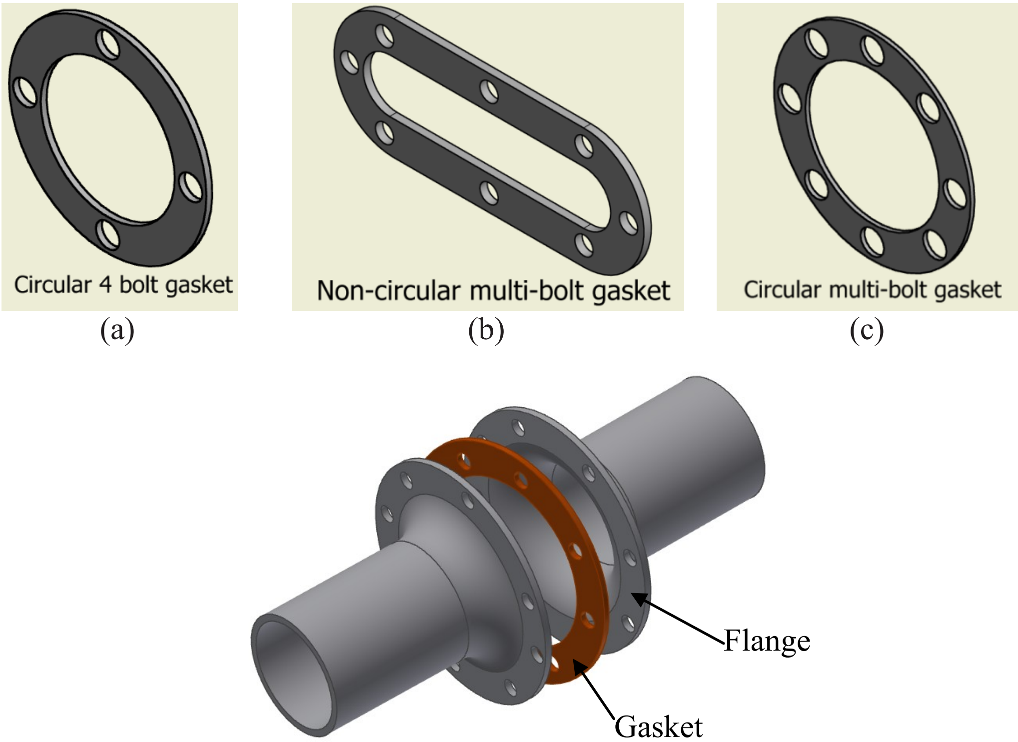
Where μ is the dynamic viscosity, h is the separation distance between the surfaces, and $\frac{dp}{dx}$= pressure gradient.

DESIGN OF GASKET

Under ideal conditions, to obtain a sealed joint between two members, they should be perfectly flat, smooth and rigid, so that they could be bolted together and sealed without the need for a gasket. However, due to manufacturing limitations a gasket is required to fill the cavities between the two members and prevent joint leakage. A host of design and analysis challenges are associated with gasketed joints. Among these challenges is the reaction of the gasket material to the sealed medium, the pressure that the gasket can withstand in the radial direction, the environmental effect on the gasket material such as temperature and humidity, and more importantly the change in the gasket thickness and stresses, which is referred to as gasket creep relaxation. The gasket must compensate for this non-uniform flange loading and distortion.

A sealing between jointed members using gasket is achieved by the compression between them. This compression causes gasket material to flow into the imperfections on the gasket seating surfaces for ensuring complete contact between the gasket and its seating surfaces thereby preventing the leakage of the pressurized fluid. Like seal, the basic function of gasket is to prevent leakage from or into the system having relatively stationary components. As there is no relative motion, there is no need of tribology and gaskets can be designed based on mechanical design guidelines. From mechanical design point of view, a gasket is required to fill the space between two mating surfaces and should be able to sustain compressive loading. Due to absence of relative motion between mating parts, 'less-than-perfect' mating surfaces may be used and their surface irregularities are filled by gasket material. In other words gasket material must be able to deform and tightly fill the space including any slight irregularities under compressive loading. The gasket is also subjected to a side load due to internal pressure that tends to extrude it through the flange clearance space. To resist this extrusion the effective compression pressure must be greater than the internal fluid pressure. For reliable sealing the gasket material must be able to withstand high compressive pressure (greater than 15MPa).

Gaskets are commonly produced by cutting from sheet materials, such as gasket paper, rubber, silicone, metal, cork, felt, neoprene, nitrile rubber, fiber glass, polytetrafluoroethylene (PTFE or Teflon) or a plastic polymer (polychlorotrifluoroethylene) as shown in figure 3. The assembled views of the different gasket joints are shown in figure 4.



(d)

Figure 3 (a), (b), (c) Types of Gasket and (d) Gasket assembly [2]

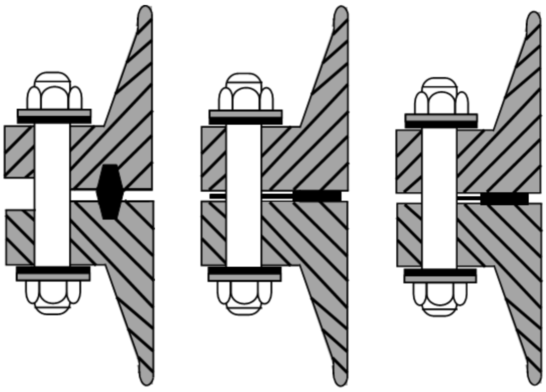


Figure 4 Assembled views of different gasket joints [2]

The design of a gasket requires careful consideration of the following aspects [2]:

i. Since the gasket material needs to fill surface irregularities, therefore it must be resilient enough to flow into and fill any irregularities in the surfaces being sealed.

ii. It must remain rigid enough to resist extrusion into the clearance gap between the surfaces under the full system pressure being sealed.

iii. Since a resilient flow is required for gasket closure therefore sufficient closure loading and consequent compressive stresses is required. This requires evaluation of the internal pressure causing leakage problems, the gasket contact pressure produced by the bolt forces, and the gasket materials, which are selected to withstand the operating conditions.

iv. Since the performance of the gasket is degraded due to stress relaxation therefore sufficient contact pressure is required to be maintained to store elastic strain energy to resist relaxation effects. Greater the stored elastic strain energy of the seal greater will be the margin available to resist any relaxation effects during use.

v. Sufficient stresses are required to cause flow of gasket into the imperfections in the seating surfaces. The load required for this deformation is dependent on the gasket material.

vi. The selection of the gasket material must be such that it will withstand the operating pressures and temperature. A material with a low relaxation is preferable as can be used with lower initial compression pressure (otherwise provides higher factor of safety at the same pressure).

vii. Surface finish of gasket seats dictates the thickness and compressibility necessary in the gasket material for providing a physical barrier in the clearance gap.

viii. Flange faces must be parallel and sufficiently rigid to resist distortion on being tightened down and under hydrostatic end loads. Distortion under working loads, often called flange rotation, can appreciably affect the working conditions of the gasket.

ix. The mechanical design of gasket should aim to distribute the load evenly over the whole area of the gasket rather than have a few points of high loading with reduced stress at mid points between the bolts. A more satisfactory arrangement is achieved by employing a large number of smaller diameter bolts rather than fewer bolts of larger diameter. The preload on the bolt must be large enough to achieve minimum seating pressure.

Following are the properties of the gasket material that are important for sealing performance in the application: chemical compatibility is to be resistant to the media being sealed, sufficient heat resistance to withstand the temperature of the environment, seal-ability to provide sealing ability both through the material and over its surface, compressibility or macro-conformability to conform to the distortions and undulations of the mating flanges, micro-conformability to “flow into” the irregularities of the mating flange surface finishes, recovery to follow the motions of the flanges caused by thermal or mechanical forces, creep relaxation to retain sufficient stress for continued sealing over an extended period of time, erosion resistance to accommodate fluid impingement in cases where the gasket is required to act as a metering device, compressive strength to resist crush and/or extrusion caused by high stresses, tensile or radial strength-to resist blowout due to the pressure of the media, shear strength-to handle the shear motion of the mating flanges due to thermal and mechanical effects of the mating flanges, strength to result in easy used gasket removal without internal fracture of the material, flexibility to be able to flex without fracture both initially and after extended storage, anti-stick property to ensure gasket removal without sticking, heat conductivity to permit the desired heat transfer of the application, acoustic isolation to provide the required noise isolation of the application, anti-corrosiveness to provide anticorrosive characteristics between the material and the mating flanges, dimensional stability-to permit correct assembly.

The static sealing of the joint is achieved by proper design of the flanges, selection of gasket type and its material along with its proper installation. The type of flange for a particular application may be selected from ASME standard flanges (which are categorized based on the pressure rating) as given in ASME B16.5. The ASME Unfired Pressure Vessel Code Section VIII, Division I defines the different types of gaskets and their materials to enable selection by the designer as per the operating conditions. The material for the gasket must have good chemical resistance, heat resistance and compressive strength [3]. There are three categories of gasket materials:

1. Non-metallic (elastomers, compressed non-asbestos, PTFE, flexible graphite, mica slabs etc) as given in ASME B16.21
2. Semi-metallic (metallic gaskets containing filler materials like PTFE, flexible graphite, mica, ceramics etc. as given in ASME B16.20 and to be used with ASME standard flanges (ASME B16.5), and
3. Metallic, mostly available in ring type with oval, octagonal and other cross sectional shapes.

The type of gasket material is selected based on the operating conditions. Figure 5 gives the operating range of the different gasket materials.

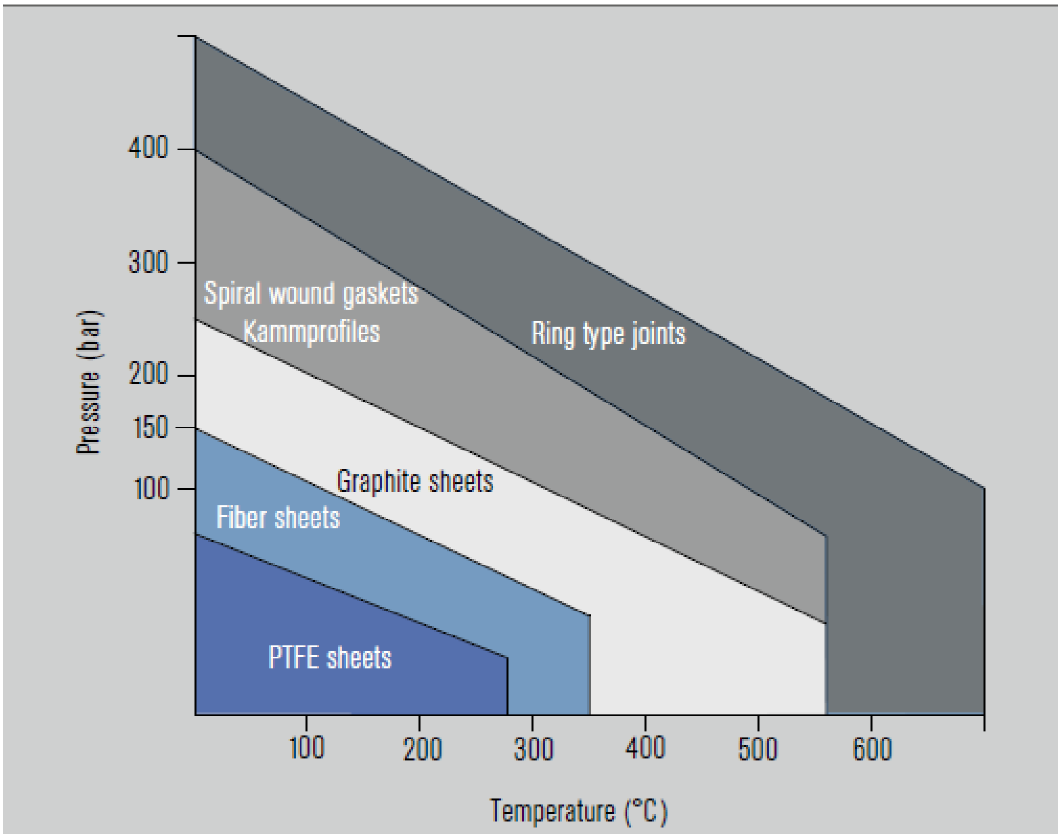


Figure 5 Standard gasket types – Operating temperature range [8]

In the first step in the design of a gasket joint, the selection of the gasket type and its material is made that suits the operating conditions (internal fluid pressure, operating temperature, environment, etc.) (Figure 5). The yield value (minimum pressure required to maintain a leak proof gasket joint in the absence of the internal fluid pressure) of the gasket, denoted by 'y', is read from table [3]. Similarly, the ratio between the resultant contact pressure and internal fluid pressure, denoted by 'm', is also read from table [3] corresponding to the given gasket type. This ratio must not be less than a critical value for maintaining leak proof joint because the internal fluid pressure reduces the gasket contact pressure. Since the compression of the gasket is not uniform over its entire compression area due to distortion caused by bolt tightening and fluid pressure therefore only a narrow band on the outer edge is considered for gasket pressure estimation. It is known as effective gasket yielding width and is denoted by 'b'. The equations for determining this width is available in [1]. The determination of the flange type, bolt size, number of bolts & their arrangement and bolt preload are then determined. The figure 6 gives the details of the forces acting on a gasketed joint. The gasket pressure developed due to these forces is shown in figure 7.

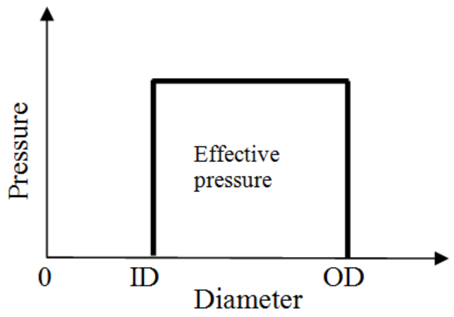


Figure 7 Gasket pressure at the time of assembly [9]

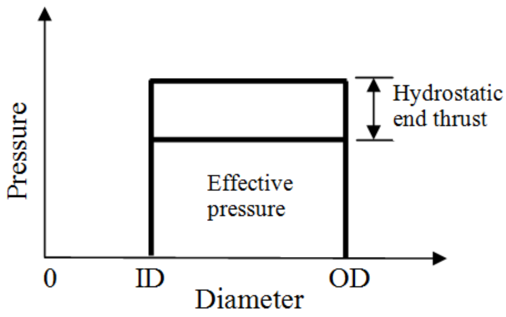


Figure 8 Gasket pressure when the internal fluid pressure is applied [9]

The force in the bolt due to initial tightening is given by:

$$F_g = A_g \cdot q \tag{3}$$

Where F_g is force in the bolt, A_g is the effective gasket area and q is the pressure on the gasket due to bolt tightening. With the consideration of internal fluid pressure, a force $F_p = A_i \cdot p$ is produced where A_i is the area subjected to internal fluid pressure and p is the internal fluid pressure. The total force on the gasket is thus equal to A_g m p. The total bolt force is given by

$$F_b = p(A_i + A_g \cdot m) \tag{4}$$

The force on gasket must then be equal or greater than F_b.
On equating equation 1.1 and 1.2, we obtain

$$A_g \cdot q = p(A_i + A_g \cdot m) \tag{5}$$

The figure 8 depicts a joint proposed to be fitted with a gasket for preventing leakage of pressurized fluid.

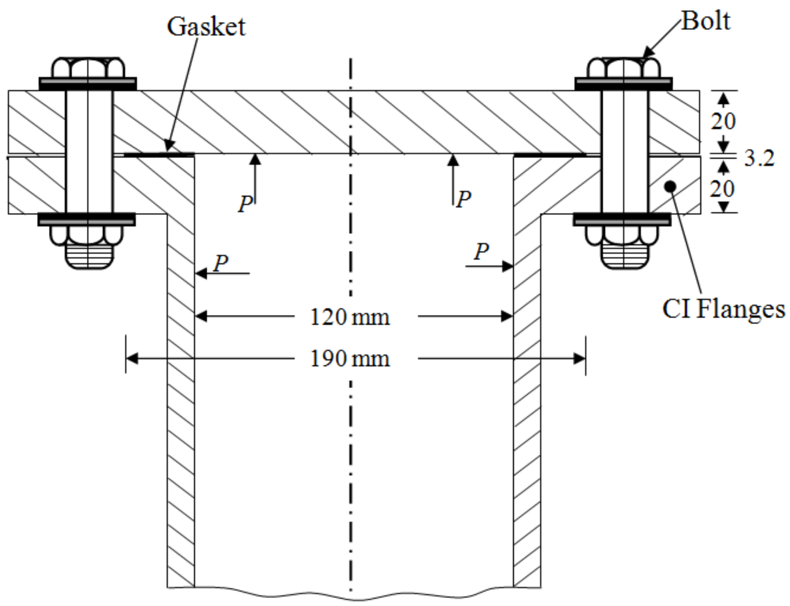


Figure 8 Gasket assembly [2]

The internal fluid is non-corrosive and is at a pressure '*p*' of 12x10^6 N/m^2 (gauge). 24 bolts of 1/2"-12 UNF series are required to keep the cover in place. In order to select a suitable gasket the bolt loading is required to be determined for ensuring a leak proof joint.

The fluid is non-corrosive therefore aluminum may be selected as the gasket material. For the aluminum corrugated gasket, the geometry given in figure 8 may be used The fluid is non-corrosive therefore aluminum may be selected as the gasket material. For the aluminum corrugated gasket, the geometry given in figure 1.2.5 may be used. The effective gasket width '*b*' is taken to be 3.2mm. The gasket factor 'm' is 2.5 and yield value for the gasket material 'y' is 20x10^6 N/m^2 (Table 2-5.1, pp 356, Reference [3]).

The area subjected to internal pressure, $A_i = \pi \cdot 0.120 \cdot 0.0032 = 0.0012m^2$

The effective gasket area $A_g = \frac{\pi}{4}\left(0.190^2 - 0.120^2\right) = 0.017m^2$

Using equation 1.3 with m=2.5,

$$q = \frac{12\times10^6\left(0.0012 + 0.0170\times2.5\right)}{0.0170} = 30.85\times10^6\ N/m^2$$

Since the gasket pressure is more than the yield value for the gasket material (20x10^6 N/m^2), therefore this pressure causes the yielding of the gasket that fills the surface asperities and produces a leak proof joint.

The bolt force required for the joint is $F_b = p\left(A_i + A_g \cdot m\right)$= 0.5 MN.

After the initial sealing stress is applied to a gasket, it is necessary to maintain a sufficient stress for the designed life of the unit. This is most important for maintenance of the seal. All materials exhibit decrease in applied stress as a function of time referred to as stress relaxation. The reduction of stress on a gasket is actually a combination of two major factors, stress relaxation and creep (compression drift). The stress relaxation is a change in stress on a gasket under constant strain and creep (compression drift) is a change in strain of a gasket under constant stress. Figure 9 and 10 depicts the effect of creep relaxation on the gasket pressure for high grade gasket subjected to heavy load and low grade gasket subjected to light loads respectively.

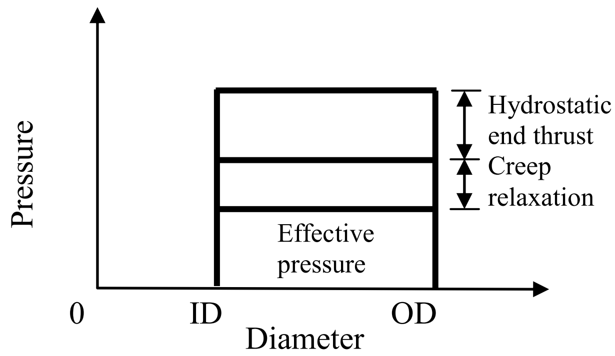


Figure 9 Effect of creep relaxation on the pressure on the high grade gasket [9]

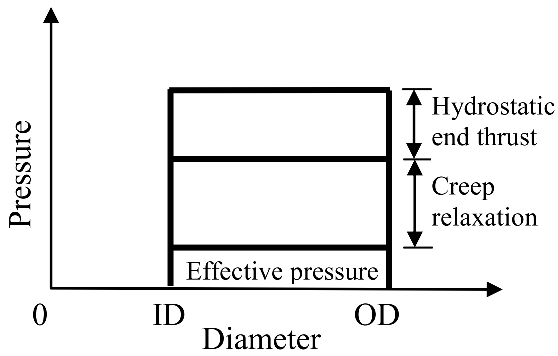


Figure 10 Effect of creep relaxation on the pressure on the low grade gasket [9]

CONCLUSIONS

The paper presented an overview of the design of seal and gasket. The design considerations and desirable material properties for the seal and gasket are described. It was highlighted that the design of mechanical seal requires the tribological considerations whereas design of gasket requires only mechanical considerations. For proper functioning of the oil seals, the shafts should have a highly polished surface free from scratches and tool marks so that wear of the seal is minimized. No such requirements are necessary for a gasket joint. However, the gasket design is affected by the operating conditions and life of the joint is dependent upon the creep relaxation.

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