Chapter 1

Introduction

1.0 Introduction to Tribology

1.0.1 Definition of Tribology

The word tribology is defined as "a study that deals with the design, friction, wear, and lubrication of interacting surfaces in relative motion as in bearings or gears". Tribology word comes from the Greek word "Tribos" which means rubbing or sliding and the suffix "Ology" means "the study of". It deals with phenomena related to friction, wear and lubrication. In everyday life we come across surfaces in contact and in relative motion against each other.

1.0.2 History of Tribology

The word "Tribology" was first introduced in the "Department of Education and Science Report" known as "Jost Report" published in England in 1966. It encompasses the interdisciplinary aspects of science and technology of interacting surfaces in relative motion and associated subjects and practices. It includes part of physics, chemistry, solid mechanics, fluid mechanics, heat transfer, material science, mathematics, lubricant rheology, reliability and performance. Although, the name tribology comes later, the constituent parts of tribology encompassing friction and wear were as old as history. It is known that drills made during the

Paleolithic period for drilling holes or producing fire were fitted with bearings, made from antlers or bones, and potters' wheels or stones for grinding cereals, etc. (Bhushan (2013)).

A ball thrust bearing dated about AD 40 was found in Lake Nimi near Rome. Record shows the use of wheels from 3500 BC, which illustrates our ancestors' concern for reducing friction in translationary motion. The transportation of large stone building blocks and monuments requires the know-how of frictional devices and lubricants, such as water lubricated sleds. A sledge to transport a heavy statue was used by the Egyptians, circa 1880 BC. A tomb in Egypt that was dated several thousand years BC provides the evidence of use of lubricants. A chariot in this tomb contained some of the original animal-fat lubricant in its wheel bearings. During and after the Roman Empire, military engineers rose to prominence by devising both war machinery and methods of fortification, using tribological principles. It was the Renaissance engineer-artist Leonardo da Vinci (1452-1519) was first postulated a scientific approach to friction. Da Vinci deduced the rules governing the motion of a rectangular block sliding over a flat surface. He introduced the coefficient of friction as the ratio of the friction force to normal load. His work had no historical influence, however, because his notebooks remained unpublished for hundreds of years (Bhushan (2013)).

In 1699, the French physicist Guillaume Amontous rediscovered the rules of friction after he studied dry sliding between two flat surfaces. First the friction force that resists sliding at in interface is directly proportional to the normal load. Second the amount of friction force does not depend on the apparent area of contact. These observations were verified by the French physicist Charles-Augustin Coulomb (better known for his work on electrostatics). He added a third law that the friction force is independent of velocity once motion starts. He also made a clear distinction between static friction and kinetic friction (Bhushan (2013)).

Many other developments occurred during the 1500s, particularly in the use of the improved bearing materials. In 1684, Robert Hooke suggested that the combination of steel shafts and bell-metal bushes would be preferable to wood shod with iron for wheel bearings. Further, developments were associated with the growth of industrialization in the latter part of the eighteenth century. Early developments in the petroleum industry started in Scotland, Canada and the United states in the 1850s (Bhushan (2013)).

Though essential laws of viscous flow were postulated by Newton in 1668, scientific understanding of lubricated bearing operations did not occur until the end of nineteenth century. Indeed, the beginning of our understanding of the principle of hydrodynamic lubrication was made possible by the experimental studies of Tower (1884) and the theoretical interpretation of Reynolds (1886). Since then, developments in hydrodynamic bearing theory and practice have been extremely rapid in meeting the demands for reliable bearings in new machinery systems. Tribology attracted serious attention with the publication of Osborne Reynolds' classical paper on hydrodynamic lubrication in 1886. Reynolds' investigated that hydrodynamic pressure of liquid entrapped between sliding surfaces was sufficient to prevent contact between surfaces even at very low skidding speeds. The work of Reynolds' initiated countless new direction of research efforts aimed at improving the interaction between two contacting surfaces. In the west, the industrial revolution (AD 1750-1850) is recognized as the period of rapid and impressive development of machinery of production. The use of steam power and the subsequent development of the railways in 1830s, automobiles in early 1900s and aircraft in the 1940s led to the need for reliable machine components.

Since the beginning of the 20^{th} century, from enormous industrial growth leading to demand for better Tribology, knowledge in all areas of Tribology has expanded tremendously (Bhushan (2013)).

1.0.3 Some Examples of Tribology

Tribology has been used in numerous industrial applications requiring relative motion, for example, railroads, automobiles, aircraft, and the manufacturing process of machine components. Some of the tribological machine components used in these applications includes bearings, seals, gears and metal cutting. Other applications can be had in magnetic storage devices and micro electro-mechanical systems / nano electro-mechanical systems (MEMS / NEMS) as well as biomedical and beauty care products (Bhushan (2013)).

Tribology is not only, important to heavy industry; but also affects our day-to-day life. For example, writing is a tribological process. During writing with a pencil there should be good adhesion between the lead and the paper, so that a small quantity of lead transfers to the paper and the lead should have adequate toughness or hardness so that it does not fracture or break. Shaving cream is used as a lubricant to minimize friction between the razor and the skin. Friction is helpful during walking and driving. Tribology is also important in sports. For example, a low friction between the skis and the ice is desirable during skiing. Body joints need to be lubricated for low friction and low wear to avoid osteoarthritis and joint replacement. The surface layer of cartilage present in the joint provides the bearing surface and is lubricated with a joint fluid consisting of lubricants, hyaluronic acid (HA) and lipid. Hair conditioner coats hair in order to repair hair damage and lubricate it. It contains silicone and fatty alcohols. Low friction and adhesion provide a smooth feel in wet and dry environments, reduce friction between hair fibers during shaking and bouncing and provide easy combing and styling. Skin creams and lotions are used to reduce friction between the fingers and body skin (Bhushan (2013)).

1.0.4 Friction

Friction is the tangential resistance to motion. The occurrence of friction is a part of everyday life, it is needed to have a control on walking. In the most of machines in operation, friction is undesirable as it causes loss of energy and deteriorates performance due to heat generation.

Friction is not a material property, it is a system response. If two solid surfaces are clean without chemical films and adsorbents, high friction occurs. However, a small quantity of liquid present at the interfaces results in liquid-mediated adhesion which may result in high friction; especially between two smooth surfaces. Friction forces can be either good or bad, without friction it would be impossible to walk, use of automobile tires on a roadway, or pick up of objects. Even in some machine applications such as vehicle brakes, clutches and frictional transmission of power (such as belt drives), friction is maximized. However, in most other sliding and rotating components such as bearings and seals, friction is undesirable. Friction causes energy loss and wear of moving surfaces in contact. In these cases, friction is required to be minimized (Hirani (2016)).

Mainly, following are the types of friction :

1.0.4.1 Dry Friction

As its name suggests dry friction, also called ‘coulomb” friction, describes the tangential component of the contact force that exists when two dry surfaces move or tend to move relative to one another. Dry friction is subdivided into:

- *Static friction:* Static friction occurs when surfaces are static or non-moving surfaces.
- *Sliding friction:* In sliding friction, the frictional force opposes any attempt to move a stationary object along a surface.

1.0.4.2 Fluid Friction

Fluid friction describes the tangential component of the contact force that exists between adjacent layers in a fluid that are moving at different velocities relative to each other as in a liquid or gas between bearing surfaces.

- *Lubricated friction :* It is a case of fluid friction where a fluid separates two solid surfaces.
- *Skin friction :* It is a component of drag, the force resisting the motion of a fluid across the surface of a body.

1.0.4.3 Internal Friction

Internal friction is the force resisting motion between the elements making up a solid material while it undergoes deformation. Rolling friction is experienced when a body roles over another body.

- ***Laws of friction :*** Three important laws discovered in 15th to 18th centuries as are follows:
- *Amontons' first law :* The force of friction is directly proportional to the applied load.
- *Amontons' second law :* The force of friction is independent of the apartment area of contact.
- *Coulomb's law :* It states that sliding friction is independent of the sliding velocity.

Here note that first two laws given by Amontons' were description of a tribology process. Thus, these laws remained crucial to the development of Tribology.

1.0.5 Wear

Undesirable removal of material from one or both of the operating solid surfaces in relating motion sliding, rolling or impact is known as wear. Wear may also be defined as the surface damage due to material displacement with no net charge in volume or weight. It may occur as a nature consequence and mostly through the surface interactions at asperities. Wear is strongly dominated by operating conditions in material properties. It is a system responds.

Wear damage precedes the actual loss of material, and it may also occur independently. The definition of wear is generally based on the loss of material, but it should be emphasized that damage due to material displacement on a given body with no net change in weight or volume, also constitutes wear. Wear, as friction, is not a material property, it is a system response. Operating conditions affect interface wear. Erroneously, it is sometimes assumed that high friction interfaces exhibit high wear rates. This is not necessarily true. For instance, interfaces with solid lubricants and polymers exhibit relatively low friction and relatively high wear, whereas ceramics exhibit moderate friction but extremely low wear. Wear can be either good or bad. Examples of productive wear are writing with a pencil, machining, polishing and shaving, which require controlled wear. Wear is undesirable in almost all machine applications such as bearings, seals, gears and cams.

Wear includes six major, quite distinct phenomena which have only one thing in common: the removal of solid material from rubbing surfaces.

These are

1) adhesive
2) abrasive
3) fatigue
4) Impact by erosion and percussion
5) Corrosive
6) Electrical-arc-induced wear
7) Fretting and fretting corrosion.

Wear is a much younger subject then friction and bearing development and it was initiated on largely empirical basis scientific studies of wear scarcely developed until the mid-twentieth century. Holm made one of the earliest substantial contributions to the study of wear (Holm (1946), Hirani (2016)).

1.1 Bearing

Bearing is a load support that permits relative motion between two parts, such as the shaft and the housing, with minimum friction. The load may be radial, axial or combination of these. There are two mainly types of bearings commonly used in practice. They are rolling-element and fluid film bearings. Rolling-element bearings are often referred to as antifriction bearings, as their name implies, minimize friction by removing any possible sliding between bearing surfaces and replacing all contacts with rolling interfaces. If two matting surfaces during operating conditions are completely separated by a lubricant film, such a type of lubrication is called fluid film lubrication. Bearing operating under this kind of lubrication are called fluid film bearings (Harnoy (2002)).

Essentially, the bearings are used to support rotating shafts in machines. The most important objectives of bearing design are to extend bearing's life in machines, reduce friction, energy losses and wear, and minimize maintenance expenses and downtime of machinery due to frequent bearing failure. In manufacturing plants, unexpected bearing failure often causes serious situations for examples in aircraft, there are very important safety considerations and unexpected bearing failure must be prevented at any cost (Harnoy (2002)).

The objective of the basic research in Tribology is similar to those of bearing design, focusing on the reduction of friction and wear. These efforts resulted in significant advances in bearing technology during the past century. This improvement is particularly in lubrication, bearing materials and the introduction of rolling-element bearings and bearings supports by lubricated films. The improvement in bearing technology resulted in the reduction of friction, wear and maintenance expenses as well as in the longer life period of machinery. The selection of proper bearing type for each application is essential to the reliable operation of machinery and it is an important component of machine design. Most of the maintenance work in machines is in bearing lubrication as well as in the replacement of damage or worn bearings. To appropriate selection of a bearing type for each application is very important to minimize the risk of early failure by wear or fatigue, thereby, to secure adequate bearing life. Also, cost is always an important consideration in bearing selection. The designer considers not only the initial cost of the bearing but also the cost of maintenance and of the possible loss of production over the complete life cycle of the machine. Therefore, the first step in the process of bearing design is the selection of the bearing type suitable for each application.

Bearings can also be classified according to their geometry related to the relative motion of elements in machinery. Some examples are journal, plane slider and spherical bearings. The bearing selection involves variety of choices based on application that may be broadly placed in following general classification.

1.1.1 Solid Bearings

In all solid bearings the shaft or bearing can only be removed endways and the bearings cannot be adjusted when worn. Solid bearings are used to support the vertical high-speed ring spindles used in textile mills. These bearings are always small in size. They are used for loose pulleys and small shafts and in a variety of machinery such as cranes; hosting machinery as piston-pin bearings.

1.1.2 Thrust Bearings

Thrust bearings are designed to counteract pressure in the direction of the shaft and to keep the shaft in its correct position while supporting the load in vertical units or acting against the thrust forces in horizontal units. Thrust bearings are extensively used in hydro-electric units, steam turbines, for ship propulsion, for centrifugal pumps etc. Machines fail to operate at high speed in their familiar way without some mean of reducing friction and the wear of moving parts. Several important engineering inventions made it possible to successfully operate heavily loaded shafts at high speed, including the rolling element bearing and hydrodynamic, hydrostatic and magnetic bearings.

1.1.3 Rolling-Element Bearings

These bearings are characterized by rolling motion, such as in ball bearings or cylindrical rolling element bearings. The advantage of rolling motion is that it involves much less friction and wear in comparison to the sliding motion of regular sleeve bearings (Harnoy (2002)).

1.1.4 Hydrodynamic Bearing

The term hydrodynamic bearing refers to a sleeve bearing or an inclined plane-slider where the sliding plane floats on a thin film of lubrication. The fluid film is maintained at a high pressure that supports the bearing load and completely separates the sliding surfaces. The lubricant can be fed into the bearing at atmospheric or higher pressure. The pressure wave in the lubrication film is generated by hydrodynamic action due to the rapid rotation of the journal. The fluid film acts like a viscous wedge and generates high pressure and load carrying capacity. The sliding surface floats on the fluid film and wear are prevented (Harnoy (2002)).

One major disadvantage of hydrodynamic bearings is that a certain minimum speed is required to generate a full fluid film to separate the sliding surfaces. Below that speed, there is mixed or boundary lubrication with direct contact between the asperities of the rubbing surfaces. A second important disadvantage is that hydrodynamic bearings are completely dependent on a continuous supply of lubricant. If the fluid or oil supply is interrupted even for a short time for some unexpected reason, it can cause overheating and sudden bearing failure. The well known example of this is that motor vehicle engines do not last a long time if run without oil. A third disadvantage is that the hydrodynamic journal bearing has a low stiffness to radial displacement of the journal, particularly, when the eccentricity is low (Harnoy (2002)).

1.1.5 Magnetic Bearing

Magnetic bearing is recently introduced and it is still in development stage but has already been used in some imperfect applications. The concept of operation is that a magnetic force is used to support the bearing load. The bearing load capacity is generated by the magnetic field between rotating laminators, mounted on the journal and stator poles, on the stationary bearing side. The advantage is that there is no contact between the sliding surfaces, so wear is completely prevented as long as there is magnetic levitation.

During the last decade, a lots of research works on magnetic bearings has been conducted in order to optimize the performance of the magnetic bearing. The research work includes optimization of the direction of magnetic flux, comparison between electromagnetic and permanent magnets and optimization of number of magnetic poles. This research work has resulted in improved load capacity and lower energy losses.

Although significant improvement has been achieved, there are still several disadvantages in comparison with other conventional bearings. The most important limitations are as follows:

- Electromagnetic bearings are relatively much more expensive than other non contact bearings such as the hydrostatic bearing.
- Electromagnetic bearings have less damping of journal vibrations in comparison to hydrostatic oil bearings.
- Magnetic bearings must be quite large in comparison to conventional non contact bearings in order to generate equivalent load capacity.
- Lastly, electromagnetic bearings involve complex design problems to ensure that the heavy spindle with its high inertia, does not fall and damage the magnetic bearing

when power is shut off or momentarily discontinued. Therefore, a non interrupted power supply is required to operate the magnetic bearing even at no load or at shutdown conditions of the system (Patel (2015 b)).

1.2 Lubrication

1.2.1 Basic Concept

Lubrication is a process by which the friction and wear rates in moving contacts are reduced. It is known since ages that liquids and grease reduce the friction between sliding surfaces, by filling the surfaces cavities and making the surface smoother. Lubricant is a substance introduced between relatively moving parts to reduce friction and wear rate. The lubricant decreases adhesion component of friction to a greater extent compared to abrasion component of friction.

When the interacting surfaces are completely separated and the influence from the surface asperities is negligible, lubrication is turned as thick lubrication. Thick lubrication is it governed by Reynolds theory (Hirani (2016)).

As an aid in understanding the features that distinguish the lubrication regimes from one another are discussed below :

1.2.2 Hydrodynamic Lubrication

Hydrodynamic lubrication is generally characterized by conformal surfaces. In hydrodynamic lubrication the films are generally thick so that opposing solid surfaces are prevented from coming into contact. This condition often referred to as “the ideal form of lubrication” since it provides low friction and high resistance to wear. The lubrication of the solid surfaces is governed by the bulk physical properties of the lubricant, notably; the viscosity and the frictional characteristics arise purely from the shearing of the viscous lubricant (Hamrock et al. (2004)).

Positive pressures will be generated only when the film thickness is diminishing. In an externally pressurized bearing, sometimes referred as “a hydrostatic bearing”, the pressure drop across the bearing supports the load. The load carrying capacity is independent of the bearing motion and lubricant viscosity. There is no surface contact wear at starting and stopping as there is with the slider bearing (Hamrock et al. (2004)).

1.2.3 Elastohydrodynamic Lubrication

Elastohydrodynamic lubrication (EHL) is a form of hydrodynamic lubrication where elastic deformation of the lubricated surfaces becomes significant. The features in a hydrodynamically lubricated slider bearing converging film thickness, sliding motion and a viscosity fluid between the surfaces are also important here. EHL is normally associated with non conformal surfaces (Hamrock et al. (2004)).

1.2.4 Boundary Lubrication

Boundary lubrication occurs when the film thickness is very small typically less than the composite surface roughness. However, it should be noted that this corresponds to the separation of the surface; the minimum film thickness in the boundary regime is on the order of molecular dimensions. Hence effective boundary lubrication requires the preference of materials that satisfy the various functions of a lubricant with only one or two molecular layers (Hamrock et al. (2004)). Because in boundary lubrication the solids are not separated by the lubricant, fluid film effects are negligible and there is considerable asperity contact. The contact lubrication mechanism is governed by the physical and chemical properties of thin films surfaces of molecular proportions. The properties of the bulk lubricant are of minor importance and the friction coefficient is essentially independent of fluid viscosity (Hamrock et al. (2004)).

In boundary lubrication, although the friction is much higher than in the hydrodynamic regime, it is still much lower than for unlubricated surfaces. The mean friction coefficient increases a total of three orders of magnitude in going from the hydrodynamic to the elastohydrodynamic to the boundary to the unlubricated regime. In the hydrodynamic and EHL regimes there is little or no wear, since there is no asperity contact. In the boundary lubrication regime the degree of asperity interaction and the wear rate increases as the load increases. Boundary lubricants are present to some extent in most natural oils and petroleum lubricants, but are often purposefully added to a formulation to improve performance. Boundary lubrication is a multi-disciplinary field, drawing heavily on chemistry, materials science and engineering. There are a large number of mechanisms through which boundary films act and a wide variety of chemicals are known to be advantageous with respect to boundary lubrication. However, it is a common practice among lubricant formulators to classify additives as either organic or inorganic additives. Organic boundary lubricants, also referred to simply as boundary lubricants, are typically fatty acids and esters. Inorganic boundary lubricants also referred to as extreme pressure lubricants are inorganic molecules that provide good lubrication at elevated temperatures and pressures. Inorganic additives traditionally involve compounds of chlorine, phosphorous, sulfur and iodine, although there has been a significant effort to eliminate these additives for environmental reasons and also because these materials are often carcinogenic.

1.2.5 Thick Film Lubrication

When the interacting surface are completely separated and the influence from the surface asperities is negligible, lubrication is turned as thick film lubrication.

1.3 Squeeze Film

Fluctuation in load and/ or relative velocity to develop positive fluid pressure is known as squeeze film action. And the fluid film is called the squeeze film. In the mechanism of squeeze lubrication, viscosity of lubricant plays very important role (Hirani (2016)).

A finite time is required to squeeze the fluid out of gap, and this action provides a useful cushioning effect in bearings. The reverse effect which occurs when the surfaces are moving apart, can lead to cavitations in liquid films. For squeeze film bearings a relationship needs to be developed between load and normal velocity at any instant. The time required for the separation of the surfaces to change by a specified amount can then be determined by a single integration with respect to time (Hamrock et al. (2004)). When a shaft, tyre or skeletal joints stops sliding on a lubricant film i.e. the velocity becomes zero, the equations of hydrodynamics would suggest that the fluid film reduces to zero immediately. Actually, there is a slight time delay, while the fluid squeezes out of the contact region. For most steady-state engineering systems, the time to squeeze out a film is very small, on the order of milliseconds. For sliding surfaces, film thinning as speed decreases is much slower than the squeeze film effect (Ludema (1996)).

Applications of Squeeze film are seen in many mechanical components. The fluid offers a certain amount of useful cushioning – that is, load carrying capacity – even in the absence of sliding motion or a physical wedge effect. By this means, a significant amount of load carrying capacity can be generated between two parallel plates or disks when one surface is pressed against the other (Khonsari and Booser (2008)).

Reynolds (1886) introduced the squeeze effect in his famous paper on lubrication and stated that it was an important mechanism, together with the wedge effect, for the generation of pressure in a lubricating film. Especially, when a sufficiently large wedge effect is not expected, for example in the case of the small end bearing of a crank for a reciprocating engine or in the case of an animal joint, it is known that the squeeze film effect is the only mechanism for pressure generation. It is surprising that the lubrication mechanism of animal joints was discussed over 100 years ago. In another case, negative pressure arises in the fluid film, this phenomenon is called negative squeeze. The case of two approaching surfaces is called positive squeeze. Further, it is also interesting to consider situations in which positive and negative squeeze occur alternately. In the small end bearing of a crank and in an animal joint, a positive and negative load act by turns, and positive and negative squeeze occurs alternately. In this case, fluid is sucked into the gap between two surfaces during the negative squeeze and the fluid is squeezed out during the positive squeeze and supports a load. A squeeze film is, unlike a wedge film, always in an unsteady state. Even when the added load is constant, a squeeze film becomes either thinner gradually with time or thicker, and is never in a stationary state except for the case of zero load. Therefore, a squeeze film cannot be maintained for a long time under a constant load, but is maintained for a long time only when positive and negative squeezes are repeated alternately (Hori (2005)).

1.4 Ferro- fluid as Lubricant

1.4.1 Basic concept

Ferro-fluids or Magnetic fluids are stable colloidal suspensions of magnetic metal nano particles in a carrier liquid such as hydrocarbon, diester, water and mercury.

Ferro-fluid is a liquid which becomes strongly magnetized in the presence of magnetic field. There are at least three components required to prepare Ferro-fluid i.e. magnetic particles of colloidal size, carrier liquid and stabilizer (surfactant). Ferro-fluids are stable suspensions of colloidal single domain ferromagnetic particles of the order of 10 nm in suitable non-magnetic carrier liquid. The presence of surfactant helps to maintain proper spacing between the particles to provide colloidal stability (Sharma (2012)). Ferro-fluids were first discovered at National Aeronautics and Space Admistration (NASA) research center in 1960. The scientists at NASA found that they could make to flow this amazing ferro-fluid by varying the external magnetic field.

The main advantage of magnetic fluid as lubricant lies in the possibility of supplying a lubricating medium only to the friction zone and it's positioning in this zone with the aid of a magnetic field. This requires a specific design of a magnetic system. One of the most important properties of the magnetic fluid is that they can be retained at a desired location by an external magnetic field. The magnetic fluid can be made to move with the help of a magnetic field gradient, even in the regions where there is no gravity. This makes the magnetic fluid amenable for the use in space vehicles (Shimpi (2013), Shukla (2013), Patel (2015 a) and Patel (2015 b)).

According to the coating, the ferro-fluids are classified into two main groups.

- *Surfacted:* If the coating is a surfactant molecule.
- *Ionic:* If it is an electrical shell.

Magnetic nano particles play an important role in magnetic fluid which is probably the first prepared nano-object in the history of nano area.

1.4.2 Magnetic Fluid Flow Model

There are number of mathematical models associated with the flow in the presence of a magnetic fluid:

1.4.2.1 Neuringer-Rosenweig Flow Model

In 1964, Neuringer-Rosenweig developed a phenomenological treatment for the fluid dynamics and thermodynamics of strongly polarizable magnetic fluid continuum in the presence of non uniform magnetic fields and found that vorticity might be generated by thermo magnetic interaction even in the absence of viscosity and this leads to the development of augmented Bernoulli relationships. He derived an analytical solution for the problem of source flow with heat addition in order to display the thermo magnetic and magneto mechanical effects attendant to simultaneous heat addition and fluid motion in the presence of a magnetic field.

In this discussion, ferrohydrodynamics was defined as the fluid dynamics and heat transfer processes associated with the motion of incompressible, magnetically polarizable fluids in the presence of magnetic field and temperature gradients. In their flow model, the magnetic state of the material may vary from point to point as may the field. Also each element of fluid experiences a thermodynamic history which was however, independent of the detailed manner in which the magnetic work was performed for momentum equation, they assumed that the magnetic force term might be simply superimposed on the usual force terms, while for the energy equation the magneto caloric heat source term was simply superimposed on the corresponding energy terms in the heat convection equation. This model discussed about weak form of Bernoulli's equation and assumed the flow was irrational. also, they discussed two separate cases. The first was the material magnetization, it was temperature independent and another one was the gradient of temperature, it was parallel to the gradient of the magnitude of the applied field strength which implies coincidence of the surfaces of constant temperature and constant magnetic intensity (Bhat (2003)).

In short, Neuringer-Rosenweig (1964) presented a phenomenological treatment of the fluid dynamics and thermal interactions attendant to the flow of heated and unheated, incompressible, magnetically polarizable, dielectric fluids.

1.4.2.2 Shliomis Flow Model

The effect of a homogeneous magnetic field on the viscosity of a suspension whose solid particles possess intricate magnetic moments was investigated by Shliomis (1972). Also, he studied the effect of the orienting field impends rotation of the particles in a vertical liquid flow, the result being an increase of the effective viscosity and investigated the effect of Brownian motion and hydrodynamic forces exert a disorienting effect on the magnetic moments. The influence of the aforementioned factors on the rotation of suspended particles was taken into account macroscopically within the framework of the hydrodynamics of a homogenous liquid with an internal angular momentum.

He derived Einstein's formula for the viscosity of suspensions without taking into account the fact that the solid particles of the suspension could, in principle, rotate in ordered fashion relative to the liquid. It was noticed that the "rotational" viscosity could become noticeable only if the difference of particle rotation velocity and rotation of the liquid was maintained by moments from some extraneous forces acting directly on the particles. He dealt with the influence of a magnetic (electric) field on the motion of particle having their own magnetic (electric) moments (Bhat (2003)).

It was concluded that the action of the magnetic field will far from always be reduced to a simple “renormalization” of the viscosity. Thus, when a suspension moved in an inhomogeneous field there arise forces which change the very character of the motion. In general case, the dependence of the viscosity on the field was only a fraction of the effect of the influence of the field on the motion of a suspension of magnetic particles.

1.4.2.3 Jenkins Flow Model

In this model, the magnetizable liquid was regarded as an anisotropic fluid and added to the motion and the temperature the vector magnetization density to complete the description of the material (Jenkins (1972)). The use of the local magnetization as an independent variable allowed to treat static and dynamic situations in a uniform fashion and to make a natural distinction between paramagnetic and ferromagnetic fluids. He discussed about electromagnetic laws, conservation laws for mass, linear momentum, angular momentum, energy and a balance law for magnetization. He assumed that these expressions govern the magnetic and thermo mechanical phenomena in non-conducting magnetic materials when electric fields were absent and when the frequency associated with any time variation was much less than the ratio of the speed of light to a typical dimension of the system. The entropy flux was given by a constitutive relation and when formulating the constitutive theory, the distinction was made between paramagnetic and ferromagnetic fluids. For paramagnetic fluids, the most general objective form of the entropy flux consistent with the entropy inequality was given by the heat flux divided by the temperature: however, for ferromagnetic fluids, it was shown that this classical relation did not, in general, apply. He presented the isothermal static equilibrium for magnetic fluids in some details. In this paper was also derived, the system of equations governing these states. Integrals of the linear momentum equations and indentify the magnetic energy density function for both ferromagnetic and paramagnetic fluids were obtained. With natural restrictions, a uniqueness theorem was established for incompressible paramagnetic fluids and determined that, in these materials, the magnetization must vanish with the applied magnetic field (Bhat (2003), Patel (2015 b)).

1.4.3 Preparation of Ferro-fluids

The use of magnetic fluid as a lubricant modifying the performance of bearing system has drawn considerable attentions. ferro-fluids in fact are magnetically controllable nano fluids which are colloids of magnetic nano particles such as Fe_3O_4, $CoFe_2O_4$, Co, Fe or Fe-C, uniformly dispersed in a carrier liquid with an application of external magnetic field these fluids can be confined, positioned, shaped and controlled at desire places. It is well known that the load carrying capacity of a lubricant film of ferro-fluid can also be increased with an appropriate magnetic field. These fluids are used in engineering and biomedical applications. Usually, the diameter of magnetic nano particles varies from 3-15 nm (Shimpi (2013), Patel (2015 a) and Patel (2015 b)).

1.4.4 Magnetic Behavior of Ferro-fluids

When the magnetic field is absent and the fluid does not have net magnetization, the magnetic moments of the particles are randomly distributed. However, the magnetic movements of the particles orient instantly along the field lines when a magnetic field is applied to magnetic fluid. The magnetization of the ferro-fluid responds to the changes in the applied magnetic field and the moments randomized quickly when the applied field is withdrawn. In a gradient field, the whole mass of fluids responds as a homogeneous magnetic liquid which moves to the region of highest flux. Therefore, it is noticed that ferro-fluids can be precisely positioned and controlled by an external magnetic field. (Shimpi (2013), Patel (2015 a) and Patel (2015 b)).

1.4.5 Characteristics of Ferro-fluids

Mainly the particle density decides the thermal stability of a magnetic fluid. The particles behavior like a catalyst and produced free radicals leading to cross linking of molecular change and eventual congealing of the fluid. Ferro-fluids congeal more rapidly at elevated temperatures as catalytic activity is higher then. High magnetization ferro-fluids produce volumetric efficiencies of magnetic circuit designs for light weight and low cost product. These high magnetization ferro-fluids are deployed nowadays to reduce the impact of fringing field. Ferro-fluid is an active component contributing immensely towards the enhanced performance of mechanical (seals, bearings and dampers), electromechanical devices (loudspeakers, motors, shock absorbers and sensors). If correctly and judiciously applied ferro-fluid may produce dramatic improvements in the performance level on attainable by any other technological methods (Shimpi (2013), Patel (2015 a) and Patel (2015 b)).

1.4.6 Advantages of Magnetic Fluid

The following are some of the advantages of magnetic fluids (Bhat (2003)) :

1. Zero leakage occurs within the operating specifications.
2. No rubbing takes place between solid materials.
3. Particles are not generated by wear.
4. Accurate surface finish is not required on the shaft.
5. Wider dimensional tolerance on the shaft can be accommodated.
6. No external lubrication is required.
7. No overhaul is necessary to recharge sealed fluid.
8. Heat generation is almost nil.
9. Very high operating surface speeds are possible.
10. Vibration is absent.

1.4.7 Properties and Applications of Ferro-fluids

The choice of Ferro-fluids depends on many factors such as environments, thermal conductivity, operating life etc. There are many different combinations of saturation magnetization and viscosity resulting in a Ferro-fluid, suitable for various applications (Shukla (2013), Patel (2015 b)).

- ❖ Magnetic fluids can change their apparent viscosity in proportion to the strength of an applied magnetic field. Therefore, the viscosity can be well controlled dynamically which allows for active damping. They are used to dampen automotive devices, space structures, wing oscillations in aircraft, protect devices and some buildings from vibration damage, and to improve comfort during transport. They are introduced into the voice coil gap of loudspeakers for damping, undesired vibrations and for cooling.
- ❖ Ferro-fluids are widely used in rotating X-ray tubes, rotating shafts, rods and sink-float systems for separation of materials by using ferro-fluid as a lubricant. They are

also used as heat controller in electric motors and hi-fi speaker systems without the need of change in their geometrical shape. Ferro-fluids are being greatly used in many magnetic fluid based scientific devices like sensors, accelerometer, pressure transducers etc. and are also used in actuating machines like electromechanical converters, energy converters etc. One important application of magnetic fluids is their use as magnetic ink for high-speed, inexpensive and silent printers (Sharma (2012)).

- ❖ An important property of concentrated Ferro-fluids is that they are strongly attracted by permanent magnets while their liquid character is preserved. The attraction can be strong enough to overcome the force of gravity. Many applications of magnetic fluids are based on this property which makes them used in lubricating, airtight seals in rotary shafts.
- ❖ A magnetic field gradient keeps the magnetic fluid in place, even in case of pressure differences between the two separated compartments. Today, many computer hard disk drives contain a magnetic fluid sealed shaft.
- ❖ In the aforementioned applications, the magnetic fluid was considered to be homogeneous. However, structural changes can occur on a microscopic level when magnetic fluids are subjected to a magnetic field.
- ❖ An external field aligns the dipole moments of magnetic colloids; it can increase the average interaction strength between magnetic colloids sufficiently to induce aggregation of the colloids into concentrated micron-sized droplets. Because, the size of such droplets is comparable to the wavelength of light, the optical properties of magnetic fluids depend on the direction and strength of the external field. Optical devices employing the strong magneto-optical effects of magnetic fluids are still in development.
- ❖ Magnetic fluids have also been used in the separation of metals from ores by taking advantage of a density change that appears in the fluid under application of a magnetic field. A South African company has even, been utilizing ferro-fluids to separate diamonds from beach sand.
- ❖ Colloidal suspensions of magnetic nanoparticles are of special interest, particularly, in bio-imaging, and more recently, in Magnetic Fluid Hyperthermia (MFH). MFH promises to be a viable alternative in the treatment of localized cancerous tumors.

- ❖ Magnetic fluids are also found to be very useful in the field of biomedicine due to magnetically targeted drug delivery (anti-cancer agents such as radio-nuclides, cancer specific antibodies, genes etc.) to a certain area of human body, targeted destruction of tumors, in-vivo monitoring of chemical activity in the brain and toxin removal from the body for cancer treatment. Magnetic fluids are also used in the contrast medium in X-ray examinations and for positioning tamponade for retinal detachment repair in eye surgery. A potential application of magnetic fluid is found in the subsurface environmental engineering, in which externally applied magnetic fields are used to direct and control the flow of magnetic fluids under the ground (Sharma (2012)).

Various applications of magnetic fluid lubrication can be discussed in different studies such as Prajapati (1995), Bhat (2003), Sharma (2012), Shimpi (2013), Patel (2015 a), Patel (2015 b) and Shukla (2013).

1.5 Surface Roughness

1.5.1 Basic Concept

Engineering surfaces are created in various ways, typically by machining, surface treatment and coating. Most often a combination of various machining, treatment and coating operation are employed to produce surfaces with characteristics that are desirable for particular application. Each surface generation process produces surface topography characteristics of the process and process variables used. Surface topography establishes a correspondence between an engineering surface phenomenon (e.g. wear, chatter etc.) and its topographical characteristics (e.g. Bearing area, oil retention volume etc.). The high frequency or short wave components correspond to those that are perceived to be rough and hence called “roughness” (Vyas (2005)).

The surface roughness of interacting surfaces consists of micro asperities that are micro or nano sized peaks and valleys. Depending on the size, shape, orientation and distribution of these asperities, the hydrodynamic lubrication characteristics of the surfaces can vary significantly. In order to archive enhanced and cost effective performance of engineering components, surface engineering embraces traditional and innovative surface technologies which modify the surface properties of metallic and non-metallic engineering components for specific and sometime unique engineering purpose. The surface roughness of an engineered surface is classified as: the random surface roughness which is a product of surface finishing and the deterministic surface roughness which is engineered to increase the lubrication characteristics of the hydrodynamically lubricated surface (Vyas (2005)).

In practical, surface roughness is essential for product quality, production efficiency and cost. It is known that the surface roughness and even the material processed may play important roles in this tribological phenomenon when the viscosity is considered in lubricating regimes. To study the effect of surface roughness on lubrication is very complex tribological problem. Firstly, it involves a time dependent fluid domain resulting from the motion and deformation of the moving solid surfaces. This geometrical complexity is itself more or less difficult to analyze depending on the surface roughness patterns. Moreover, physical effects, such as cavitations, piezo viscosity or compressibility, among others, may contribute to the complexity of the problem. Such effects could be studied at the different scales for which they occur, for that is for a few asperities, for the statistically representative region, or for the system scale.

Two basic approaches are developed to investigate the performance of the surface roughness on the bearing system, one is the deterministic and another is stochastic.

There are two types of surface characteristics in lubricant flow :

1. Both surfaces are rough and moving relatively.
2. One surface is rough and stationary while the other one is smooth and moving.

Mainly two types of one dimensional roughness are used to evaluate the effect of surface roughness on systems.

- *Longitudinal roughness:* The shape of such type of roughness is only dependent on Y-coordinate. In this way the shape is constant in the lubricant and therefore, the problem reduces to a two dimensional stationary one, whether or not both surfaces have a velocity. Also, this kind of roughness is assumed to avoid the pure slip condition.
- *Transverse roughness:* This type of roughness has edges perpendicular to the direction of lubricant entrainment. So, it is a pure slip situation. Because the Coquette flow dominates the total fluid flow, it leads to more favorable conditions than the case of longitudinal roughness.

Surface texture is concerned with the geometric irregularities of the surface of a solid material which is defined in terms of surface roughness, waviness and flows. Surface roughness consists of the fine irregularities of the surface texture, including feed marks generated by the machining process. The mechanism behind the formulation of surface roughness is very dynamic, complicated and process dependent. Therefore, a mathematical model using a statistical method provides a better solution. Multiple regression analysis is suitable to find the best combination of independent variables which is spindle speed, feed rate and the depth of cut in order to achieve desired surface roughness (Mohammad (2009)).

Roughness plays an important role to determine how a real object interacts with its environment. Rough surfaces usually Produce wear more quickly and have higher friction coefficients than smooth surfaces. Roughness is often a good predictor of the performance of mechanical components, since irregularities in the surface may form nucleation sites for crakes or corrosion. Although, roughness is usually undesirable, it is difficult and expensive to control it in manufacturing. Decreasing the roughness of a surface will usually increase exponentially its manufacturing costs (Mohammad (2009)).

In the theory of lubrication, bearing surfaces are considered to be smooth which is not realistic phenomena in real practice. Solid surfaces, irrespective of the method of formulation, contain irregularities or deviations from the prescribed geometrical form (Thomas (1999)). The surfaces contain irregularities of various orders ranging from shape deviations to irregularities of the order of inter atomic distances. Even some times the contamination of lubricant and materials used in making the design, contribute to roughness. Roughness appears to be random in nature which does not follow any particular structured pattern.

1.5.2 Significance of Roughness

The challenge of modern machining industries is mainly, focused on the achievement of high quality in terms of work piece dimensional accuracy, surface finish, high production rate, less wear on the cutting tools, economy of machining in terms of cost saving and increase of the performance of the product with reduced environmental impact (Mohammad (2009)).

The degree of control on the surface finish required on a product, determines the machining time of the product. A surface may be intentionally made rough for spherical requirements, e.g. knurling. An understanding of the relationship between surface texture and performance properties of the surface can lead to the specification of optimized manufacturing process for various surface function needs. Also, in the global market place, with the machining centers located around the world, new parameters are required to describe the surface topography, so that information can be transmitted worldwide in real time.

The surface roughness of machine parts is significant design specification that is known to have considerable influence on properties such as wear resistance and fatigue strength. Consequently, it is important to achieve a consistent tolerance and surface finish.

1.5.3 Mechanical Behavior of a surface

The mechanical behavior of a surface can be characterized in terms of four quantities (Shimpi (2013), Patel (2015 a) and Patel (2015 b)):

- *Hardness:* The hardness describes the resistance of materials to plastic deformation.
- *Young's modulus and the elasticity limit (or plastic flow threshold):* It characterizes material's elastic properties.
- *Toughness:* Toughness accounts for the relative brittleness of a material.
- *Residual stresses:* This plays an important role in the resistance of the material for wear.

There are many techniques to measure the roughness parameter. The first amplitude parameter used for roughness measurements was the vertical distance between the highest peak and the lowest valley of the unfiltered profile. The second is to detect variations in height as function of distance which can be measured by the stylus instruments which are based on the principle of running probe across a surface. Also, using one of the instruments that employs specular reflection to characterize roughness is the light-section microscope, in which, an image of a slit is projected onto the surface and the objective lens captures the image at the specular reflection angle. If the surface is smooth, the image obtained will be straight; but if the surface is rough, an undulating pattern will be observed (Takadoum (2008)).

1.5.4 Application of Surface Roughness

- The roughness of the interior surface of pipes affects flow parameters, such as the Reynolds' number, which is used to evaluate the flow regime (laminar or turbulent) (Shukla (2013), Patel(2015 b)).
- Even, some investigators have found a correlation between initial roughness of sliding surfaces and their wear rate. In fact, the correlations have been used to predict failure time of contact surfaces.
- Further, the influence of roughness extends to various engineering disciplines such as noise and vibration control, dimensional tolerance, abrasive process, bio-engineering and geomorphometry.
- Another, area where surface roughness plays a critical role is contact resistance.
- The characterization of surface topography has a key role in applications dealing with friction, lubrication and wear. By, now it is well recognized that the friction increases with increase in average roughness. This means that roughness parameters are, therefore, important in applications such as automobile brake linings, floor surfaces and tires.
- In order to achieve enhanced and cost effective performance of engineering components, surface engineering embraces traditional and innovative surface technologies which modify the surface properties of metallic and non-metallic engineering components for specific and sometime unique engineering purpose. Surface engineering as a generic activity, with applications through engineering, from machinery and manufacturing equipment, to power transmission, aerospace design and technology has a crucial role to play in the development and maintenance of engineering components.

1.6 Porous Medium

Porous medium is also important and used in various research problems. Porous medium is defined as a solid body, which contains pores (void spaces). Void spaces must be distributed more or less frequently through the material. In a porous medium, the pores may be interconnected or non-interconnected. Examples of porous materials are rocks, human bones, soils, beach sand, glass beads, catalyst pellets, soil, gravel, sandstone, limestone, concrete, cement, bricks, paper, cloth, rye bread, wood etc. The flow through porous media is of great interest in chemical engineering (for filtration, adsorption etc.), geophysics, biophysics. The four macroscopic properties of non-ideal porous media used to describe flow of the fluid are porosity, permeability, tortuosity and connectivity (Sharma (2012)).

- *Porosity*: Porosity is the ratio of the void spaces to the total volume of the medium. This is expressed either in percent or as a fraction of one, which means it lies between 0 and 1. In homogeneous isotropic materials, Porosity is a pure constant but in non-homogeneous materials, Porosity may depend upon position. Porosity value may approach the value one for man-made materials (such as cements and ceramics), however, for natural media, Porosity does not normally exceed 0.6.
- *Permeability*: Permeability is a measure of the flow conductivity in a porous medium. The ‘medium permeability’ is measured in Darcy and Darcy is defined as the permeability that permeates a velocity of 1 cm/sec of a fluid with viscosity 1 centipoises under a pressure gradient of 1 atm/cm. The porous medium of very low permeability allows us to use Darcy’s model and of moderately large permeability allows us to use the Brinkman’s model.
- *Tortuosity*: An important characteristic for the combination of the fluid and the porous medium is the ‘tortuosity’ which represents the hindrance to the flow diffusion imposed by local viscosity or local boundaries. It is noticed that the tortuosity is also a function of the porosity and can be represented by square root of porosity (Sharma (2012)).
- *Connectivity*: ‘Connectivity’ is the number of pore-connections; but when the pores are of small size, connectivity is the average number of pores per junction. Some complexities due to the interactions between fluids and porous material are to be taken when flow through porous medium is considered. When a fluid passes through a porous material, the real path of the individual particles cannot be traced analytically.

1.7 Bearing Design Characteristics

Bearing design requirements are generally established by the restrictions and environmental conditions imposed by the bearing systems such as choice of lubricant, bearing material specifications, bearing life, cost, bearing alignment, positioning precision, direction and magnitude of loads, bearing ambient pressure, supply pressure, flow rate available from the system, heat flow etc. The assurance of the compatibility of the bearing and its design requires definition of both the range of imposed bearing requirements and bearing performance limitations. Following parameters that characterize the performance of a fluid film bearing are required to be designed and analyzed:

- Lubricant flow in the bearing
- Lubricant side leakage from the bearing
- Pressure distribution in the film
- Load carrying capacity
- Centre of pressure (or attitude angle in case of journal bearing)
- Friction force (or coefficient of friction)
- Film stiffness
- Squeeze film versus film thickness relationship(in case of squeeze film bearings)
- Range for stability of the bearing both for initial velocity disturbances and initial position disturbances.

Usually, the bearings are designed to perform optimally for a parameter. Typically, one or more of the following functional characteristics are required in bearing design

1. Optimum load capacity
2. Minimum friction
3. Control of film thickness within a specified range
4. Aspect of stability of the bearing rotor system,
5. Minimum power requirement.

1.8 Some Important Terminology

- **Slip Velocity:** In fluid dynamics, the no-slip condition for viscous fluids states that at a solid boundary, the fluid will have zero velocity relative to the boundary. But it was noticed that this phenomena was not always true. The fluid will have some velocity relative to the solid boundary; this velocity is defined as Slip velocity. Slip velocity is the difference between the average velocities of two different fluids flowing together in a pipe. In vertical ascending flow, the lighter fluid flows faster than the heavier fluid. The slip velocity depends mainly, on the difference in density between the two fluids, and their holdups.

- **Angular Velocity:** In physics, the angular velocity is defined as the rate of change of angular position of a rotating body. It is a vector quantity which specifies the angular speed (or rotational speed) of an object and the axis about which the object is rotating. The SI unit of angular velocity is radians per second, although, it may be measured in other units such as degrees per second, degrees per hour, etc. Angular velocity is usually represented by the symbol Ω.
- **Probability Distribution Function:** In probability theory, a probability density function (PDF), or density of a continuous random variable, is a function that describes the relative likelihood for this random variable to take on a given value. The probability of the random variable falling within a particular range of values is given by the integral of this variable's density over that range-that is, it is given by the area under the density function but above the horizontal axis and between the lowest and greatest values of the range. The probability density function is non-negative everywhere, and its integral over the entire space is equal to one.
- **Variance:** In probability theory and statistics, variance measures how far a set of numbers is spread out. A variance of zero indicates that all the values are identical. Variance is always non-negative: a small variance indicates that the data points tend to be very close to the mean (expected value) and hence to each other, while a high variance indicates that the data points are very spread out around the mean and from each other. It is represented by the Greek letter alpha.
- **Standard Deviation:** In statistics and probability theory, the standard deviation (SD) measures the amount of variation or dispersion from the average. A low standard deviation indicates that the data points tend to be very close to the mean (also called expected value) and a high standard deviation indicates that the data points are spread out over a large range of values. The standard deviation of a random variable, statistical population, data set, or probability distribution is the square root of its variance. It is represented by the Greek letter sigma.
- **Skewness:** In probability theory and statistics, skewness is a measure of the asymmetry of the probability distribution of a real-valued random variable about its mean. The skewness value can be positive or negative, or even undefined. It is denoted by epsilon.

- **Viscosity:** The viscosity of a fluid is a measure of its resistance to gradual deformation by shear stress or tensile stress. For liquids, it corresponds to the informal concept of "thickness". For example, honey has a much higher viscosity than water. Viscosity is a property arising from collisions between neighboring particles in a fluid that are moving at different velocities. A fluid that has no resistance to shear stress is known as an ideal fluid. Zero viscosity is observed only at very low temperatures, in super fluids. Otherwise, all fluids have positive viscosity, and are technically said to be viscous or viscid. However, a liquid is said to be viscous if its viscosity is substantially greater than water's, and may be described as mobile if the viscosity is noticeably less than water's.
- **Pressure:** Pressure is the ratio of force to the area over which that force is distributed. Pressure is measured in any unit of force divided by any unit of area. The SI unit of pressure is the Newton per square meter, which is often called the Pascal (Pa).
- **Density:** The density, or more precisely, the volumetric mass density, of a substance is its mass per unit volume. The symbol most often used for density is Greek letter rho. For a pure substance the density has the same numerical value as its mass concentration. Different materials usually have different densities, and density may be relevant to buoyancy, purity and packaging. The density of a material varies with temperature and pressure. This variation is typically small for solids and liquids but much greater for gases. Increasing the pressure on an object decreases the volume of the object and thus increases its density. Increasing the temperature of a substance (with a few exceptions) decreases its density by increasing its volume. The SI unit of density is of kilogram per cubic meter.
- **Volume Concentration:** The volume concentration is defined as the volume of a constituent divided by the volume of the mixture. Being dimensionless, it is expressed as a number or as a percentage. Its unit is 1.
- **Magnetic Field Intensity:** Magnetic field intensity at a point is the number of magnetic lines of force crossing per unit area around that point, the area being held perpendicular to the direction of lines of forces. In SI system, the unit of magnetic intensity is Ampere/metre.
- **Intensity of Magnetization:** It is a measure of the extent to which a substance gets magnetized. Intensity of magnetization of a magnetic substance is defined as its

magnetic moment per unit volume, the specimen being so small that its magnetization can be supposed to be uniform. In SI system, the unit of intensity of magnetization is Weber/metre^2.

- **Magnetic Induction:** The total number of magnetic lines crossing per unit area normally through a magnetic substance is called magnetic induction. When a magnetic material is placed in a uniform magnetizing field, it acquires magnetism and develops its own magnetic field due to induction. As a result of this induction, the original magnetic field is modified both inside as well as outside the magnetic material. This modified or resultant field is called magnetic induction and is measured as the number of lines of induction passing normally through unit area of the material. It is expressed in Tesla in SI units.
- **Magnetic Susceptibility:** It measures the ease with which a specimen takes magnetism. Magnetic susceptibility of a magnetic substance is defined as the ratio of the intensity of magnetization induced in the substance to the strength of magnetizing field H in which the substance is placed. Susceptibility is zero for air, is positive in case of paramagnetism, ferromagnetism and negative in case of diamagnetism. As it is the ratio of same quantities, it has no units.
- **Magnetic Permeability:** It measures the degree to which the specimen can be penetrated. The magnetic permeability of a material is defined as the ratio of magnetic induction to the strength of magnetization. In SI system, the unit of Magnetic Permeability is henry/metre. For free space, permeability is $4\pi \times 10^{-7}$ henry/metre.
- **Load carrying capacity:** The meaning of Load carrying capacity is different according to system environment. In mechanical engineering, the meaning of Load carrying capacity is treated in terms of basic dynamic load rating. The basic dynamic load ratings for bearings are dependent on performance standards and the fatigue behavior of the materials. The magnitude of load rating is always influenced by running speed. Every bearing is introduced or known worldwide with its maximum load carrying capacity which is specified corresponding to various running speeds. The Load carrying capacity is considered to be valid only for bearing having normal dimensional running accuracy, proper method of lubrication. Moreover, the permissible load for a bearing is determined by the permanent deformation caused by the load at the race way or rolling element.

- **Rotational Inertia:** Rotational inertia is the rotational analog of mass for linear motion. It appears in the relationships for the dynamics of rotational motion. The rotational inertia must be specified with respect to a chosen axis of rotation. Rotational inertia would also be known as mass moment of inertia, polar moment of inertia, or the angular mass.

1.9 Significant Contribution of the Thesis

The purpose of research in Tribology is understandably the minimization and elimination of losses resulting due to friction and wear at all levels of technology where the rubbings of surfaces are involved. Tribology also plays an important role in the improvement of product, performance and durability and the reduction of environmental impact. When two surfaces of a machine are interacting with each other their lubrication depends on a number of factors such as load on the surfaces, geometry of the surfaces, the types of materials out of which the surfaces are made and physical & chemical properties of the lubricants etc.

The bearing surfaces tend to be rough after having some run-in and wear. The roughness is random in nature without following any definite structural pattern. The motion of the lubricant gets opposed by the roughness and hence the roughness aspect deserves to be dully addressed, which entails stochastically applications. The transverse surface roughness has been a subject of discussion in many recent investigations because of its adverse effect on the performance of the bearing system.

The magnetic fluid is a suspension of solid magnetic particles in a liquid carrier. Depending upon the ferromagnetic material and the method of preparation, the mean diameter of a particle varies from 3nm to 15nm. The liquid carrier can be polar or non polar. Since 1960, when these magnetic materials were initially synthesized, their technological applications have been always on rise. The application of a magnetic field causes an increase of the viscosity. When a magnetic field is applied to a ferro-fluid, the magnetic moments of the particles orient along the field lines almost instantly. The magnetization of the ferro-fluid responds immediately to the changes in the applied magnetic field and when the applied magnetic field is removed, the moments randomize quickly. The use of magnetic fluid as a lubricant modifying the performance of the bearing system has been an intensive field of investigations and it is not surprising that the magnetization invariably leads to improved bearing performance.

In this thesis, Chapter 2 is a review of related literature with discussion.

Chapter 3 introduces various types of governing equations for fluid flow in general and magnetic fluid flow in particular. The method of deriving the associated generalized Reynolds' type equation for the pressure distribution in a bearing system is presented here. This modified Reynolds' type equation takes into account the effect of magnetic fluid, geometry of the surfaces and roughness of the bearing surfaces. The differential equations governing the fluid flow are developed here so as to meet the requirements of the bearing geometry. The mathematical modelling of bearing system is found here. The investigations carried out in this thesis are based on the stochastic modeling of roughness. (Christensen and Tonder (1969 a, 1969 b, 1970)).

In Chapter 4 the performance of the hydrodynamic lubrication of a Rayleigh step bearing is discussed. An attempt has been made to study and analyze the effect of transverse roughness in the presence of a magnetic fluid on a Rayleigh step bearing. The bearing surfaces are assumed to be transversely rough. The roughness of the surfaces has been characterized by a random variable with non-zero mean, variance and skewness. The stochastically averaged Reynolds equation is solved with suitable boundary conditions to obtain the pressure distribution in turn, which is used to get the load carrying capacity. This chapter establishes that there exists a sufficient scopes for improving the performance of the bearing system in the case of negatively skewed roughness. The adverse effect of roughness can be minimized by the positive effect of magnetization at least in the case of negatively skewed roughness. Therefore, this investigation offers some measures even for bearing's life period point of view.

The performance of an idealized rough porous hydrodynamic plane slider bearing is analyzed in Chapter 5. The stochastic model of Christensen-Tonder has been used (with some modification of the probability density function) to study the effect of transverse surface roughness on the performance of the bearing system. The modified Darcy's law has been used to account for porosity effect. Solving the associated stochastically averaged Reynolds's type equation, the pressure distribution in the bearing system has been obtained which results in the calculation of load carrying capacity. It is observed that the transverse surface roughness brings an adverse effect on the performance, which compounds further due to the negative effect of porosity. However, the situation is relatively better in the case of negatively skewed roughness, which further improves when variance (–ve) occurs.

Chapter 6 deals with the squeeze film behaviour for a Shliomis model based magnetic fluid lubrication of a rough porous secant slider. To evaluate the effect of transverse surface roughness, the model of Christensen-Tonder has been adopted. After solving the averaged Reynolds' type equation one gets the pressure distribution. Then the load carrying capacity of bearing is derived. It is found that the adverse effect of surface roughness can be reduced to a large extent by the Ferro-fluid lubrication. Further, Shliomis model proves to be a little bit superior to the Neuringer-Rosensweig model, so far as the Ferro-fluid lubrication is concerned.

Chapter 7 presents the ferro-fluid lubrication of a rough, porous convex pad slider bearing considering slip velocity. The magnetic fluid flow is governed by Jenkins model. The associated stochastically averaged Reynolds type equation is solved to obtain the pressure distribution which gives the load carrying capacity. Further the friction is evaluated. The graphical results suggest that the magnetization may not go a long way for reducing the adverse effect of roughness, even if the slip parameter is minimum, However the situations improves when negatively skewed roughness occurs. Besides, the magnetization fails to have any impact on friction.

At the end, general conclusion and future research scope are mentioned.