International Journal of Research in Advent Technology, Vol.7, No.1, January 2019
E-ISSN: 2321-9637
Available online at www.ijrat.org

Analysis of Rough Porous Inclined Slider Bearing Lubricated With a Ferrofluid Considering Slip Velocity

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Abstract- The current study focuses on performance of the ferrofluid, Slider bearing which inclined through the porosity with lubrication based rough surface to examine the impacts of slip velocity. The magnetic fluid flow is directed by the Neuringer and Rosensweig model. The Christensen and Tonder models have been taken to derive the transverse roughness stochastically. The impacts of slip velocity are studied by using the Beavers and Joseph model. While the distribution of pressure measured by cracking from the equation of Reynolds which is stochastic. This is followed by a numerically using Simpson's 1/3 rule of the expression for the dimensionless load carrying capacity to study its correlation with the bearing system. A graphical study demonstrates the efficacy of load on magnetic, roughness and slip parameter. The outcome show, there is a positive correlation among the ability of load as well as left-ward skewed surface. The results were more prominent in the case of negative variance. This study focuses on finding a possible way of increasing load capacity by decreasing the slip parameter and porosity. An appropriate selection of magnetic strength may lead to some compensation for poor effect of porosity, slip and roughness.

Keywords- Ferrofluid, slip velocity, porosity.

1. INTRODUCTION

The slider bearings are primarily created to aid the transverse load in any given engineering system. The inclined plane slider bearing study is a classical one. Slider bearing has a lot of applications in various fields including clutch plates, automobile transmissions and domestic appliances. Bearing surfaces usually develop roughness after a certain level of wear and tear.

The impact of surface roughness and slip velocity discipline was lately overcome through many researchers based on the performance of bearing system. Some other important research work includes considering the outcome of magnetic fluid also. The magnetic fluid is a typical hybrid of soft material and the nanoparticles. The ferrofluid contain excessive magnetic nanoparticles and thus it can be impacted either by parallel or perpendicular magnetic field.

[1] stochastic model was further advanced by [2-4]. Many researchers like [5, 6, 7] have used this study. [8] started a study and analyzing the impact through squeeze film on surface roughness represent among circular plates of porous structure. Plenty of papers are existing in the world which provides the sources in the field of research and that analysis we can identify on various kinds of bearing, [9-10] in composite slider bearing with porosity, [11] in journal bearing, [12, 13, 14] in slider bearing, Rayleigh step bearing by [15]. [16] prepared an article on plane slider bearing of rough surface with porosity. [17] carried out a theoretical study of the magneto-hydrodynamic conducting composite slider bearing with transverse magnetic field. [18] investigated the influence of the transverse magnetic field on hydrodynamic inclined porous slider bearing. The study suggested that with an increasing Hartmann number, the load carrying capacity and friction also increased. [19] presented an entire review of ferrofluid lubrication theories derived from Neuringer and Rosensweig, Shliomis and Jenkins models. [20] examined the experimental performance of ferrofluid based on hydrodynamic journal bearing taking into account the combination of various shafts and bearing materials. [21] talked about the impacts of slip velocity on the short bearing's performance that was lubricated with a magnetic fluid. The graphical results showed that for huge values of aspect ratio, slip had a substantial impact. Some researchers [22, 23, 24, 25, 26, 27] have also used magnetic fluid as a lubricant in order to aid the Tribological performance of a different sliding interface. [28] dealt with the impact of squeeze film of step bearing with magnetic fluid. [29] studied and introspect the slider bearing with porous structure on performance of fluid film by keep in mind the velocity of slip. Also [30] has extended above analysis by including anisotropic permeability of a porous matrix. [31] dealt the performance of slider bearings considering surface roughness effect.

[32] examined ferrofluid lubrication of a slider bearing with convex pad using Shliomis model which is more effective than Neuringer and Rosensweig model. A lot of studies have attempted to explore the impact of slip on different bearings in a theoretical as well as experimental manner [33-35]. All these investigations have concluded that slip has a substantial impact on the working of any bearing system.

The researchers (Neuringer-Rosensweig, Shliomis and Jenkins) introduced new horizon in the field of magnetic fluid flow and then after [36] compares these three models in detail and they came up with new notion. The comparison suggested that the Shliomis model is the most competent for higher loads. [37] analyzed the impact of magnetic fluid lubrication on a rough composite porous slider bearing. It was accomplished that the pessimistic outcome of porosity and standard deviation could be reduced by the optimistic effect of magnetization by properly choosing length of curved and length of flat pads.

And so on, it has been recommend analyzing and study inclined slider bearing and the efficacy of slip velocity on the performance of Ferro fluid with rough surface and porosity.

2. ANALYSIS

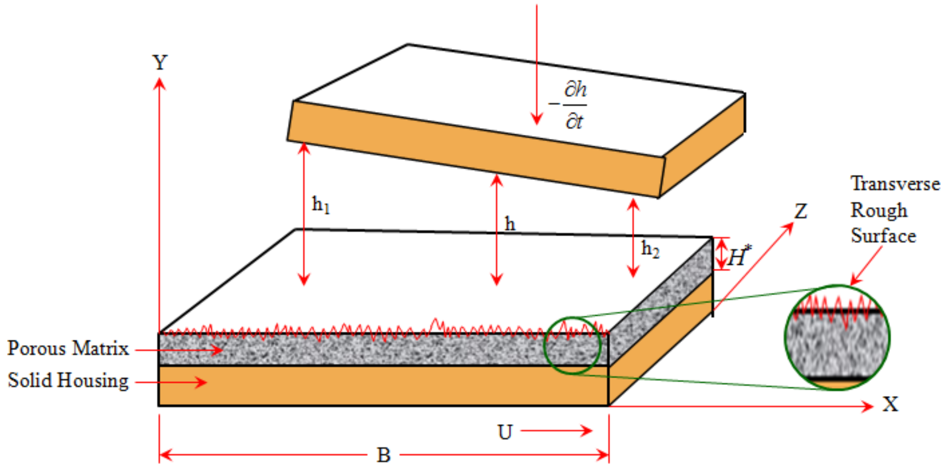


Fig. 1. Physical geometry of porous plane inclined slider bearing

Figure 1 schematically displays a diagram of the porous inclined slider bearing. The bearing has two distinct surfaces separated by a Ferro fluid film thickness h. The porous bearing's lower surface is at rest while the upper solid surface is at motion with a constant velocity U. The bearing surfaces are supposedly rough and the bearing is infinitely wide in the z-direction. The stochastically modeling of the surface roughness by [2-4] considered the following form

$$h = \boldsymbol{h} + h_s \tag{1}$$

where

$$\boldsymbol{h} = h_1 - (h_1 - h_2)\frac{x}{B}$$

Also, the study uses h_s using the probability density function

$$f(h_s) = \begin{cases} \dfrac{35}{32c}\left(1 - \dfrac{h_2^2}{c^2}\right)^3, & -c \le h_s \le c \\ 0 & \text{, elsewhere} \end{cases} \tag{2}$$

In this case, c is the highest possible deviation from the average width of the film. α, σ and ε are considered in view of relationship

$$\alpha = E(h_s),\ \sigma^2 = E(h_s - \alpha)^2,\ \varepsilon = E(h_s - \alpha)^3 \tag{3}$$

where E is the expectation operator defined by

$$E(R) = \int_{-c}^{c} R\, f(h_s)\, dh_s \tag{4}$$

[38] devised a theory that describes the stable movement of magnetic fluid. The model was:

$$\rho(\bar{q}.\nabla)\bar{q} = -\nabla p + \eta\,\nabla^2 \bar{q} + \mu_0 (\overline{M}.\nabla)\overline{H} \tag{5}$$

$$\nabla.\bar{q} = 0 \tag{6}$$

$$\nabla \times \overline{H} = 0 \tag{7}$$

$$\overline{M} = \bar{\mu}\overline{H} \tag{8}$$

$$\nabla.\left(\overline{H}+\overline{M}\right)=0 \tag{9}$$

$$q=ui+vj+wk \tag{10}$$

where ρ, $\overline{q}$, $\overline{M}$, p and η are fluid density, fluid velocity, magnetization vector, film pressure and fluid viscosity respectively.

Further, the magnetic field's magnitude [22] is given by

$$H^2=k\,x(B-x) \tag{11}$$

where $k\,(A^2/m^{-4})$ is suitable constant.

Combining Eq. (5) to (10) under the traditional assumption of hydrodynamic lubrication theory

$$\frac{\partial^2 u}{\partial z^2}=\frac{1}{\eta}\frac{\partial}{\partial x}\left(p-\frac{1}{2}\mu_0\overline{\mu}H^2\right) \tag{12}$$

Using slip boundary condition [39, 28]

$$u=\frac{1}{\beta}\frac{\partial u}{\partial z};\ \frac{1}{\beta}=\frac{\sqrt{K}}{\xi}\ \ when\, z=0 \tag{13}$$

and

$u=0$ (no slip) and $z=h$ (at the upper solid surface) (14)

Eq. (12) becomes

$$u=\frac{z^2}{2\eta}\frac{\partial}{\partial x}\left(p-\frac{1}{2}\mu_0\overline{\mu}H^2\right)-\frac{h^2(\beta z+1)}{2\eta(h\beta+1)}\frac{\partial}{\partial x}\left(p-\frac{1}{2}\mu_0\overline{\mu}H^2\right) \tag{15}$$

Integrating Eq. (15) over the film region, yields

$$\int_0^h u\,dz=\frac{h^3}{6\eta}\frac{\partial}{\partial x}\left(p-\frac{1}{2}\mu_0\overline{\mu}H^2\right)-\frac{h^2(\frac{h^2\beta}{2}+h)}{2\eta(h\beta+1)}\frac{\partial}{\partial x}\left(p-\frac{1}{2}\mu_0\overline{\mu}H^2\right) \tag{16}$$

Using Eq. (16) in continuity equation

$$\frac{\partial}{\partial x}\int_0^h u\,dz+w_{z=h}-w_{z=0}=0 \tag{17}$$

yields

$$\frac{\partial}{\partial x}\left[\frac{h^3}{6\eta}\frac{\partial}{\partial x}\left(p-\frac{1}{2}\mu_0\overline{\mu}H^2\right)-\frac{h^2(\frac{h^2\beta}{2}+h)}{2\eta(h\beta+1)}\frac{\partial}{\partial x}\left(p-\frac{1}{2}\mu_0\overline{\mu}H^2\right)\right]+V-w_{z=0}=0 \tag{18}$$

where

$$w_{z=h}=V=-\frac{dh}{dt}=-\dot{h} \tag{19}$$

shows the influence of squeeze velocity in the downward z direction.

Using Darcy's law, the velocity components in the porous region are represented by

$$\overline{u}=\frac{-K}{\eta}\frac{\partial}{\partial x}\left(p-\frac{1}{2}\mu_0\overline{\mu}H^2\right)\quad (x \text{ direction}) \tag{20}$$

$$\overline{w}=\frac{-K}{\eta}\frac{\partial}{\partial z}\left(p-\frac{1}{2}\mu_0\overline{\mu}H^2\right)\quad (z \text{ direction}) \tag{21}$$

Substituting equation (20) and (21) in the continuity equation for porous region

$$\frac{\partial\overline{u}}{\partial x}+\frac{\partial\overline{w}}{\partial z}=0 \tag{22}$$

and integrating over $(-H^*,0)$

$$\left[\frac{\partial}{\partial z}\left(p-\frac{1}{2}\mu_0\overline{\mu}H^2\right)\right]_{z=o}=-H^*\frac{\partial^2}{\partial x^2}\left(p-\frac{1}{2}\mu_0\overline{\mu}H^2\right) \tag{23}$$

We know that $z=-H^*$ is a solid surface hence

$$\left[\frac{\partial}{\partial z}\left(p-\frac{1}{2}\mu_0\overline{\mu}H^2\right)\right]_{z=-H^*}=0 \tag{24}$$

Considering continuous normal velocity components across the film-porous interface, therefore

$$\left[w\right]_{z=0}=\left[\overline{w}\right]_{z=0} \tag{25}$$

yields

$$\frac{\partial}{\partial x}\left[\left(2h^3-\frac{3h^3(h\beta+2)}{(h\beta+1)}-12KH^*\right)\frac{\partial}{\partial x}\left(p-\frac{1}{2}\mu_0\bar{\mu}H^2\right)\right]=-12\eta V \tag{26}$$

using Eqs. (18), (21), (23) and [40, 28] which suggests that the porous region's pressure can be substituted by the average pressure with regards to bearing wall thickness.
The following dimensionless quantities are used,

$$X=\frac{x}{B},\bar{h}=\frac{h}{h_2},\bar{p}=-\frac{h_2^3 p}{\eta V B^2},\mu^*=-\frac{\mu_0\bar{\mu}k h_2^3}{\eta V},$$
$$\bar{\beta}=h_2\beta,\ \psi=\frac{KH^*}{h_2^3},a=\frac{h_1}{h_2},\bar{B_1}=\frac{B_1}{B} \tag{27}$$

Eq. (26) becomes

$$\frac{\partial}{\partial X}\left[G\frac{\partial}{\partial X}\left(\bar{p}-\frac{1}{2}\mu^* X(1-X)\right)\right]=12 \tag{28}$$

where

$$G=\frac{\left(\bar{h}\bar{\beta}+4\right)\bar{h}^3+12\psi\left(\bar{h}\bar{\beta}+1\right)}{\left(\bar{h}\bar{\beta}+1\right)}$$

which is the modified Reynolds' equation [28]. The presumptions of usual hydrodynamic magnetic lubrication theory are used in the analytical study. Following the method adopted in [28] and resorting to [39] slip model as well as [2-4] roughness model; Eq. (28) turns out to be

$$\frac{\partial}{\partial X}\left[G(\bar{h})\frac{\partial}{\partial X}\left(\bar{p}-\frac{1}{2}\mu^* X(1-X)\right)\right]=12 \tag{29}$$

where

$$G(\bar{h})=\frac{\left(\left[g(\bar{h})\left(\frac{4+\frac{\bar{h}}{\bar{\beta}}}{2+\frac{\bar{h}}{\bar{\beta}}}\right)\right]^{1/3}\bar{\beta}+4\right)\left[g\left(\bar{h}\right)\left(\frac{4+\frac{\bar{h}}{\bar{\beta}}}{2+\frac{\bar{h}}{\bar{\beta}}}\right)\right]+12\psi\left(\left[g(\bar{h})\left(\frac{4+\frac{\bar{h}}{\bar{\beta}}}{2+\frac{\bar{h}}{\bar{\beta}}}\right)\right]^{1/3}\bar{\beta}+1\right)}{\left(\left[g(\bar{h})\left(\frac{4+\frac{\bar{h}}{\bar{\beta}}}{2+\frac{\bar{h}}{\bar{\beta}}}\right)\right]^{1/3}\bar{\beta}+1\right)} \tag{30}$$

$$g\left(\bar{h}\right)=\left(\bar{h}^3+3\bar{\alpha}\bar{h}^2+3\left(\bar{\alpha}^2+\bar{\sigma}^2\right)\bar{h}+3\bar{\sigma}^2\bar{\alpha}+\bar{\alpha}^3+\bar{\varepsilon}+12\bar{\psi}\right)$$

and

$$\bar{h}=a-(a-1)X,\ 0\le X\le 1$$

Solving Eq. (29) under related pressure limit settings

$$\bar{p}(0)=0,\ \bar{p}(1)=0$$

one obtains

$$\bar{p}=\frac{1}{2}\mu^* X(1-X)+12\int_0^X\frac{1-X}{G(\bar{h})}dX \tag{31}$$

The load bearing capacity in dimensionless forms is obtained

$$\bar{W}=\int_0^1\bar{p}\ dX=\frac{\mu^*}{12}+12\int_0^1\frac{(1-X)^2}{G(\bar{h})}\ dX \tag{32}$$

3. RESULTS AND DISCUSSION

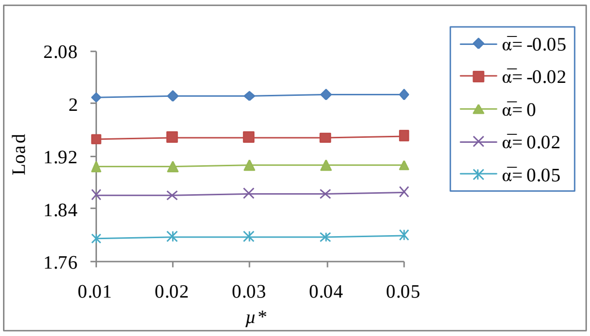
Eq. (31) is used for calculating the $\bar{p}$ and eq. (32) is used to find the $\bar{W}$.
From these two equations, it can be said that dimensionless pressure increases by

$$\frac{1}{2}\mu^* X(1-X)$$

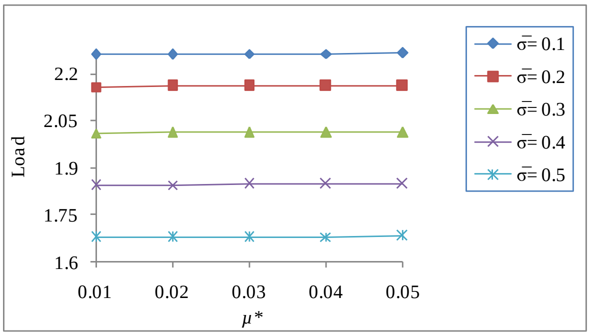
and non-dimensional load bearing capacity increases by

$$\frac{\mu^*}{12}$$

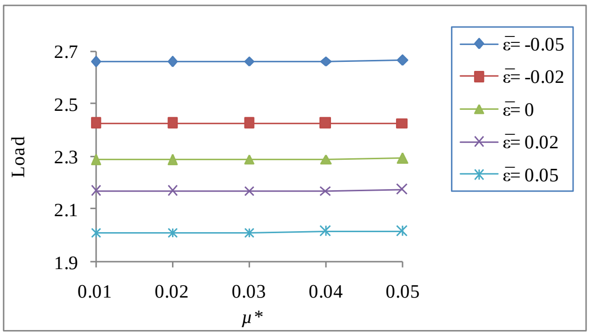
due to the magnetic fluid lubricant. From fig 2, it can be said that there is a positive correlation between the $\overline{W}$ and μ^*. Fig 3 present the variation of $\overline{W}$ concerned with $\overline{\sigma}$. With an increase in $\overline{\sigma}$, the load reduces. Fig 3(d) shows that slip velocity has a substantial impact on the bearing system's performance. From fig 4, the impact of $\overline{\alpha}$ on the performance of characteristic can be seen. It suggests that with increasing positive variance, the $\overline{W}$ decreases and with decreasing negative variance increases the $\overline{W}$. From fig 5, it can be understood that the $\overline{W}$ is improving with negatively skewed roughness. Fig 6(a) suggests that slip velocity and load carrying capacity have a negative correlation.



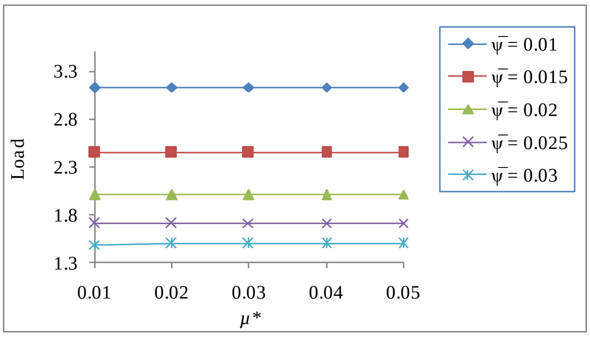
(a) $\overline{\alpha}$



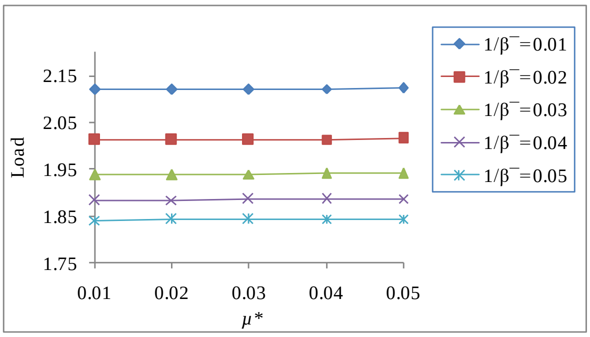
(b) $\overline{\sigma}$



(c) $\overline{\varepsilon}$

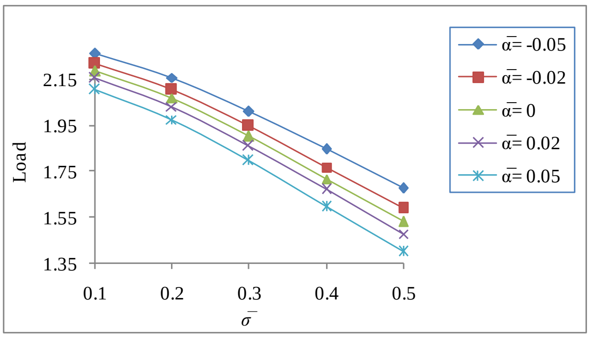


(d) $\overline{\psi}$

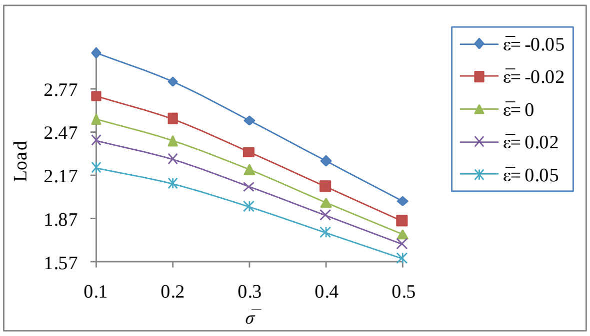


(e) $1/\overline{\beta}$

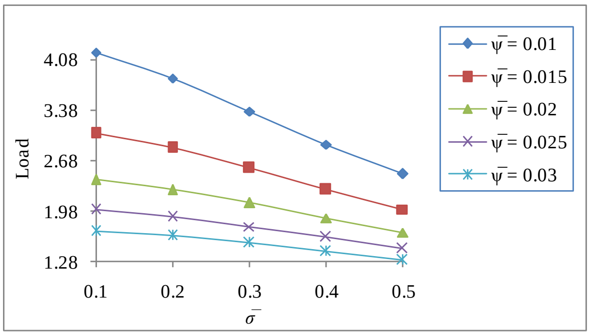
Fig. 2. Profile of $\overline{W}$ with regards to μ^*



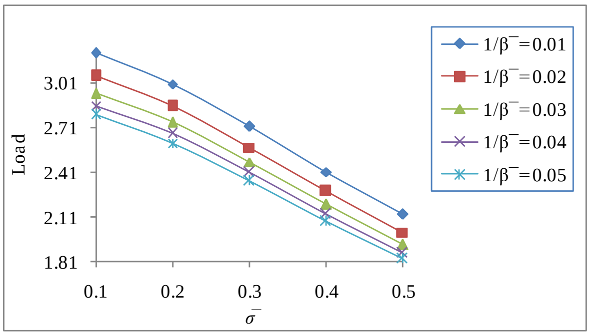
(a) $\overline{\alpha}$



(b) $\bar{\varepsilon}$

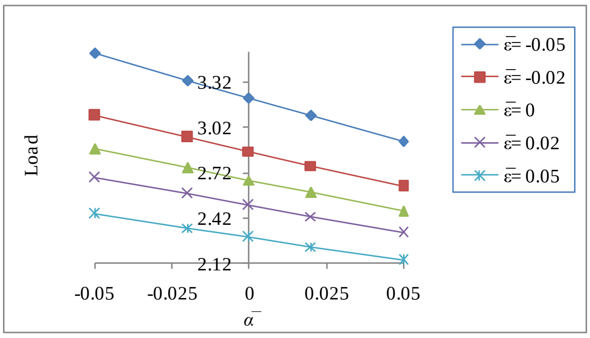


(c) $\bar{\psi}$

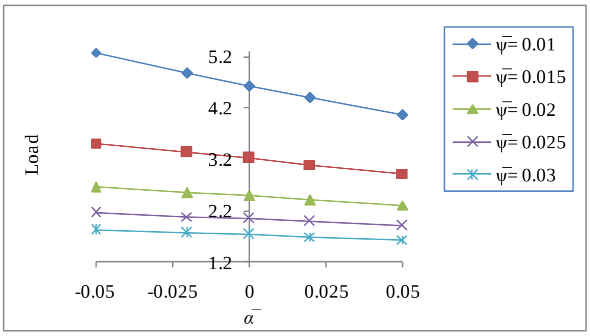


(d) $1/\bar{\beta}$

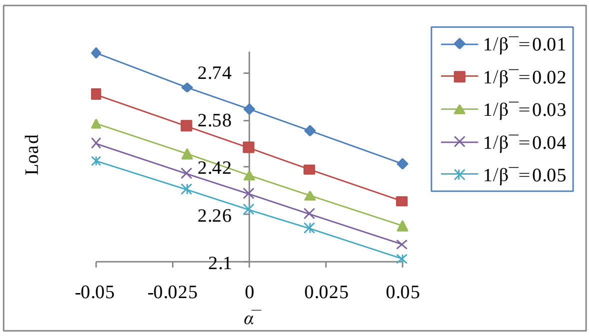
Fig. 3. Profile of $\bar{W}$ with regards to $\bar{\sigma}$



(a) $\bar{\varepsilon}$

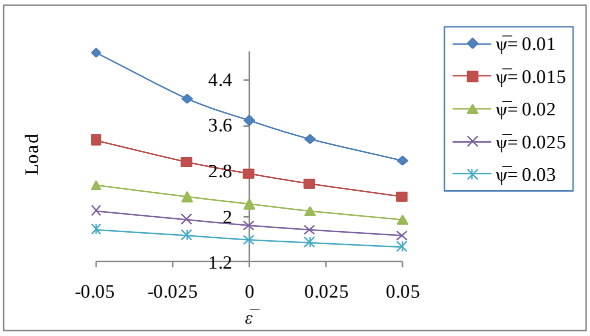


(b) $\bar{\psi}$

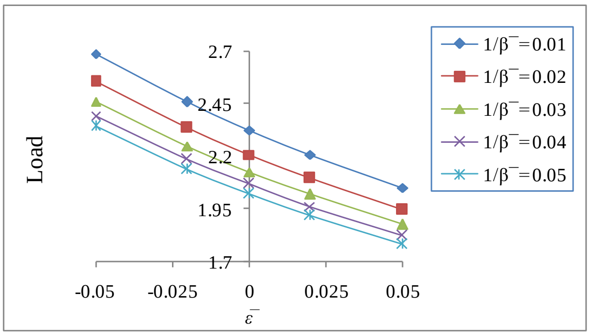


(c) $1/\bar{\beta}$

Fig. 4. Profile of $\bar{W}$ with regards to $\bar{\alpha}$

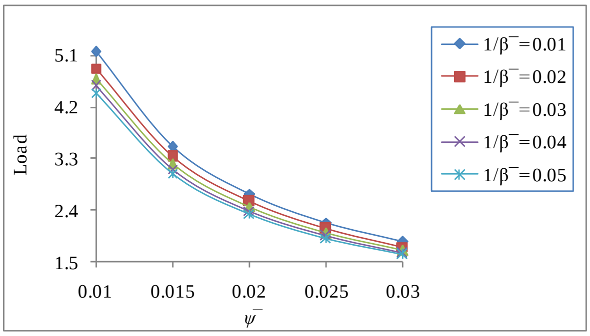


(a) $\bar{\psi}$



(b) $1/\bar{\beta}$

Fig. 5. Profile of $\bar{W}$ with regards to $\bar{\varepsilon}$



(a) $1/\overline{\beta}$

Fig. 6. Profile of $\overline{W}$ with regards to $\overline{\psi}$

4. VALIDATION

Table 1-3 presents the impact of magnetization, porosity and slip parameter on load bearing capacity.

Table 1. Comparison of load bearing capacity calculated for μ^*

Quantity	Load bearing capacity calculated for $\overline{\alpha}=-0.05, \overline{\sigma}=0.1, \overline{\varepsilon}=-0.05, \overline{\psi}=0.03$, $1/\overline{\beta}=0.02$	
μ^*	With rough porous surface as in this study	With smooth porous surface by [28]
0.01	1.5834207	2.594387
0.02	1.5842541	2.59522
0.03	1.5850874	2.596054
0.04	1.5859207	2.596887
0.05	1.5867541	2.59772

Table 2. Comparison of load bearing capacity calculated for $\overline{\psi}$

Quantity	Load bearing capacity calculated for $\mu^*=0.01, \overline{\alpha}=-0.05, \overline{\sigma}=0.1, \overline{\varepsilon}=-0.05$, $1/\overline{\beta}=0.02$	
$\overline{\psi}$	With rough porous surface as in this study	With smooth porous surface by [28]
0.01	3.2561125	4.2759738
0.015	2.5635708	3.6613228
0.02	2.1211911	3.2129435
0.025	1.8122076	2.8685645
0.03	1.5834207	2.5943869

Table 3. Comparison of load bearing capacity calculated for $1/\overline{\beta}$

Quantity	Load bearing capacity calculated for $\mu^*=0.01, \overline{\alpha}=-0.05, \overline{\sigma}=0.1, \overline{\varepsilon}=-0.05$, $\overline{\psi}=0.03$	
$1/\overline{\beta}$	With rough porous surface as in this study	With smooth porous surface by [28]
0.01	1.6143886	2.5885601
0.02	1.5834207	2.5943869
0.03	1.5563495	2.6001801
0.04	1.5325744	2.6059399
0.05	1.5116124	2.6116666

The results of this article have been validated by making a comparison of the results with the work of [28].

Table 2-3 suggests that the slip parameter and porosity lead to a decrease in the load bearing capacity as compared to the [28]. A lot of different parameters are responsible for decreasing the load bearing capacity. However, the ferrofluid lubrication makes the situation when there is a minimum influence of standard deviation, porosity and slip parameter.

Acknowledgments
The author would like to express gratitude towards Dr. Paresh A. Patel whose constructive criticism and feedback made this paper better. I also express my sincere respect to the reviewers who studied the depth of paper and help to explore the horizon of research for me.

5. CONCLUSION

To sum up, it can be said that though transverse surface roughness has a negative impact on the load bearing capacity in general, the performance can be improved by using negatively skewed roughness along with negative variance. Roughness is also an important parameter for the bearing life. The study also emphasizes on the fact that ideal magnetic strength is crucial for a better bearing performance. The lowest slip levels are advised for enhancing the overall performance.

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NOMENCLATURE

a	Inlet-outlet ratio
B	Length of the bearing (mm)
h_1	Minimum film thickness (m)
h_2	Maximum film thickness (m)
h	Fluid film thickness (mm)
$\mathbf{h}$	Mean film thickness (mm)
h_s	Deviation from mean level
$\bar{h}$	Non- dimensional film thickness
$\bar{H}$	Magnetic field (Gauss)
H^2	Magnitude of the magnetic field (N/A.m)
H^*	Non dimensional porous layer thikness
K	Permeability (m^2)
p	Lubricant film Pressure (N/mm^2)
$\bar{p}$	Non-dimensional pressure
U	Uniform velocity in the direction of x-axis (m/s)
V	Velocity approach
u	Velocity in x direction (m/s)
v	Velocity in y direction (m/s)
w	Velocity in z direction (m/s)
$\bar{u}$	Dimensionless velocity in x direction
$\bar{v}$	Dimensionless velocity in y direction
$\bar{w}$	Dimensionless velocity in z direction
W	Load carrying capacity (N)
$\bar{W}$	Dimensionless load carrying capacity
α	Variance (mm)
$\bar{\alpha}$	Non- dimensional variance
β	Slip parameter (m^{-1})
$\bar{\beta}$	Dimensionless slip parameter
ε	Skewness (mm^3)
$\bar{\varepsilon}$	Skewness in dimensionless form
η	Viscosity of lubricant (mm^2/s)
μ_0	Permeability of the free space (N/A^2)
$\bar{\mu}$	Magnetic susceptibility of particles (mm^3/kg)
μ^*	Dimensionless magnetization parameter
ξ	Slip coefficient
σ	Standard deviation (mm)
$\bar{\sigma}$	Dimensionless standard deviation
ψ	Porosity