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Influence Of Viscosity Changes On The MHD Squeeze Film Lubrication Using Couple Stress Fluids Between Circular Plates

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Abstract
A circular bearing has been analysed to evaluate the effect of couple stress, viscosity pressure dependence (VPD) and magnetic field. Using the Barus formula and Stokes theory, the Reynolds equation has been obtained. The squeeze film pressure, load carrying capacity, and squeeze film time are expressed mathematically. For various parameters, outcomes are graphically shown in two- and three-dimensional formats. Presence of the viscosity variation parameter, MHD, and couple stress parameter clearly amplifies the film pressure, load-carrying capacity, and squeeze film time in comparison to the scenario with non-viscosity variation, non-magnetic, and Newtonian cases.
Keywords: *Circular plates, Viscosity variation, Magnetohydrodynamic, squeeze film, Couple stress fluids.*

INTRODUCTION

To improve the life of mechanical tools, lubrication is essential. Among the fluid lubrication techniques, squeeze film is quite effective in reducing wear and tears. A squeeze film is a thin layer of fluid that is applied between moving parts to minimise friction and prevent significant damage. The couple stress fluid, out of all the fluids, has made a major contribution in numerous applications, including gears, bearings, rolling elements, and bio-lubrication. Couple stress fluid is a fluid with more than one type of molecule with opposing forces. Many researchers have diligently investigated on couple stress fluid and its effect on the bearing performance. As reported by Pinkus et al. [1] and Jones et al. [2], the lubricant is considered is a Newtonian fluid. Also, in the majority of investigations on classical hydrodynamic lubrication Newtonian fluid is considered. Recent experimental findings show that the ideal lubricant can be obtained by incorporating a less quantity of long-chained polymers into a Newtonian fluid. Spikes [3] have demonstrated experimentally that lubricant behaviour in hydrodynamic contacts can be improved by blending base oil with viscosity index improvers. Ariman and Sylvester [4, 5] developed distinct micro continuum theories and rheological characteristics of these non-Newtonian lubricants. Stokes theory [6] is regarded as the most basic modification of classical continuum theory of fluids, including polar features like the existence of body couples and couple stresses. Numerous investigators have studied the impact of couple stresses on the squeeze film properties of different systems such as Ramanaiah [7], Bujurke and Naduvinamani [8], Lin et al [9], Naduvinamani et al [10] and Manivasakan and Sumathi [11] and concluded that couple stress fluid enhances the lubricating properties as compared to classical case.

The fundamental ideas of magnetohydrodynamics (MHD) can be used to study the physical-mathematical system that governs the dynamics of magnetic fields in fluids that carry electricity. The basic principle of MHD is that magnetic fields can produce currents in conductive fluids in motion, which leads to fluid forces, changes in the geometry, and intensities of magnetic fields. They provide strong resistance to radioactive radiation and can operate at high temperatures. The use of electrically conductive liquid metal as a lubricant is recommended to prevent undesired variations in viscosity with temperature. Numerous authors [12–16] have examined the MHD performance of electrically conductive fluid-lubricated bearings. The results show that, in comparison with a non-magnetic case, there is a rise in film pressure, load, and squeeze film time in the presence of a magnetic field. It has been noted that the work is restricted to constant viscosity in all the studies. Many investigations ignore the impact of pressure on fluid viscosity (μ), assuming it to be constant even though it varies with pressure and temperature. Gould [17] study highlights the significance of viscosity variations with pressure, particularly in high-pressure squeeze films. Reddy et al. [18] estimated how viscosity affects narrow journal bearings with couple stress fluid. Lin et

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al. [19, 20] examined the effects of couple stress fluid and VPD on the squeeze film behaviour of sphere and circular plates. The study of viscosity variation in incompressible Poiseuille flow of Newtonian liquids was conducted by Kalogirou et al. [21]. Lu and Lin [22] have investigated the combined effects of couple stresses and VPD on the sphere-plate squeeze film system and found that these effects increase the squeeze film's capacity to support loads. Various configurations have been considered by many researchers [23-27] to study the effect of change in viscosity under different conditions and came to the conclusion that viscosity variation improves the squeeze characteristics when compared to a non-viscous case.
The flow of couple stress fluids between a circular plate is investigated in this paper, with particular attention paid to the effects of viscosity Changes and MHD. The nonlinear Reynolds equation is obtained using Stokes model and Barus formula. The film pressure, load carrying capacity and squeeze film time are derived analytically. This study examines how couple stresses, Hartmann number, and viscosity variation with pressure affect squeeze film properties and compares them to the smooth case.

SOULTION OF THE PROBLEM

Figure 1 depicts a systematic diagram circular plates moving at a normal velocity (V). The magnetic field that is applied vertically, in *z*-direction to the plates is B_0. Lubricant between the plates is a non-Newtonian, incompressible couple stress fluid [6]. The analysis assumes absence of body forces and couplings.

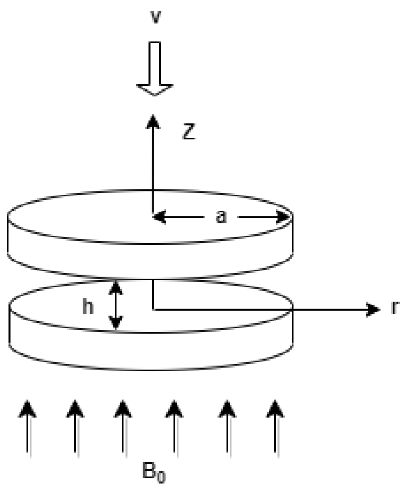

Figure-1: Geometry of circular plate with Magnetic field

The fundamental equations in polar coordinates that govern the motion of a couple stress fluid in a constant laminar flow inside the film region are as follows, assuming thin film lubricants [28]:

$$\mu \frac{\partial^2 u}{\partial z^2} - \eta \frac{\partial^4 u}{\partial z^4} - \sigma B_0^2 u = \frac{\partial p}{\partial r} \tag{1}$$

$$\frac{\partial p}{\partial z} = 0 \tag{2}$$

$$\frac{\partial}{\partial r}(ru) + r\,\frac{\partial w}{\partial z} = 0 \tag{3}$$

The required boundary specifications are as follows:
On the top surface ($z = h$):

$$u = 0 \quad \text{and} \quad \frac{\partial^2 u}{\partial z^2} = 0 \tag{4a}$$

$$\text{and} \quad w = -V \tag{4b}$$

On the bottom surface ($z = 0$):

$$u = 0 \quad \text{and} \quad \frac{\partial^2 u}{\partial z^2} = 0 \tag{5a}$$

$$\text{and} \quad w = 0 \tag{5b}$$

Under the boundary conditions (5a) and (6a), the solution of equation (2) is

$$u = \left\{ \left(\omega_1 - \omega_2 \right) - 1 \right\} \frac{h_0^2}{\mu M_0^2} \frac{\partial p}{\partial x} \tag{6}$$

here 'l' represent couple stress parameter which is given by $l = (\eta / \mu)^{1/2}$ and M_0 is the Hartmann number which is given by $M_0 = B_0 h_0 \left(\sigma / \mu \right)^{1/2}$.

$$\omega_1 = \omega_{11},\ \omega_2 = \omega_{12} \qquad \text{for } 4M_0^2 l^2 / h_0^2 < 1 \tag{7a}$$

$$\omega_1 = \omega_{21},\ \omega_2 = \omega_{22} \qquad \text{for } 4M_0^2 l^2 / h_0^2 = 1 \tag{7b}$$

$$\omega_1 = \omega_{31},\ \omega_2 = \omega_{32} \qquad \text{for } 4M_0^2 l^2 / h_0^2 > 1 \tag{7c}$$

Refer the Appendix for equations (7a), (7b), and (7c) in the study carried out by Haewon Byeon et al [31].
Integrating equation (3) using (6) and the boundary conditions (4b) and (5b) gives a Reynolds equation as

$$\frac{1}{r\mu} \frac{\partial}{\partial r} \left\{ \xi(h, l, M_o)\, r \frac{\partial p}{\partial r} \right\} = -V \tag{8}$$

where

$$\xi(h,l,M_0) = \begin{cases} \dfrac{h_0^2}{M_0^2} \left\{ \dfrac{2l}{(\mathrm{A}^2 - \mathrm{B}^2)} \left(\dfrac{\mathrm{B}^2}{\mathrm{A}} \tanh \dfrac{\mathrm{A} h}{2l} - \dfrac{\mathrm{A}^2}{\mathrm{B}} \tanh \dfrac{\mathrm{B} h}{2l} \right) + h \right\}, & \text{for } M_0^2 l^2 / h_0^2 < 1 \\ \dfrac{h_0^2}{M_0^2} \left\{ \dfrac{h}{2} \operatorname{sech}^2 \left(\dfrac{h}{2\sqrt{2l}} \right) - 3\sqrt{2l} \tanh \left(\dfrac{h}{2\sqrt{2l}} \right) + h \right\}, & \text{for } M_0^2 l^2 / h_0^2 = 1 \\ \dfrac{h_0^2}{M_0^2} \left\{ \dfrac{2lh_0}{M} \left(\dfrac{\left(\mathrm{A}_2 \cot\theta - \mathrm{B}_2 \right) \sin \mathrm{B}_2 h - \left(\mathrm{B}_2 \cot\theta + \mathrm{A}_2 \right) \sin \mathrm{A}_2 h}{\cos \mathrm{B}_2 h + \cosh \mathrm{A}_2 h} \right) + h \right\}, & \text{for } M_0^2 l^2 / h_0^2 > 1 \end{cases}$$

The viscosity variations depending on pressure given by Barus and Co-authors [29-30] is given in the following formula:

$$\mu = \mu_0 e^{\alpha p} \tag{9}$$

where α is the viscosity coefficient and μ_0 is viscosity at constant temperature and ambient pressure.

Using below non-dimensional components in equation (8)

$$l^* = \frac{2l}{h_0},\ r^* = \frac{r}{a},\ h^* = \frac{h}{h_0}, M_0 = B_0 h_0 \left(\frac{\sigma}{\mu} \right)^{1/2}\ P^* = \frac{p h_0^3}{\mu_0 a^2 (-dh/dt)}\ G = \frac{\beta \mu_0 a^2 (-dh/dt)}{h_0^3}$$

The dimensionless Reynolds equation is as follows

$$\frac{\partial}{\partial r^*} \left\{ \frac{r^*}{e^{Gp^*}} \frac{\partial P^*}{\partial r^*} \right\} = -\frac{r^*}{\xi^*(h^*, l^*, M_o)} \tag{10}$$

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Where

$$\xi^*(h^*,l^*,M_0)=\begin{cases}\dfrac{1}{M_0^2}\left\{\dfrac{l^*}{(\mathrm{A}^{*2}-\mathrm{B}^{*2})}\left(\dfrac{\mathrm{B}^{*2}}{\mathrm{A}^*}\tan h\dfrac{\mathrm{A}^*h^*}{l^*}-\dfrac{\mathrm{A}^{*2}}{\mathrm{B}^*}\tan h\dfrac{\mathrm{B}^*h^*}{l^*}\right)+h^*\right\} & \text{for}\quad 4M_0^2l^{*2}<1\\ \dfrac{1}{M_0^2}\left\{\dfrac{h^*}{2}\sec h^2\left(\dfrac{h^*}{\sqrt{2}\,l^*}\right)-\dfrac{3l^*}{\sqrt{2}}\tan h\left(\dfrac{h^*}{\sqrt{2}\,l^*}\right)+h^*\right\} & \text{for}\quad 4M_0^2l^{*2}=1\\ \dfrac{1}{M_0^2}\left\{\dfrac{l^*\left(\mathrm{A}_2^*\cot\theta^*-\mathrm{B}_2^*\right)\sin\mathrm{B}_2^*h^*-l^*\left(\mathrm{B}_2^*\cot\theta^*+\mathrm{A}_2^*\right)\sin h\mathrm{A}_2^*h^*}{M_0\left(\cos\mathrm{B}_2^*h^*+\cos h\mathrm{A}_2^*h^*\right)}+h^*\right\} & \text{for}\quad 4M_0^2l^{*2}>1\end{cases}$$

$$A^*=\sqrt{\frac{1+\sqrt{\left(1-M_0^2l^{*2}\right)}}{2}}\qquad B^*=\sqrt{\frac{1-\sqrt{\left(1-M_0^2l^{*2}\right)}}{2}},$$

Integrate equation (10) using below pressure boundary conditions gives

$$\frac{\partial P^*}{\partial r^*}=0\quad \text{at}\quad r^*=0\text{ , and }\;P^*=0\quad\text{at}\quad r^*=1$$

Pressure distribution expressions as:

$$P^*=-\frac{1}{G}\ln\left\{1-\frac{G\left(1-r^{*2}\right)}{4\xi^*(h^*,l^*,M_0)}\right\}\tag{11}$$

The load-supporting capacity expressions is as follows:

$$W=2\pi\int_0^a p\,r\,dr\tag{12}$$

Load-supporting capacity expressions in non-dimensional form:

$$W^*=\frac{Wh_o^3}{\mu_o a^3(dh/dt)}=-\frac{1}{G}\int_0^1\left[\ln\left\{1-\frac{G\left(1-r^{*2}\right)}{4\xi^*(h^*,l^*,M_0)}\right\}\right]dr^*\tag{13}$$

Squeeze film time in dimensionless form is:

$$T^*=\frac{th_o^2}{\mu_o a^3}=-\frac{1}{G}\int_{h_1^*}^1\left[\int_0^1\ln\left\{1-\frac{G\left(1-r^{*2}\right)}{4\xi^*(h^*,l^*,M_0)}\right\}dr^*\right]dh^*\tag{14}$$

where $h_1^*=\dfrac{h_1}{h_o}$

RESULT AND DISCUSSION

This study predicts the combined effects of viscosity variations and MHD on the characteristics of couple stress squeeze film in circular plates. Analysis of these effects is based on several dimensionless parameters, that includes viscosity variation parameter G, Hartmann parameter M_0, and couple stress parameter l^*. Hence the range of these parameters considered in the analysis are l^* : 0.0 - 0.6, G : 0.0 - 0.006, M_0 : 0 - 6.

Pressure

In fig.-2, the variance of P^* with respect to r^* as function of viscosity parameter G is shown and it is inferred that the value of the pressure enhances with the rising values of viscosity variation parameter G. Graph of P^* versus r^* for distinctive values of Hartmann number M_0 is shown in the fig.-3 and it is found that pressure rises with increasing values of M_0. Fig.- 4 displays the variation in P^* with r^* for distinctive l^* values. It has been noticed that the dimensionless pressure increases with an increase in l^*, in contrast to the Newtonian case ($l^*=0$). Fig.- 5 represents the study of squeeze film pressure due to variation in the Hartmann number and viscosity parameter. It is found that the combined effect enhances pressure significantly in contrast with non-magnetic and iso-viscos case. Whereas Fig - 6 depicts variation of l^* & G to study the effect of film pressure. In comparison to Newtonian case, there is an increase in pressure. This implies that bearing pressure is low in the absence of additives and increased in the presence of additives. Consequently, the viscosity parameter, couple stress parameter, and Hartmann number each contribute enhance pressure distribution.

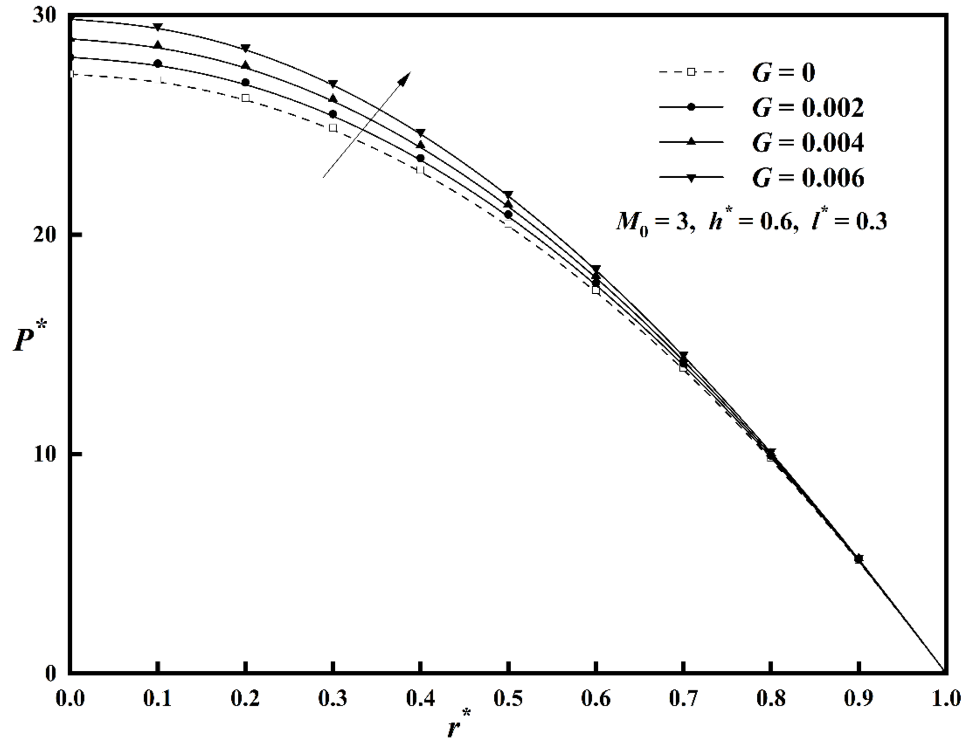

Figure-2: Changes in P^* versus r^* for several G values.

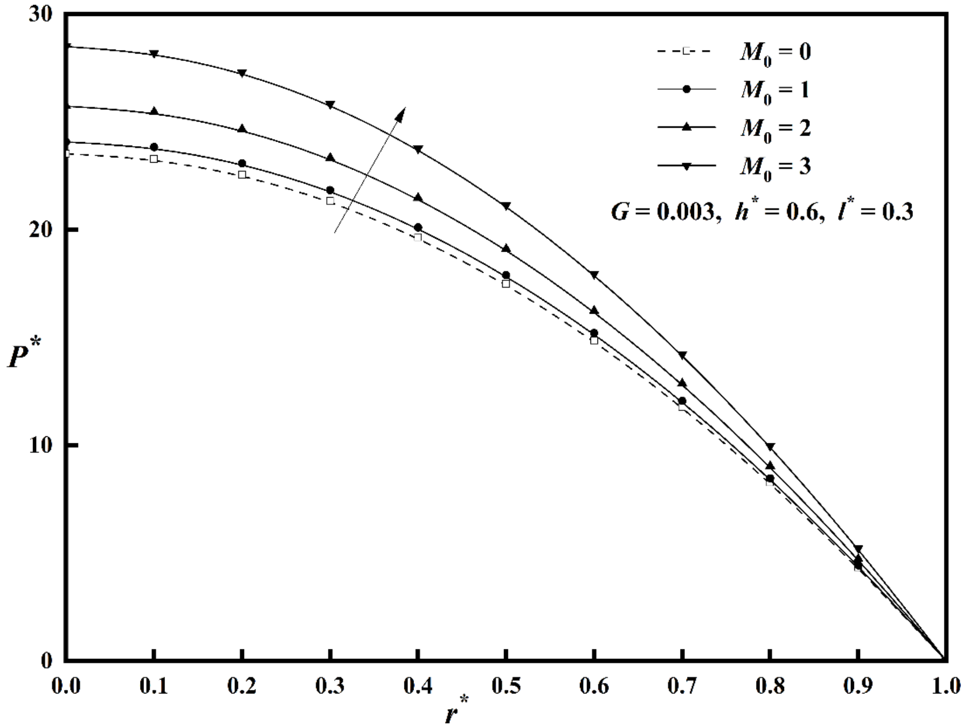

Figure-3: Changes in P^* versus r^* for several M_0 values.

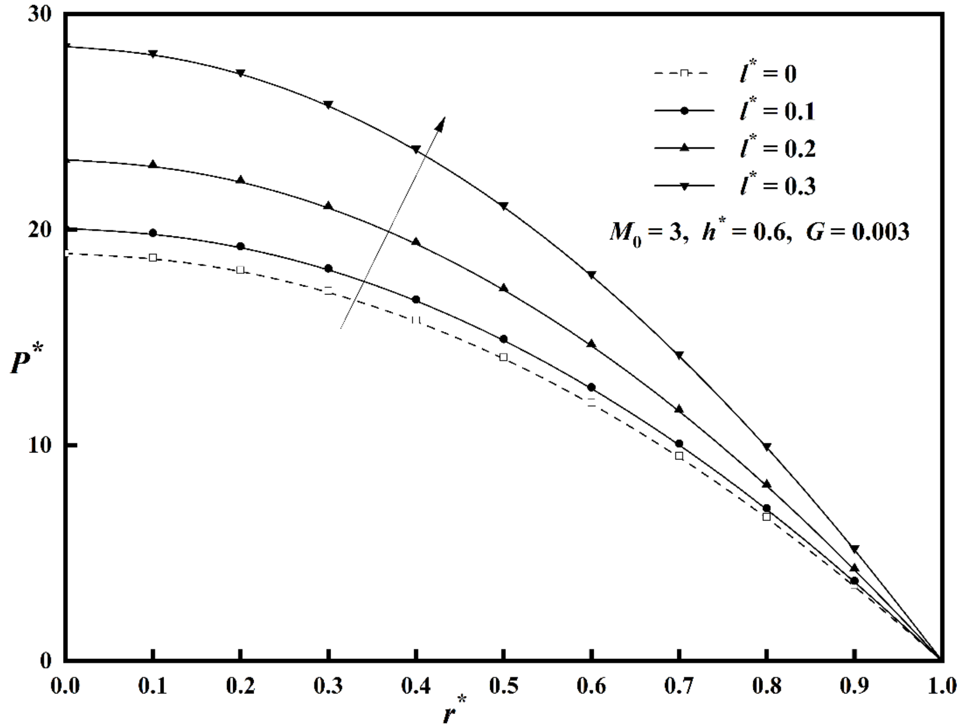

Figure-4: Changes in P^* versus r^* for several l^* values.

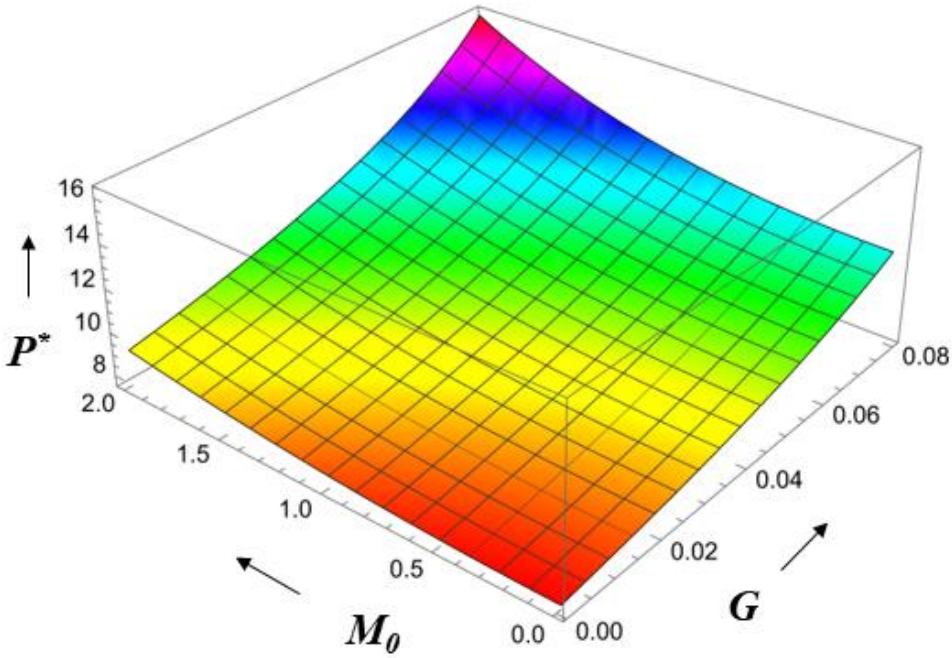

Figure-5: Changes in P^* versus M_0 and G values.

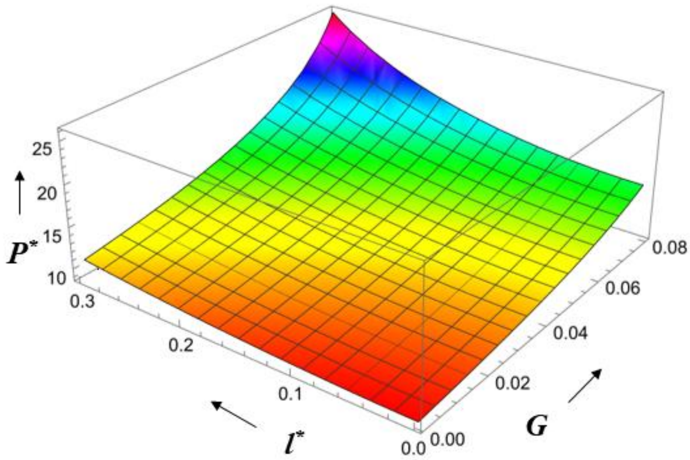

Figure-6: Changes in P^* versus G and l^* values.

Dimensionless Load

Variance in the load W^* for distinct G values against h^* is presented in fig - 7. It has been demonstrated that when viscosity parameter rises, the load rises as well. Conversely, the load reduces for increasing values of h^*, and it is more for smaller film thickness values. For distinctive values M_0 and l^* a graph is plotted for W^* against h^* which is presented in Fig - 8 and Fig - 9. It has been observed that as M_0 and l^* values increase, the load becomes substantial. The apparent increase in load is attributed to the rise in pressure, which is caused by an increase in couple stress parameter. Fig -10 shows the mixed impact of Hartmann number and viscosity variation on load W^*. Load is maximum for rising values of Hartmann number and viscosity parameter. Similar effect is study in Fig - 11 by varying couple stress parameter with viscosity parameter, as a result in contrast to non-viscos and Newtonian case, more load is observed for larger values of l^* and G.

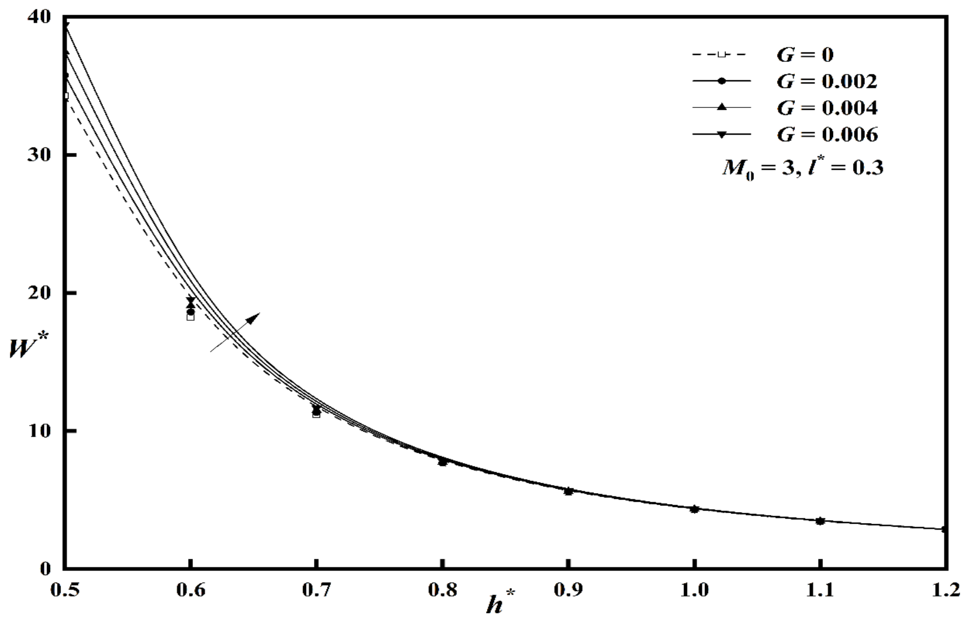

Figure-7: Changes in W^* versus h^* for several G values

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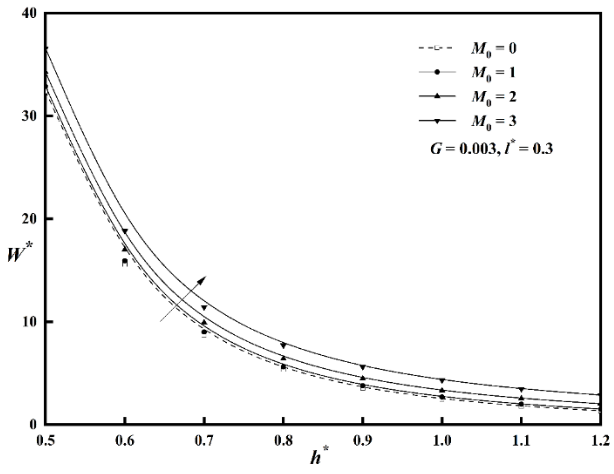

Figure-8: Changes in W^* versus h^* for several M_o values

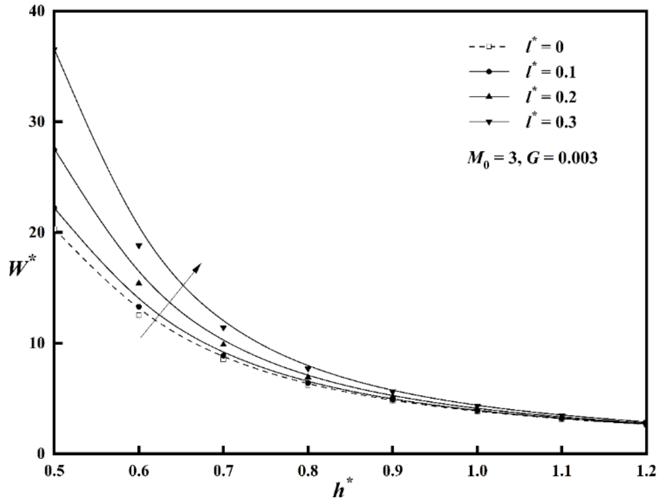

Figure-9: Changes in W^* versus h^* for several l^* values.

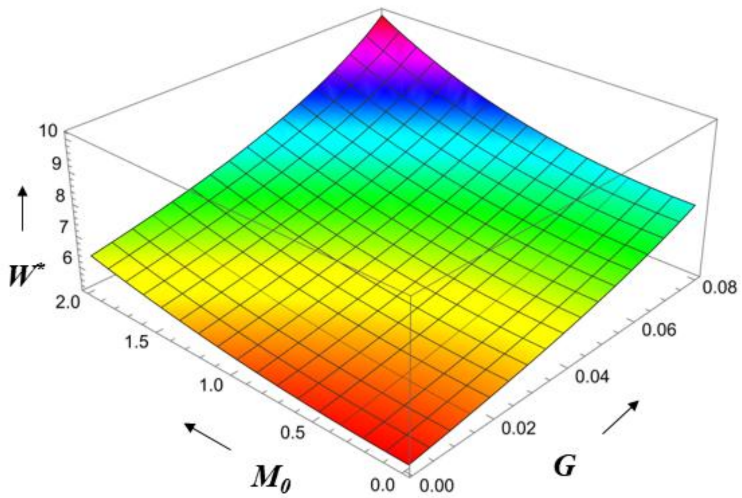

Figure-10: Changes in W^* versus M_0 and G values.

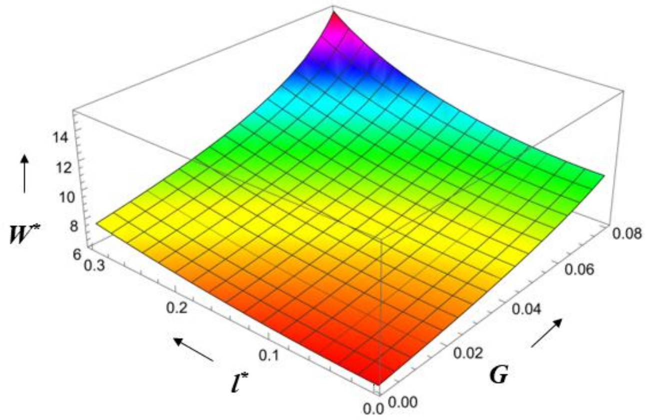

Figure-11: Changes in W^* versus G and l^* values.

Squeeze film time

Fig -12 illustrates the changes in T^* with respect to h_1^* for distinct G values. Compared to the non-viscous situation, it has been determined that the squeeze film time increases as the viscosity variation parameter rises. Deviation in T^* with respect to h_1^* for different M_0 values can be seen in the Fig - 13 and it is found that the time T^* is significant for larger values of Hartmann number. The graph of T^* versus h_1^* for different l^* values is displayed in Fig - 14 and as the result couple stress parameter values are found to enhance the squeeze film time, and also it is noticed that T^* declines for the increasing values of h_1^*. Additionally, the graph of T^* versus viscosity variation parameter and Hartmann number is displayed in Fig - 15. It is found that T^* is more in the presence of viscosity variation parameter and magnetic effect rather than when viscosity is constant and in absence of magnetic effect. The graph of T^* versus viscosity variation parameter and Hartmann number is explained in Fig - 16. According to the results, effect of the magnetic field and viscosity variation parameter lengthens squeeze film time.

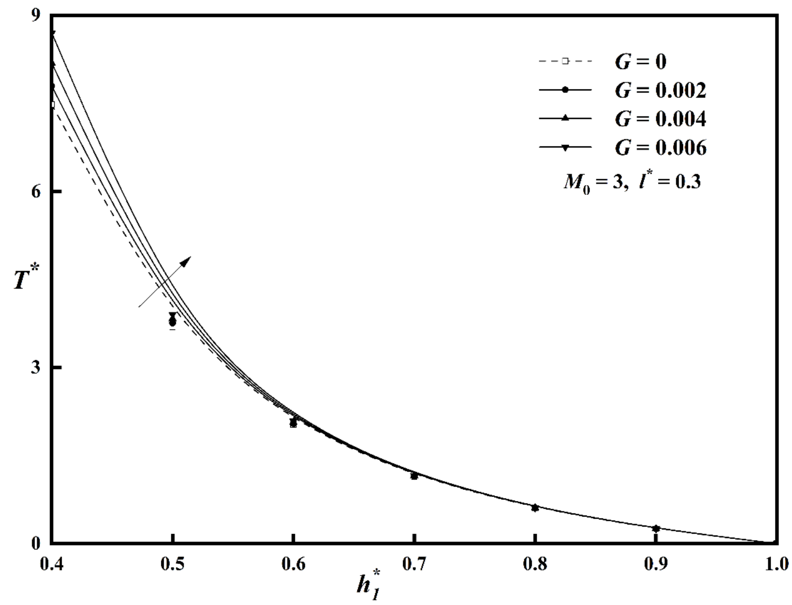

Figure-12: Changes in T^* versus h_1^* for numerous G values.

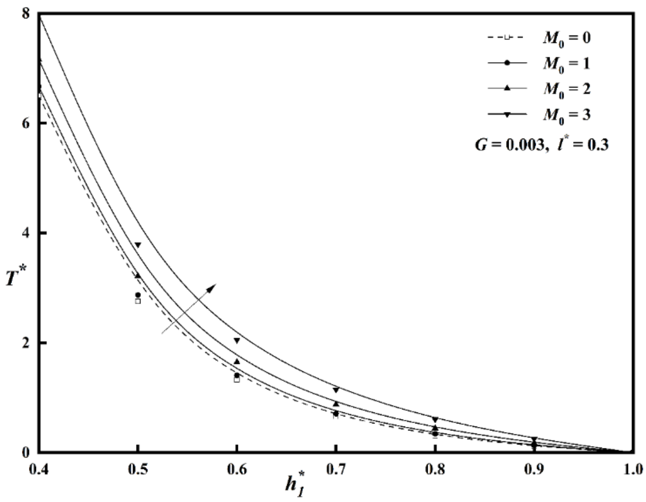

Figure-13: Changes in T^* versus h_1^* for numerous M_0 values.

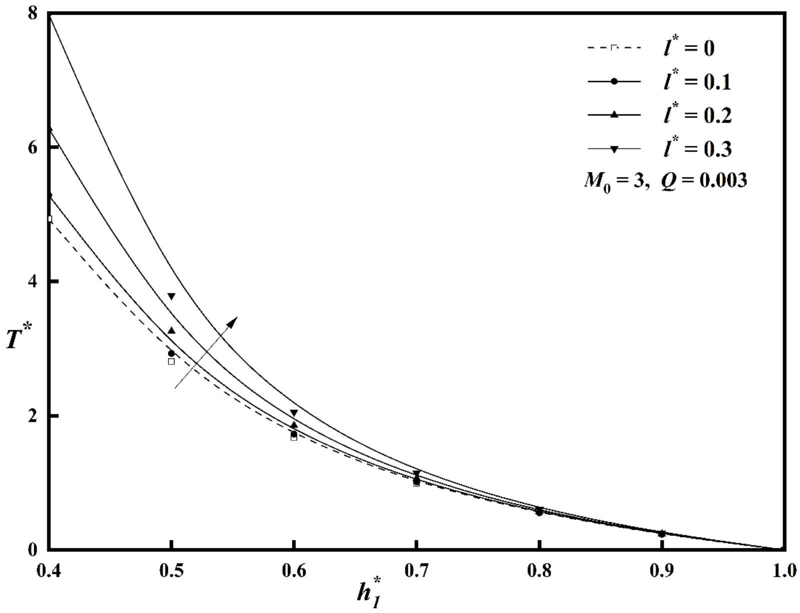

Figure-14: Changes in T^* versus h_1^* for numerous l^* values.

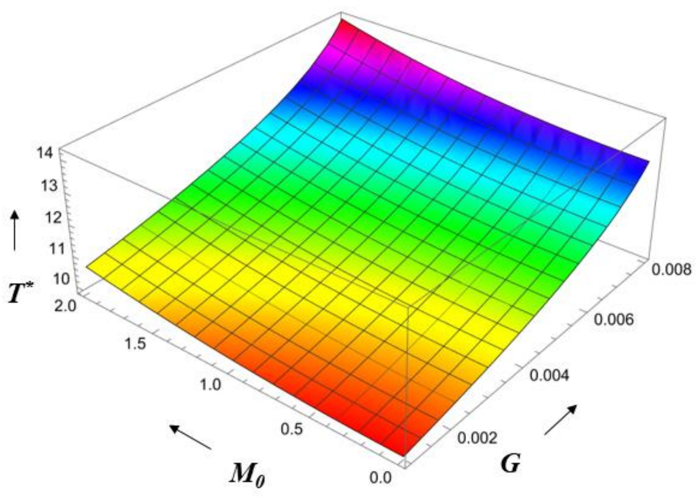

Figure-15: Changes in T^* versus M_0 and G values.

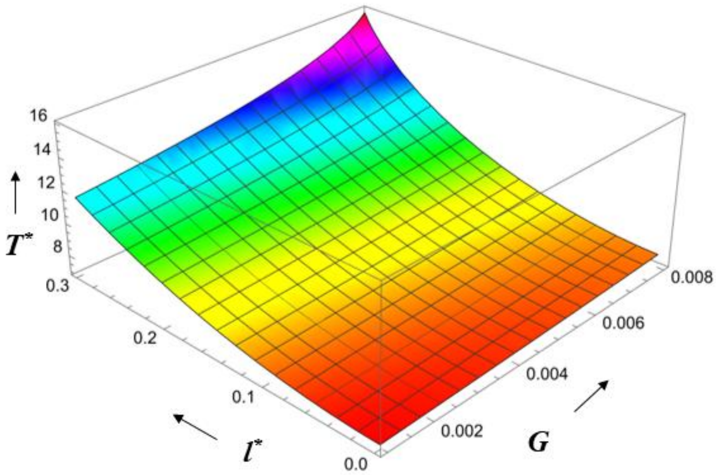

Figure-16: Changes in T^* versus G and l^* values.

CONCLUSIONS

This study examines the effect of couple stresses, magnetohydrodynamics, and variable viscosity on circular plates. The Reynolds type equation is developed by using Stokes micro continuum theory and the Barus formula. In particular, the load capacity for bearing, squeeze film time, and squeeze film pressure are examined. Squeeze film behaviour is substantially affected by the impacts of couple stresses, variations in viscosity with pressure, and the Hartmann number, as well as their combined effects. Also, from the three-dimensional graph constructed by combining three distinct factors. It is observed that the presence of the Hartmann number, non-Newtonian fluid, and viscosity variation parameter significantly impact the characteristics of squeeze film lubrication, as compared to non-magnetic, Newtonian, and non-viscos case.

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