

Squeezing Film Characteristics for Micropolar Fluid between Porous Parallel Stepped Plates

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ABSTRACT

In this paper, the theoretical study of squeeze film characteristics between porous parallel stepped plates with non-Newtonian micropolar fluid is presented. The lubricant in the film region and also in the porous is modeled as Eringen's micropolar fluid. A non-Newtonian modified Reynolds equation is derived for porous parallel stepped plates and applied to obtain solution of squeeze film characteristics. Comparing with the classical Newtonian lubricant case, the influence non-Newtonian micropolar fluids are found to enhance the load carrying capacity and lengthen the approaching the time of porous parallel stepped plates. The load capacity decreases as the step height increases.

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1. INTRODUCTION

In recent years, self-lubricating porous bearings have been studied because of their industrial applications and machine manufacturing. These bearings have self contained oil reservoir and hence do not require continuous lubrication. Most porous bearings have interconnecting pores which store the lubricating oil. Hence, when normal load is applied, the fluid is supplied through the interconnected pores to the fluid film region to support the load, and when the load is removed from the loaded part of the bearing, fluid is reabsorbed by capillary action. Since these can operate without additional lubricant for longer period, porous bearings are widely used, where relubrication would be difficult. Thus, porous metal bearings are used in manufacturing small motors, home appliances, instruments and construction equipments. Because of these

practical aspects, there have been numerous studies on the performance characteristics of such bearing [1-4]. But these studies were confined to Newtonian lubricants.

Applications of squeeze-film technology shows great importance in many areas of applied science and industrial engineering, such as machine elements, automotive components, animal joints, matching gears, wet-clutch plates. In general, research of squeeze film characteristics concentrates attentions on the use of Newtonian lubricants. For example, by Hays [5], Hamrock [6], Abell and Ames [7], Rashidi et.al. [8].

In order to satisfy the requirement of modern machine systems operating severe conditions, the increased use of different types of non-Newtonian fluids as lubricants has been emphasized. It has

been observed that the addition of small amounts of long-chain polymer solutions to Newtonian fluids gives the most desirable lubricants owing to stabilization of the flow properties of the lubricants. The use of additives minimizes the sensitivity of lubricants to changes in shear rate and which supports greater load carrying capacities. To describe accurate flow behavior of such fluids with additives, several existing microcontinuum theories can be applied. The micropolar fluid theory proposed by Eringen [9] contain a suspension of particles with individual motion. This theory is the subclass of more general type of fluids known as microfluids [10], which includes the effects of local rotatory inertia, couple stresses and inertial spin. An application of these non-Newtonian fluids includes the solidification of liquid crystals, cooling of metallic plate in a path, animal bloods and exotic solutions, for which the classical Navier Stokes theory is inadequate. Several investigators used the micropolar fluid theory for the study of several bearing systems such as slider bearings [11,12], journal bearings [13,14], squeeze film bearings [15-18] and porous bearings [19-22] and have found some advantages of micropolar fluids over the Newtonian fluids such as increased load carrying capacity and increased time of approach for squeeze film bearings.

Hence, in this paper an attempt has been made to study the effect of squeeze film characteristics between porous parallel stepped plates with micropolar fluid.

2. BASIC EQUATIONS

The field equation for micropolar fluids in vectorial form are [9]:

Conservation of linear momentum:

$$(\lambda + 2\mu)\nabla(\nabla \cdot \vec{V}) - \frac{1}{2}(2\mu + \chi)\nabla \times (\nabla \times \vec{V}) + \chi \nabla \times \vec{v} - \nabla \pi + \rho f_B = \rho \frac{D\vec{V}}{Dt} \quad (1)$$

Conservation of angular momentum:

$$(\alpha + \beta + \gamma)\nabla(\nabla \cdot \vec{v}) - \gamma \nabla \times (\nabla \times \vec{v}) + \chi \nabla \times \vec{V} - 2\chi v + \rho l_B = \rho j \frac{D\vec{v}}{Dt} \quad (2)$$

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0 \quad (3)$$

Where \vec{V} is the velocity vector, \vec{v} is the microrotation velocity vector, π is thermodynamic pressure, f_B is the body force per unit mass, l_B is the body couple, j is the microinertia constant, λ, μ are the viscosity coefficient of the classical fluid mechanics and $\chi, \alpha, \beta, \gamma$ are the new viscosity coefficients for micropolar fluids. $\frac{D}{Dt}$ indicates material differentiation. For an incompressible fluid ρ is constant, $\nabla \cdot \vec{v} = 0$ and π is replaced by the hydrodynamic pressure p .

3. MATHEMATICAL FORMULATION OF THE PROBLEM

The physical configuration of the problem is as shown in the Fig. 1 where the upper plates approaching the lower with a normal velocity V .

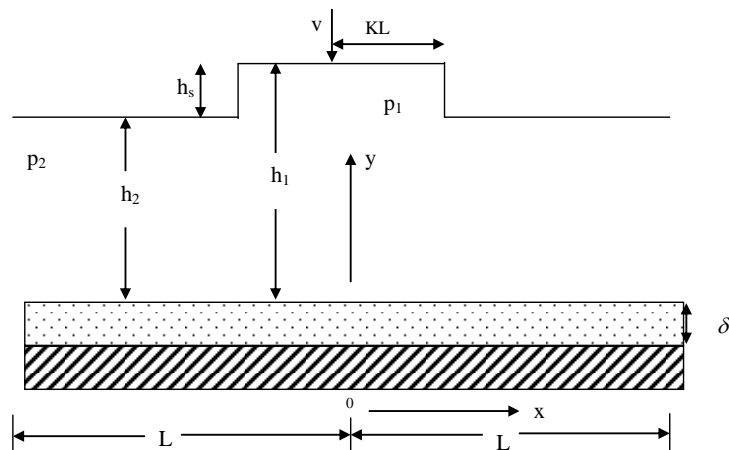


Fig. 1. Squeeze film between porous parallel stepped plates.

The lubricant in the film region and that in the porous region is considered to be an micropolar fluid. The constitutive equations for micropolar fluids proposed by Eringen's [9] simplify considerably under the usual assumptions of hydrodynamic lubrication. The resulting equations under steady-state conditions are [15]:

Conservation of linear momentum:

$$\left(\mu + \frac{\chi}{2}\right) \frac{\partial^2 u}{\partial y^2} + \chi \frac{\partial v_3}{\partial y} - \frac{\partial p}{\partial x} = 0 \quad (4)$$

$$\frac{\partial p}{\partial y} = 0 \quad (5)$$

Conservation of angular momentum:

$$\gamma \frac{\partial^2 v_3}{\partial y^2} - 2\chi v_3 - \chi \frac{\partial u}{\partial y} = 0 \quad (6)$$

Conservation of mass:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (7)$$

Where (u, v) are the velocity components of the lubricant in the x and y directions, respectively, and v_3 is micro rotational velocity component, χ is the spin viscosity and γ is the viscosity coefficient for micropolar fluids and μ is the Newtonian viscosity coefficient.

The flow of micropolar lubricants in a porous matrix is governed by the modified Darcy's law, which account for the polar effects is given by [19]:

$$\vec{q}^* = \frac{-k}{(\mu + \chi)} \nabla p^* \quad (8)$$

Where $\vec{q}^* = (u^*, v^*, w^*)$ is the modified Darcy's velocity vector, k is the permeability of the porous matrix and p^* is the pressure in the porous region. Due to continuity of fluid in the porous matrix, p^* satisfies the Laplace Equation:

$$\frac{\partial^2 p^*}{\partial x^2} + \frac{\partial^2 p^*}{\partial y^2} = 0 \quad (9)$$

The relevant boundary conditions are:

(a) at the upper surface ($y=h$)

$$u=0, v=-V, v_3=0 \quad (10a)$$

(b) at the bearing surface ($y=0$)

$$u=0, v=v^*, v_3=0 \quad (10b)$$

4. SOLUTION OF THE PROBLEM

The solution of equations (4) - (6) subject to the corresponding boundary conditions given in the equations (10a) and (10b) is obtained in the form.

$$u = \frac{1}{\mu} \left(\frac{y^2}{2} \frac{\partial p}{\partial x} + A_{11} y \right) - \frac{2N^2}{m} \times [A_{21} \sinh(my) + A_{31} \cosh(my)] + A_{41} \quad (11)$$

$$v_3 = A_{21} \cosh(my) + A_{31} \sinh(my) - \frac{1}{2\mu} \left(y \frac{\partial p}{\partial x} + A_{11} \right) \quad (12)$$

where:

$$A_{11} = 2\mu A_{21},$$

$$A_{21} = \frac{A_{31} \sinh(mh) - \frac{h}{2\mu} \frac{\partial p}{\partial x}}{1 - \cosh(mh)},$$

$$A_{31} = \frac{h}{2\mu} \frac{\partial p}{\partial x} \left[\frac{h}{2} (\cosh(mh) - 1) + h - \frac{N^2}{m} \sinh(mh) \right] \times \frac{1}{A_5},$$

$$A_{41} = \frac{2N^2}{m} A_{31},$$

$$A_5 = \frac{h}{\mu} \left[\sinh(mh) - \frac{2N^2}{mh} (\cosh(mh) - 1) \right],$$

in which:

$$m = \frac{N}{l}, \quad N = \left(\frac{\chi}{\chi + 2\mu} \right)^{\frac{1}{2}}, \quad l = \left(\frac{\gamma}{4\mu} \right)^{\frac{1}{2}}.$$

Integrating equation (9) with respect to y over the porous layer thickness, δ and using the boundary conditions of solid backing

$\left(\frac{\partial p^*}{\partial y} = 0 \right)$ at $y = -\delta$, we obtain:

$$\frac{\partial p^*}{\partial y} \Big|_{y=0} = - \int_{-\delta}^0 \left(\frac{\partial^2 p^*}{\partial x^2} \right) dy \quad (13)$$

Assuming that, the porous layer thickness, δ is very small and using the pressure continuity condition ($p=p^*$) all the interface ($y=0$) of porous matrix and fluid film, equation (13) reduces to:

$$\left. \frac{\partial p^*}{\partial y} \right|_{y=0} = -\delta \frac{\partial^2 p}{\partial x^2} \quad (14)$$

Then, the velocity component of the modified Darcy's velocity v^* at the interface ($y=0$) is given by:

$$v^* \Big|_{y=0} = \frac{k\delta}{(\mu + \chi)} \frac{\partial^2 p}{\partial x^2} \quad (15)$$

The modified Reynolds equation is obtained by integrating the equation of continuity (7) with respect to y over the film thickness, h and replacing u in equation (6) by their corresponding expression given in equation (11) and also using the boundary conditions for v given in equations (10a) and (10b) in the form.

$$\frac{d}{dx} \left[\left(f(N, l, h) + \frac{12\mu k \delta}{(\mu + \chi)} \right) \frac{dp}{dx} \right] = -12\mu V \quad (16)$$

where:

$$f(N, l, h) = h^3 + 12l^2 h - 6Nlh^2 \coth\left(\frac{Nh}{2l}\right)$$

On integrating Equation (12) using the boundary condition:

$$\begin{aligned} \frac{dp}{dx} &= 0 \quad \text{at } x=0 \\ \frac{dp_i}{dx} &= -\frac{12\mu V x}{f_i(N, l, h_i) + \frac{12\mu k \delta}{(\mu + \chi)}} \end{aligned} \quad (17)$$

where:

$$\begin{aligned} h_i &= h_1 \text{ for } 0 \leq x \leq KL; \\ &= h_2 \text{ for } KL \leq x \leq L. \end{aligned}$$

$$f_i(N, l, h_i) = h_i^3 + 12l^2 h_i - 6Nlh_i^2 \coth\left(\frac{Nh_i}{2l}\right)$$

The relevant boundary conditions for the pressure are:

$$p_1 = p_2 \quad \text{at } x = KL, \quad (18a)$$

$$p_2 = 0 \quad \text{at } x = L \quad (18b)$$

Solution of equation (17) subject to the boundary conditions (18a) and (18b) is:

$$p_1 = 6\mu V \left[\frac{K^2 L^2 - x^2}{f_1(N, l, h_1) + \frac{12\mu k \delta}{(\mu + \chi)}} + \frac{L^2(1 - K^2)}{f_2(N, l, h_2) + \frac{12\mu k \delta}{(\mu + \chi)}} \right] \quad (19)$$

$$p_2 = \frac{6\mu V}{f_2(N, l, h_2) + \frac{12\mu k \delta}{(\mu + \chi)}} (L^2 - x^2) \quad (20)$$

The load carrying capacity, w is obtained in the form:

$$w = 2b \int_0^{KL} p_1 dx + 2b \int_{KL}^L p_2 dx \quad (21)$$

Which in nondimensional form:

$$W = \frac{wh_2^3}{8\mu bV L^3} = \left[\frac{K^3}{f_1(N, l^*, H^*) + 12\psi \left\{ \frac{1-N^2}{1-N^2} \right\}} + \frac{1-K^3}{f_2(N, l^*, 1) + 12\psi \left\{ \frac{1-N^2}{1-N^2} \right\}} \right] \quad (22)$$

Where $H^* = \frac{h_1}{h_2}$, $\psi = \frac{k\delta}{h_2^3}$ and $l^* = \frac{l}{h_2}$

$$f_1(N, l^*, H^*) = H^{*3} + 12l^{*2} H^* - 6NH^{*2} l^* \coth\left(\frac{NH^*}{2l^*}\right)$$

$$f_2(N, l^*, 1) = 1 + 12l^{*2} - 6Nl^* \coth\left(\frac{N}{2l^*}\right)$$

Writing $V = -\frac{dh_2}{dt}$ in equation (22), the squeezing time for reducing the initial film thickness h_0 of h_2 to a final thickness h_f of h_2 is given by:

$$t^* = \frac{wh_0^2 t}{8\mu bL^3} = \int_{h_f^*}^{h_0^*} \left\{ K^3 \left[f_1(N, h_s^*, h_2^*, l^*) + 12\psi \left\{ \frac{1-N^2}{1+N^2} \right\} \right] + f_2(N, h_s^*, l^*) \right\} dh_2^* \quad (23)$$

Where:

$$f_1(N, h_s^*, h_2^*, l^*) = \left[\frac{(h_2^* + h_s^*)^3 + 12l^{*2} (h_2^* + h_s^*) - 6Nl^* (h_2^* + h_s^*)^2}{\coth\left(\frac{N(h_2^* + h_s^*)}{2l^*}\right)} \right]^{-1}$$

$$f_2(N, h_2^*, l^*) = \frac{1 - K^3}{\left(h_2^{*3} + 12l^{*2}h_2^* - 6Nh_2^{*2}l^* \coth\left(\frac{Nh_2^*}{2l^*}\right) \right) + 12\psi \left\{ \frac{1 - N^2}{1 + N^2} \right\}}$$

$$h_f^* = \frac{h_f}{h_0}, \quad h_2^* = \frac{h_2}{h_0}, \quad h_s^* = \frac{h_s}{h_0}, \quad l^* = \frac{l}{h_0}.$$

5. RESULTS AND DISCUSSIONS

This paper predicts the effect of squeeze film lubrication between porous parallel stepped plates with micropolar fluid. The micropolar fluid is characterized by two non-dimensional parameters such as the coupling number,

$N \left(= \frac{\chi}{\chi + 2\mu} \right)^{1/2}$ which characterizes the coupling between the Newtonian and microrotational viscosities, the parameter, $l^* \left(= \frac{l}{h_2} \right)$ in which l^*

has the dimension of length and may be considered as chain length of microstructures additives. The parameter l^* , characterizes the interaction of the bearing geometry with the lubricant properties. In the limiting case as $l^* \rightarrow 0$ the effect of microstructures becomes negligible. The effect of permeability is observed through the non-dimensional permeability parameter, $\psi \left(= \frac{k\delta}{h_2^3} \right)$

and it is to be noted that as $\psi \rightarrow 0$ the problem reduces to the corresponding solid case and as $l^*, N \rightarrow 0$ it reduces to the corresponding Newtonian case.

5.1. Load carrying capacity

The variation of non-dimensional load carrying capacity W with H^* for different values of N with $l^* = 0.15, K = 0.6, \psi = 0.01$ is presented in Fig. 2. The dotted curve in graph corresponds to Newtonian case. As compared with the Newtonian, the load carrying capacity increases with increasing values of coupling number N . It is observed that the effect micropolar fluid parameter N enhances the load carrying capacity as compared to the Newtonian case. Figure 3 depicts the variation of non-dimensional load carrying capacity W with H^* for different values of l^* with $N = 0.5, K = 0.6, \psi = 0.01$. It is observed that the increasing values of material length l^* increases the load carrying capacity as compared to the Newtonian case. The variation of non-dimensional load carrying capacity W with H^* for different values of ψ with $l^* = 0.15, K = 0.6, N = 0.5$ is presented in Fig. 4. The effect of ψ is to decrease the load carrying capacity as compared to corresponding solid case ($\psi = 0$). The adverse effects of the porous facing on the bearing surface can be compensated with the selection of the lubricants with proper microstructure additives. Figure 5 depicts the variation of non-dimensional load carrying capacity W with H^* for different values of K with $l^* = 0.15, N = 0.5, \psi = 0.01$. As the value of K increases the load carrying capacity decreases.

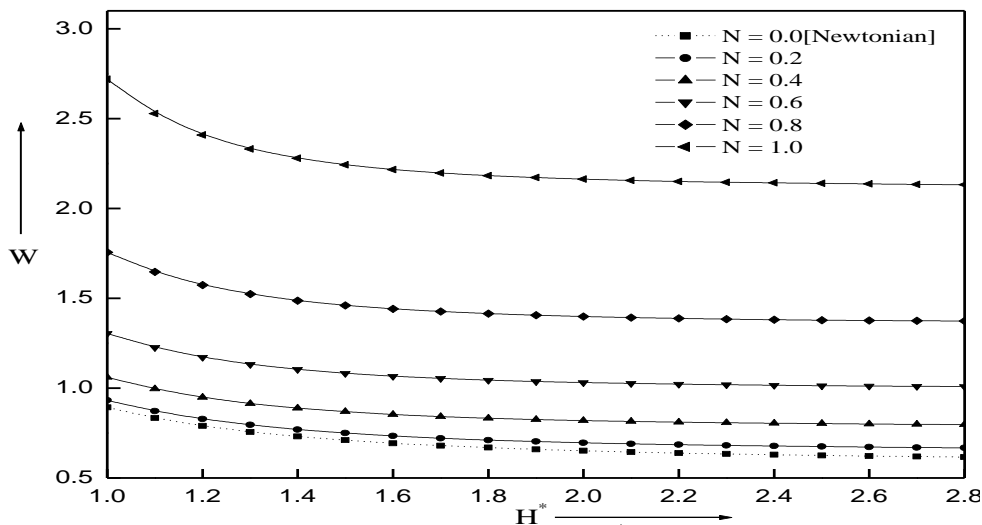


Fig. 2. Variation of non-dimensional W with H^* for different values of N with $l^* = 0.15, \psi = 0.01, K = 0.6$.

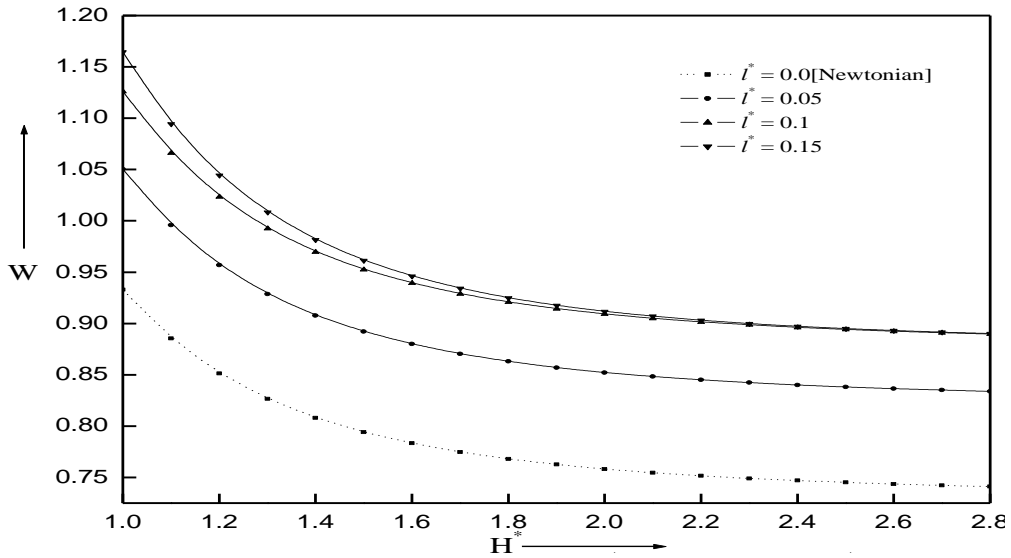


Fig. 3. Variation of non-dimensional W with H^* for different values of l^* with $\psi = 0.01$, $K = 0.6$, $N = 0.5$.

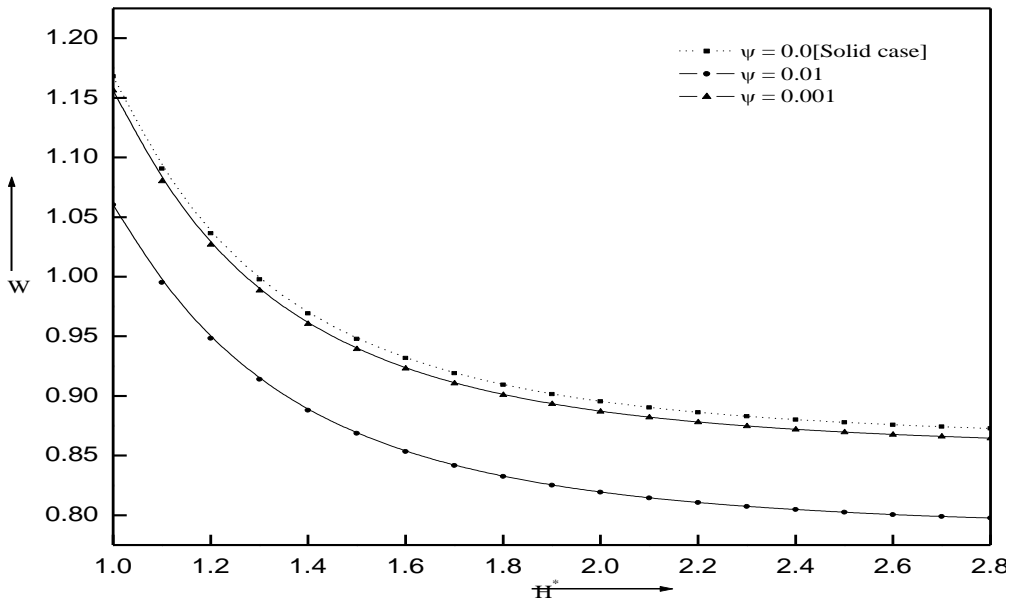


Fig. 4. Variation of non-dimensional W with H^* for different values of ψ with $K = 0.6$, $N = 0.4$, $l^* = 0.15$.

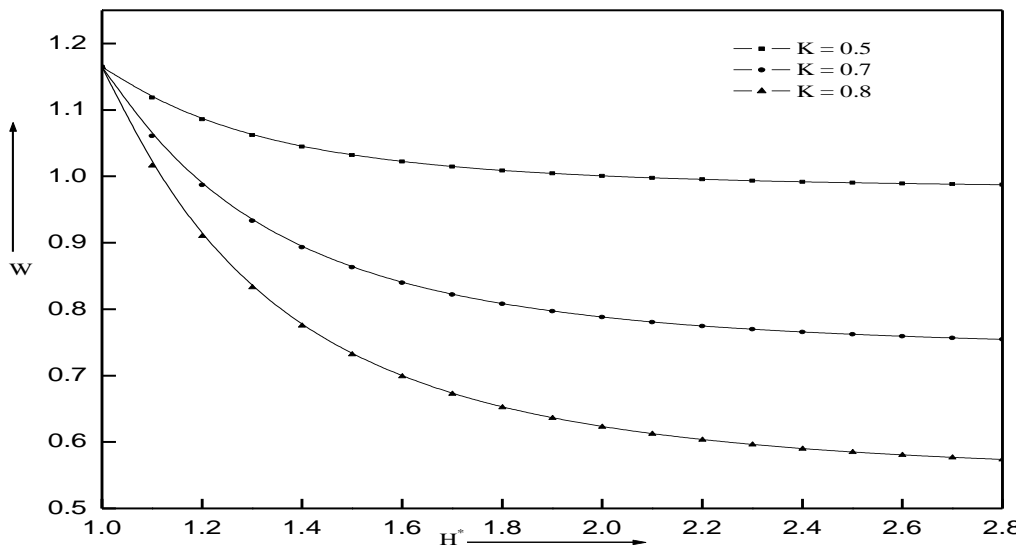


Fig. 5. Variation of non-dimensional W with H^* for different values of K with $\psi = 0.01$, $N = 0.5$, $l^* = 0.15$.

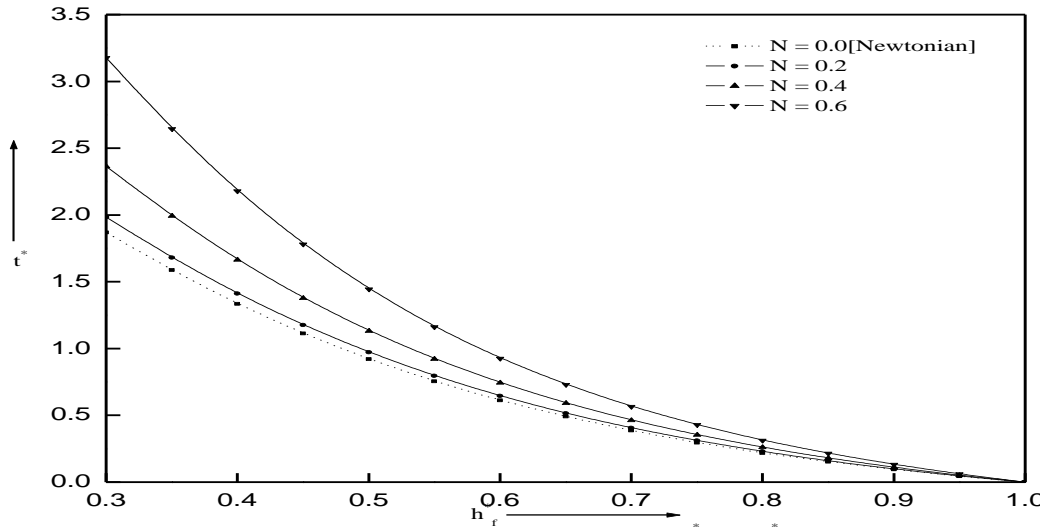


Fig. 6. Variation of non-dimensional time of approach t^* with h_f^* for different values of N with $\psi = 0.01, l^* = 0.1, K = 0.6$.

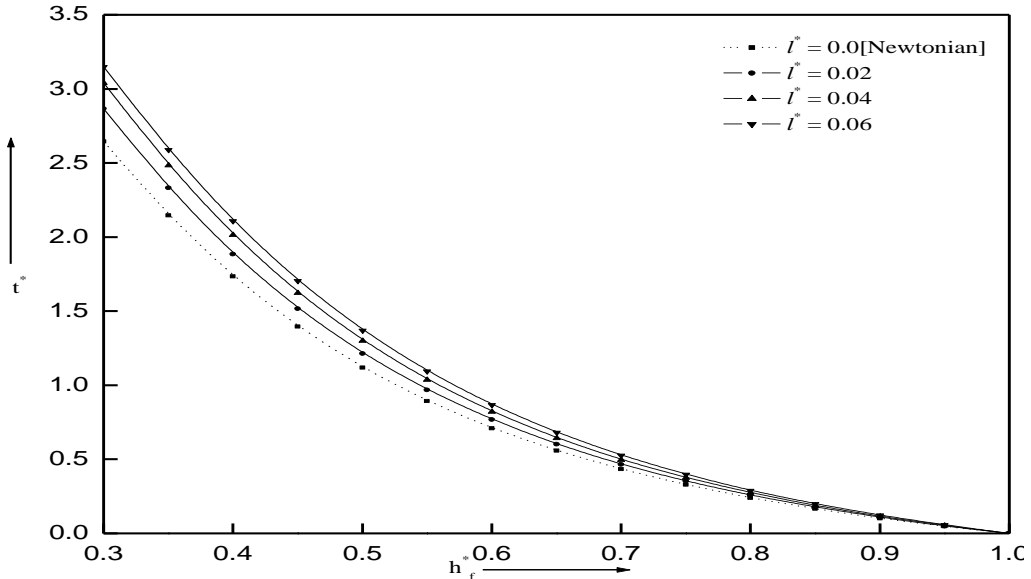


Fig. 7. Variation of non-dimensional time of approach t^* with h_f^* for different values of l^* with $K = 0.6, \psi = 0.01, N = 0.6$.

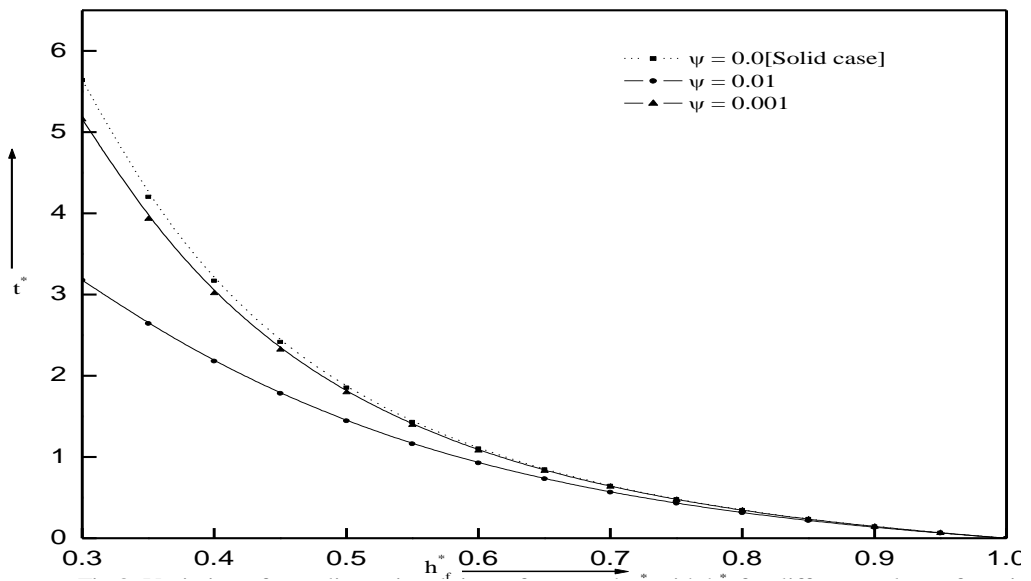


Fig. 8. Variation of non-dimensional time of approach t^* with h_f^* for different values of ψ with $K = 0.6, N = 0.6, l^* = 0.1$.

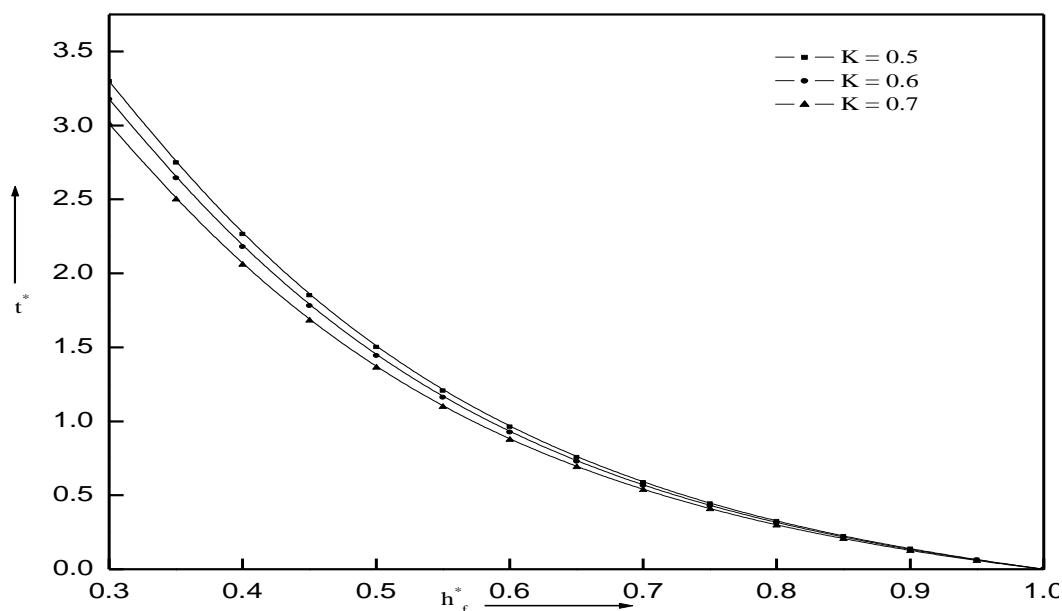


Fig. 9. Variation of non-dimensional time of approach t^* with h_f^* for different values of K with $\psi=0.01, N=0.6, l^*=0.1$.

5.2. Squeeze film Time-height relationship

The most important characteristics of the squeeze film bearings is the squeeze film time i.e. the time required for reducing the initial film thickness h_2 of h_0 to a final value h_f . The variation of non-dimensional time of approach t^* with h_f^* for different values for N with $l^*=0.1, K=0.6, \psi=0.01$ is presented in Fig. 6. It is observed that, the presence of micropolar fluid as lubricants have longer response time as compared to the Newtonian case. Figure 7 depicts the variation of non-dimensional time of approach t^* with h_f^* for different values for l^* with $N=0.6, K=0.6, \psi=0.01$. For increasing values of l^* the squeeze film time increases as compared to the Newtonian case. The variation of non-dimensional time of approach t^* with h_f^* for different values for ψ with $l^*=0.1, K=0.6, N=0.6$ is presented in Fig. 8. The effect of ψ is to decrease the squeeze film time as compared to the corresponding solid case ($\psi=0$) Fig. 9 depicts the variation of non-dimensional time of approach t^* with h_f^* for different values for K with $N=0.6, l^*=0.1, \psi=0.01$. It is observed that, the response time increases for decreasing values of K .

6. CONCLUSION

On the basis of Eringen's [9] micropolar fluid theory, this paper predicts the effect of micropolar fluid on the squeeze film lubrication characteristics between porous parallel stepped plates. On the basis of the results computed the following conclusions are drawn.

1. The effect of micropolar is to increase the squeeze film pressure and the load carrying capacity as compared to the corresponding Newtonian case.
2. The squeeze film time is lengthened for the micropolar lubricants as compared to the corresponding Newtonian case.
3. The presence of porous facing on the bearing surface affects the performance of the bearing.
4. The adverse effects of the porous facing on the bearing surface can be compensated with the selection of the lubricants with proper microstructure additives.

Nomenclature

- H^* non-dimensional mean film thickness $\left(= \frac{h_1}{h_2} \right)$.
- h_1 maximum film thickness
- h_2 minimum film thickness

h_s^*	step height $\left(= \frac{h_2}{h_0} \right)$.
KL	position of the step $0 < K < 1$.
k	permeability of the porous matrix
l	characteristic length of the polar suspension $\left(= \left(\frac{\gamma}{4\mu} \right)^{\frac{1}{2}} \right)$
l^*	non-dimensional form of $l \left(= l/h_2 \right)$
N	coupling number $\left(= \left(\frac{\chi}{\chi + 2\mu} \right)^{\frac{1}{2}} \right)$
p	pressure in the film region.
p_1	fluid film pressure in the region $0 \leq x \leq KL$.
p_2	fluid film pressure in the region $KL \leq x \leq L$.
t	time of approach
t^*	non-dimensional time of approach $\left(= \frac{wh_0^2 t}{8\mu b L^3} \right)$.
V	velocity approach.
w	load carrying capacity
W	non-dimensional load carrying capacity $\left(= \frac{W h_2^3}{8 \mu b V L^3} \right)$.
η	lubricant couple stress constant
μ	lubricant viscosity
ψ	permeability parameter
χ	spin viscosity
γ	viscosity co-efficient for micropolar fluids
μ	viscosity co-efficient

REFERENCES

- [1] P.R.K. Murti, 'Analysis of porous slider bearings', *Wear*, vol. 28, no. 1, pp. 131-134, 1974.
- [2] V. Kumar, 'Friction of a plane porous slider of optimum profile', *Wear*, vol. 62, pp. 417-418, 1980.
- [3] W.T. Rouleau and L.T. Steiner, 'Hydrodynamic porous journal bearing: part-I Finite full bearings', *Trans. ASME J. Lub. Tech.*, vol. 96, no. 3, pp. 346-353, 1974.
- [4] A. Cameron, V.T. Morgon and A.E. Stainsby, 'Critical conditions for hydrodynamic Lubrication of porous metal bearings', *Proc. Inst. Mech. Eng.*, vol. 176, no. 1, pp. 761-770, 1962.
- [5] D.F. Hays, 'Squeeze films for rectangular plates', *J. Fluids Eng.*, vol. 85, no. 2, pp. 243-246, 1963.
- [6] B.J. Hamrock, *Fundamental of fluid film lubrication*, New York, McGraw-Hill, 1994.
- [7] M.L. Abell and W.F. Ames, 'Symmetry reduction of Reynolds equation to film lubrication', *J. Appl. Mech.*, vol. 59, no. 1, pp. 206-210, 1992.
- [8] M.M. Rashid, S. Hamed and D. Saeed, 'Analytic Approximate Solutions for Unsteady Two-Dimensional and Axisymmetric Squeezing Flows between Parallel Plates', *Mathematical Problems in Engineering*, vol. 2008, pp. 1-13, 2008.
- [9] A.C. Eringen, 'Theory of micropolar fluids', *J. of Mathematics and Mechanics*, vol. 16, pp. 1-18, 1996.
- [10] A.C. Eringen, 'Simple microfluids', *Int. J. of Engg. Science*, vol. 2, no. 2, pp. 205-217, 1964.
- [11] A.B. Datta, 'Pivoted slider bearing with convex pad surface in micropolar fluid', *Jpn J Appl Phys*, vol. 11, no. 1, pp. 98-102, 1972.
- [12] N.B. Naduvinamani and T.V. Biradar, 'Effects of surface roughness on porous inclined slider bearings lubricated with micropolar fluids', *J Mar Sci Technol.*, vol. 15, no. 4, pp. 278-286, 2007.
- [13] S. Das, S.K. Guha and A.K. Chattapadhyay, 'Theoretical analysis of stability characteristics of hydrodynamic journal bearings with micropolar fluid', *Proc. Inst. Mech. Engrs. J. Eng. Tribology(part J)*, vol. 218, no. 1, pp. 45-56, 2004.
- [14] X. Wang and K.Q. Zhu, 'Numerical analysis of journal bearings lubricated with micropolar fluids including thermal and cavitating effects', *Tribol Int*, vol. 39, no. 3, pp. 227-237, 2006.
- [15] B.N. Naduvinamani and B. Kashinath, 'Surface roughness effects on the static and dynamic behaviour of squeeze film lubrication of short journal bearings with micropolar fluids', *Proc IMechE Part J: J Engineering Tribology*, vol. 222, no. 2, pp. 121-131, 2008.
- [16] J. Prakash and P. Sinha, 'Cyclic squeeze films in micropolar fluid lubricated journal bearing', *ASME J Tribol.*, vol. 98, no. 3, pp. 412-417, 1976.

- [17] J. Prakash and P. Sinha, 'Squeeze film theory for micropolar fluids', *ASME J. Tribol*, vol. 98, no. 1, pp. 139-144, 1976.
- [18] A. M.M. Rashidi, A.M. Siddiqui and M. Asadi, 'Application of Homotopy Analysis Method to the Unsteady Squeezing Flow of a Second-Grade Fluid between Circular Plates', *Mathematical Problems in Engineering*, vol. 2010, pp. 2-18, 2010.
- [19] P.D.S. Verma, V.K. Agrawal and S.K. Bhat, 'Porous inclined slider bearing lubricated with micropolar fluid', *Wear*, vol. 53, no. 1, pp. 101-106, 1979.
- [20] V.K. Agrawal and S.B. Bhatt, 'Porous pivoted slider bearings lubricated with a micropolar fluid', *Wear*, vol. 61, no. 1, pp. 1-8, 1980.
- [21] O.A. Bég, M.M. Rashidi, T.A. Bég, and M. Asadi, 'Homotopy analysis of transient magneto-bio-fluid dynamics of micropolar squeeze film in a porous medium: a model for magneto-bio-rheological lubrication', *Journal of Mechanics in Medicine and Biology*, vol. 12, no. 3, pp. 1-21, 2012.
- [22] M.E. Shimpi and G.M. Deheri, 'Magnetic fluid-based squeeze film performance in rotating curved porous circular plates: the effect of deformation and surface roughness', *Tribology in Industry*, vol. 34, no. 2, pp. 57-67, 2012.