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PERFORMANCE OF AN INCLINED PLANE POROUS SLIDER BEARING LUBRICATED WITH COUPLE STRESS FLUID: EFFECT OF SLIP VELOCITY AND SQUEEZE VELOCITY

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Abstract
This paper deals with the performance of an inclined plane porous slider bearing lubricated with couple stress fluid considering slip velocity and squeeze velocity. The expression for pressure, centre of pressure, load carrying capacity, force of friction and coefficient of friction are derived. The load capacity is calculated for choice of different values of squeeze velocity as well as slip velocity. It is seen that better load capacity is obtained when squeeze velocity as well as slip velocity are considered. Computed values of load capacity, frictional force and coefficient of friction are displayed in graphical form and the permeability parameter has been discussed for the possible increase in load capacity.
Keywords: Porous, Squeeze film, Couple stress, Slider bearings, Slip velocity.

1. Introduction

Slider bearings are generally used to carry the axial–component load or thrust in a rotating shaft which passes through the casing of a premier. An advantage of slider bearings is that they can last a lot longer than other types of bearings and are also economical. Porous bearings are simple in structure and low casting. The advantages of porous bearings in mounting horsepower motors include water pumps, sewing machines and vacuum cleaners, shaving machines, tape recorders, record players, hair dryers, coffee grinders, generators and distributors. Morgan and Cameron [1] analysed the hydrodynamic theory of porous journal bearings and gave the short bearing solution based on the Darcy model. Later Darcy's equation is widely used to study the lubrication properties of oil bearings. In addition the numerical models are more consistent due to coupling with many boundary conditions. Murti [2] has studied the analysis of porous slider Bearings and Verma *et.al.* [3] have studied the optimum profile of a porous slider bearing. Kumar V. [4] investigated the friction of a plane porous slider of optimal profile. Patel and Gupta [5] analysed the problem of inclined slider bearing by considering the slip condition at porous boundary and found that the load capacity can be increased by minimizing slip condition. Bujurke *et.al.* [6] theoretically studied the couple stress fluid effect on porous slider bearing and later on the performance of a secant-shaped porous slider bearing [7]. Shah and Bhat [8] analysed the performance of a porous exponential slider bearing with a ferrofluid lubricant, the flow was determined by the Jerkins model considering the slip velocity at the porous interface. The slip parameter lowered the carrying capacity without significantly affecting the centre of pressure. Naduvinamani and Siddangouda [9,10] analysed the problem of porous Rayleigh step bearing with couple stress fluids by modelling the flow of couple stress fluid in the porous region according to the modified Darcy's law describes the microstructural additive in the lubricant. All these studies observed that the effect of the porous facing on the bearing surface reduces the load-bearing capacity.
In a squeeze film bearing squeeze velocity is defined as a squeeze action that takes place as bearing surfaces approach each other. The squeeze film mechanism is of practical significance in many areas of applied science and industrial engineering applications such as rolling gears, bearings, damping films, aircraft engines and mechanics of synovial joints in human beings and animals etc. Owing to

this motivation several researchers have discussed such as Wu [11], Pinkus and Sternlicht [12], Cameron [13], Hamrock [14], Bujurke *et. al.*[15], Naduvinmani *et.al.* [16]. In all these studies the lubricant was assumed to be Newtonian fluid. However, the Newtonian fluid constitutive approximation is not a satisfactory engineering approach to most lubricant problems. Hence the use of non-Newtonian fluids as lubricants has gained its importance in the modern industry. The use of fluids blended with various kinds of additives has received great attention. The peculiar flow behaviour of these kinds of non-Newtonian fluids a micro continuum theory of couple stress fluids has been proposed by Stokes [17]. This Stokes micro continuum theory is the simplest theory that describes these fluids as a couple stress fluids. Liquid crystals, polymer thickened oils, synthetic fluids and even blood can be modelled as a couple stress fluids. Some numerical and analytical investigations for squeeze film performance have been carried out using this model. In partial journal bearings by Lin [18] and in sphere-plate bearings by Lin [19] the use of couple stress fluid as a lubricant has been found to increase the load capacity of the squeeze film and increase the response time of the squeeze film action. Squeeze film in bearings was studied by Ramanaiah [20] and Bujurke and Jayaraman [21]. It is found that the effect of couple stress provides an increase in the load-carrying capacity as well as a reduction in the squeezing velocity. From the analysis of rolling contact bearings by Bujurke and Naduvinami [22] and Das [23], the presence of couple stress is shown to increase the load-carrying capacity and hence the maximum Hertzian pressure. Naduvinmani and Marali [24] analysed the numerical solution of couple stress full Reynold's equation for plane inclined porous slider bearings with squeezing effect. Recently, Rajesh and Nayan [25] studied the Mathematical modelling of slider bearing of various shapes with combined effects of porosity at both ends anisotropic permeability, slip velocity and squeeze velocity. Rajesh Shah and Ramesh Kataria [26] analyzed mathematical analysis of newly designed two porous layers slider bearing with a convex pad upper surface considering slip and squeeze velocity using ferrofluid lubricant.
In this paper an attempt is made to investigate the performance of an inclined plane porous slider bearing lubricated with couple stress fluid considering slip velocity and squeeze velocity was not yet studied by any authors.

2 Mathematical formulation and solution of the problem

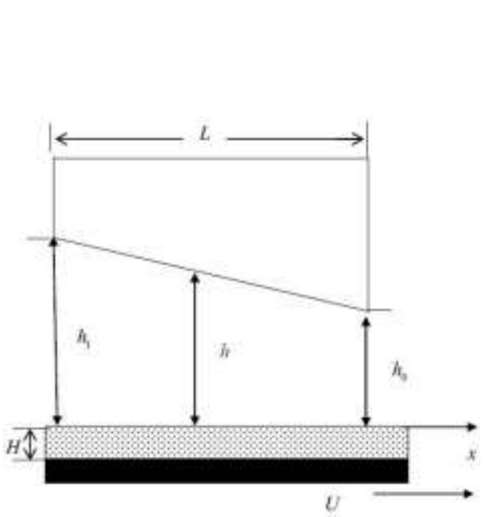

Figure 1 Geometrical configurations of the porous slider bearings with squeeze velocity $\dot{h}$
The diagram as shown in the above Figure 1 represents the inclined plane porous slider bearing. Which consists of a fluid film of thickness h, where h_1 is inlet and h_0 is outlet film thickness and inclined part of length L. The porous bearing's lower surface is at rest while the upper solid surface is in motion with a uniform velocity U including the effect of squeezing action $\dot{h}=\frac{\partial h}{\partial t}$, where t seconds. The Stokes [17] momentum and continuity equations for the couple stress fluid take the form,

$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0 \tag{2.1}$$

$$\mu\frac{\partial^2 u}{\partial y^2}-\eta\frac{\partial^4 u}{\partial y^4}=\frac{\partial p}{\partial x} \qquad (2.2)$$

$$\frac{\partial p}{\partial z}=0 \qquad (2.3)$$

The flow of couple stress fluid in a porous matrix is governed by the modified form of Darcy's law for isotropic porous materials

$$\vec{q}^{\,*}=\frac{-k}{\mu(1-\beta)}\nabla p^{*} \qquad (2.4)$$

where, $\vec{q}^{\,*}=(u^*,v^*),\beta=\dfrac{\eta}{\mu\kappa}$ and the parameter κ is the permeability of the porous material and is known as pore size and β is the ratio of microstructure size to the pore size. If $\left(\dfrac{\eta}{\mu}\right)^{1/2}\approx\sqrt{k}$ i.e., $\beta\approx 1$ then the microstructure additives present in the lubricant block the pores in the porous layer and thus reduce the Darcy flow through the porous matrix. When the microstructure size is very small when compared with the porous size, $\beta << 1$the additives percolate into the porous matrix. In the limit $\beta\to 0^+$ equation (2.4) reduces to the usual Darcy's law. The pressure in the porous region due to continuity satisfies Laplace's equation:

$$\frac{\partial^2 p^*}{\partial x^2}+\frac{\partial^2 p^*}{\partial y^2}=0 \qquad (2.5)$$

The relevant boundary conditions for the velocity components are:

(i) At the upper surface (z = *h*)

$$u=\mathrm{U}\ ,\ \frac{\partial^2 u}{\partial z^2}=0 \qquad (2.6a)$$

$$w=\frac{dh}{dt} \qquad (2.6b)$$

(ii) At the lower surface (*z* = 0)

$$u=\frac{1}{s}\frac{\partial u}{\partial z}\bigg|_{z=0}\ ,\ \frac{\partial^2 u}{\partial z^2}=0 \qquad (2.7a)$$

$$w=w^* \qquad (2.7b)$$

Solving equation (2.2) with boundary conditions (2.6a) and (2.7a) the velocity components u can be derived as follows:

$$u=\frac{1}{2\mu}\cdot\frac{\partial p}{\partial x}\left[(z-h)\left\{z+\frac{h}{3}\xi_1-2l\xi_0\tanh\left(\frac{h}{2l}\right)+2l^2\left\{1-\frac{\cosh\left[\frac{(2z-h)}{2l}\right]}{\cosh\left[\frac{h}{2l}\right]}\right\}\right\}\right]+\left(\frac{1}{1+sh}+\frac{zs}{1+sh}\right)U \qquad (2.8)$$

Where, $\xi_0=\dfrac{1}{1+sh},\ \xi_1=\dfrac{3}{1+sh},\ l=\left(\dfrac{\eta}{\mu}\right)^{1/2}$

Integrating equation (2.5) with respect to *z* over the porous layer thickness H and applying the boundary conditions $\dfrac{\partial p^*}{\partial z}=0$ at *z* = - H, we obtain,

$$\left(\frac{\partial p^*}{\partial z}\right)_{z=0}=-\int_{z=0}^{-H}\frac{\partial^2 p^*}{\partial x^2}\,dz \qquad (2.9)$$

The porous layer thickness H is assumed to be very small and applying the pressure $p=p^*$ continuity condition of the interface $z=0$ of porous matrix and fluid film equation (2. 9) reduces to

$$\left(\frac{\partial p^*}{\partial z}\right)_{z=0} = -H\frac{\partial^2 p^*}{\partial x^2} \tag{2.10}$$

Substituting the expressions for u in the continuity equation (2.1) and integrating across the film thickness and using the boundary conditions (2.6b) and (2.7b) gives the nonlinear modified Reynold's equation for

$$\frac{\partial}{\partial x}\left\{\left(f(h,s,l)+\frac{12KH}{1-\beta}\right)\frac{\partial p}{\partial x}\right\} = 6\mu U\frac{d}{dx}\left(\frac{2h+h^2s}{1+sh}\right)+12\mu\frac{\partial h}{\partial t} \tag{2.11}$$

where $f(h,s,l) = h^3\left(1+\xi_1\right)-6lh^2\xi_0\tanh\left(\frac{h}{2l}\right)-12l^2\left(h-2l\tanh\left[\frac{h}{2l}\right]\right)$

Using the following non-dimensional parameters in (2.8), we get

$$x^* = \frac{x}{L},\ ,\ \mathrm{h}^* = \frac{h}{h_0},\ l^* = \frac{2l}{h_0},\ \ p^* = \frac{ph_0^{\ 2}}{\mu UL}\ ,\ \ \mathrm{S} = \frac{-2\mathrm{L}\left(\frac{dh}{dt}\right)}{\mathrm{U}h_0}\ ,\ \psi = \frac{KH}{h_0^{\ 3}},\mathrm{s}^* = \mathrm{s}h_0$$

Hence the dimensionless Reynold's equation becomes:

$$\frac{\partial}{\partial x^*}\left\{\left(f^*(h^*,s^*,l^*)+\frac{12\psi}{1-\beta}\right)\frac{\partial p^*}{\partial x^*}\right\} = \frac{\partial G}{\partial x^*} \tag{2.12}$$

where

$$\xi_0^{\ *} = \frac{1}{1+s^*h^*};\qquad \xi_1^{\ *} = \frac{3}{1+s^*h^*};\qquad \mathrm{G}=6\left(\frac{2h^*+s^*h^{*2}}{1+s^*h^*}\right)-6\ S\ x^*;$$

$$f^*(h^*,s^*,l^*) = h^{*3}\left(1+\xi^*_{\ 1}\right)-3l^*h^{*2}\xi^*_{\ 0}\tanh\left(\frac{h^*}{l^*}\right)-3l^{*2}\left(h^*-l^*\tanh\left(\frac{h^*}{l^*}\right)\right)$$

Equation (2.12) is known as the dimensionless Reynold's equation. Since the pressure is negligible on the boundaries of the slider bearing compared to inside pressure.

The film thickness is given by,

$$h = h_1-(h_1-h_0)\ x/L, \qquad h^* = a^*+(1-a^*)\ x^* \ \text{ where } a^* = \frac{h_1}{h_0} \text{ is the taper ratio.}$$

The pressure field boundary conditions are:

$$p^* = 0 \text{ at } x^* = 0,1 \ \ \text{(Ambient pressure)} \tag{2.13}$$

Solving equation (2.12) subject to the conditions of equation (2.13). Integrating the equation of (2.12) with respect to x^*

$$\frac{\partial p^*}{\partial x^*} = \frac{G-Q}{\left(f^*(h^*,s^*,l^*)+\frac{12\psi}{1-\beta}\right)} \tag{2.14}$$

where Q is the constant of integration

The dimensionless film pressure p^* is obtained as,

$$p^* = \int_{x^*=0}^{x^*}\frac{G-Q}{f(h^*,s^*,l^*)+\frac{12\psi}{(1-\beta)}}\,dx^* \tag{2.15}$$

where,

$$Q = \frac{\displaystyle\int_{x^*=0}^{1} \frac{G}{f(h^*,s^*,l^*)+\dfrac{12\psi}{(1-\beta)}}\,dx^*}{\displaystyle\int_{x^*=0}^{1} \frac{1}{f(h^*,s^*,l^*)+\dfrac{12\psi}{(1-\beta)}}\,dx^*}$$

The load carrying capacity W^* are given in dimensionless form by,

$$W^* = \frac{Wh_0^2}{\mu UL^2} = \int_0^1 p^*\ dx^* \tag{2.16}$$

The component of the stress tensor required to calculate the frictional force is

$$\tau_{zx} = \mu\frac{\partial u}{\partial z} - \eta\frac{\partial^3 u}{\partial z^3} \tag{2.17}$$

The frictional force F per unit width on the bearing surface is given by,

$$F = \int_0^L (\tau_{zx})_{z=h}\ dx \tag{2.18}$$

Use of expression (2.8) for u in equation (2.17) and substituting it in equation (2.17) gives frictional force, which after non-dimensional becomes,

$$F^* = \int_0^1 \left\{ \frac{s^*}{\left(1+s^*h^*\right)} - \left(\frac{\left(h^*(1+s^*h^*) - l^*\tanh\left(\dfrac{h^*}{l^*}\right)\right)\{G-Q\}}{2\ (1+s^*h^*)\ \left\{ f^*(h^*,s^*,l^*) + \dfrac{12\psi}{1-\beta} \right\}} \right) \right\} dx^* \tag{2.19}$$

The coefficient of friction is,

$$f^* = \frac{F^*}{W^*} \tag{2.20}$$

The location of the centre of pressure, where the resultant force acts are,

$$x^* = \frac{1}{W^*}\int_0^1 p^*\cdot x^*\ dx^* \tag{2.21}$$

3. Results and discussions

In the present paper the performance of an inclined plane porous slider bearing lubricated with couple stress fluid considering slip velocity and squeeze velocity is analysed with the aid of various dimensionless parameters viz; the couple stress parameter l^*, the squeeze velocity $\dot{h}\neq 0$, the slip velocity s* and the permeability parameter ψ.

3.1 Non-dimensional pressure (*p**)

The graphs illustrated in Figure 2 to Figure 4 represent variation in non-dimensional pressure p^* against x^* with the effect of squeeze velocity $\dot{h}\neq 0$. In Figure 2 by fixing β =0.3, ψ =0.001, s*=0.3, S=0.5, a*=1.2 and varying l^* the non-dimensional pressure p^* is found to be increasing. In Figure 3 by fixing β =0.3, ψ =0.001, $l^*=0.5$, S=0.5, a*=1.2 and increasing values of s*, it is found that the effect of velocity slip on the porous interface reduces non-dimensional pressure p^* significantly as compared to the no-slip case (s*=∞). In Figure 4 by fixing β =0.3, $l^*=0.5$, s*=0.3, S=0.5, a*=1.2 and increasing values of permeability ψ the non-dimensional pressure p^* is found to be decreasing.

3.2 Non-dimensional load (W*)

The graphs illustrated in Figure 5 to Figure 7 represent variation in non-dimensional load W^* against a* with the effect of squeeze velocity $\dot{h}\neq 0$. In Figure 5 by fixing β =0.3, ψ=0.001, s*=0.3, S=0.5 and different values of l^*, it is observed that W^* increases with increasing the values of l^*. In Figure 6 by fixing β =0.3, ψ =0.001, $l^*=0.5$, S=0.5 and different values of s*, it is noted that the significant reduction in dimensionless load W^* as compared to the no-slip case ($s^*=\infty$). In Figure 7 by fixing $\beta=0.3$, $l^*=0.5$, $s^*=0.3$, $S=0.5$ and different values of ψ, it is found that W^* decreases with increasing the values of ψ. Figure 8 shows the variation in non-dimensional load W^* against a* for and different values of $\dot{h}$ with $\beta=0.3$, $l^*=0.5$, $s^*=0.3$, $\psi=0.001$, $h_0=0.02$, $L=0.005$ and $U=1.0$ and it is found that W^* increases considerably in the presence of squeeze velocity.

3.3 Non-dimensional friction (F*)

The graphs illustrated in Figure 9 to Figure 11 represent variation in non-dimensional friction F^* against a* with the effect of squeeze velocity $\dot{h}\neq 0$. In Figure 9 by fixing $\beta=0.3$, $\psi=0.001$, $s^*=0.3$, $S=0.5$ and increasing values of l^*, it is observed that F^* increases. In Figure 10 by fixing $\beta=0.3$, $\psi=0.001$, $l^*=0.3$, $S=0.5$ and increasing values of s*, a drastic reduction in F* is observed for no-slip case ($s^*=\infty$). In Figure 11 by fixing $\beta=0.3$, $l^*=0.5$, $s^*=0.3$, $S=0.5$ and increasing values of permeability ψ, it is found that F^* decreases.

3.4 Coefficient of friction (f*)

The graphs illustrated in Figure 12 to Figure 14 represent variations in non-dimensional coefficient friction f* against a^* with the effect of squeeze velocity $\dot{h}\neq 0$. In Figure 12 by fixing $\beta=0.3$, $\psi=0.001$, $s^*=0.3$, $S=0.5$ and increasing values of l^*, the coefficient of friction f* is found to be f* decreasing. In Figure 13 by fixing $\beta=0.3$, $\psi=0.001$, $l^*=0.3$, $S=0.5$ and increasing values of s*, a drastic reduction in f* is observed for no-slip case ($s^*=\infty$). In Figure 14 by fixing $\beta=0.3$, $l^*=0.3$, $s^*=0.3$, $S=0.5$ and increasing values of ψ the coefficient of pressure coefficient of friction f* is found to be increasing.

3.5 Centre of pressure (x*)

The graphs illustrated in Figure 15 to Figure 17 represent variations in the non-dimensional centre of pressure x* against a^* with the effect of squeeze velocity $\dot{h}\neq 0$. In Figure 15 it is found that increasing values of l^* the centre of pressure x* increases. In Figure 16 it is seen that a significant reduction in x* is observed for no-slip case ($s^*=\infty$). In Figure 17 it is observed that increasing values of ψ the centre of pressure x* is found to be decreasing.

4. Conclusions

In this paper the performance of an inclined plane porous slider bearing lubricated with couple stress fluid considering slip velocity and squeeze velocity are investigated. From this investigation, the following observations have been made.

- Pressure increases with an increase in couple stress parameters.
- Load carrying capacity and non-dimensional friction increase with increases in the value of couple stress but the coefficient of friction decreases.
- Load capacity, friction of force, coefficient of friction and centre of pressure decrease with increases in the value of slip velocity for distinct values of couple stress, permeability and squeeze velocity.
- Load capacity and non-dimensional friction decrease with increases in the value of permeability but the coefficient of friction decreases.

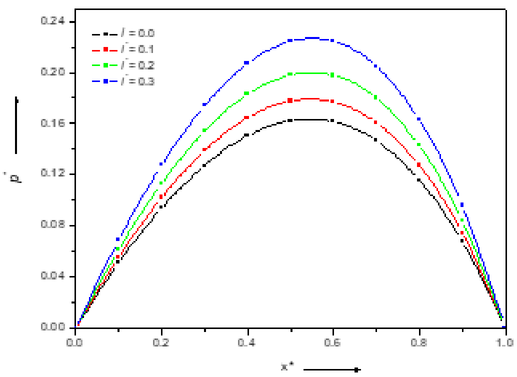

Figure 2 Variation of non-dimensional pressure p^* with x* for different values of couple stress l^* with β =0.3, s*=0.3, S=0.5, a*=1.2, ψ=0.001.

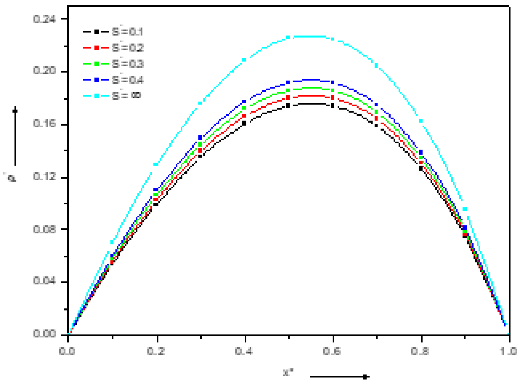

Figure 3 Variation of non-dimensional pressure p^* with x* for different values of slip velocity s* with S=0.5, l^* =0.3, β =0.3, ψ=0.001, a*=1.2.

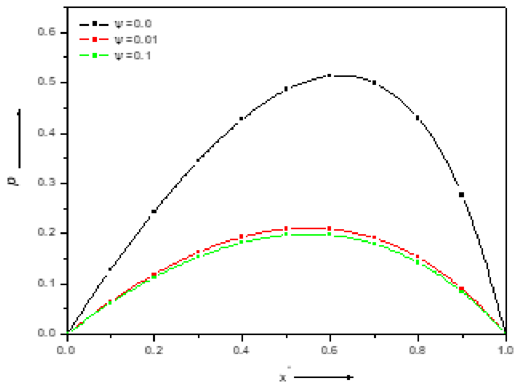

Figure 4 Variation of non-dimensional pressure p^* with x* for different values of $\psi$with s*=0.3, S=0.5, l^* =0.3, β =0.3, a*=1.2.

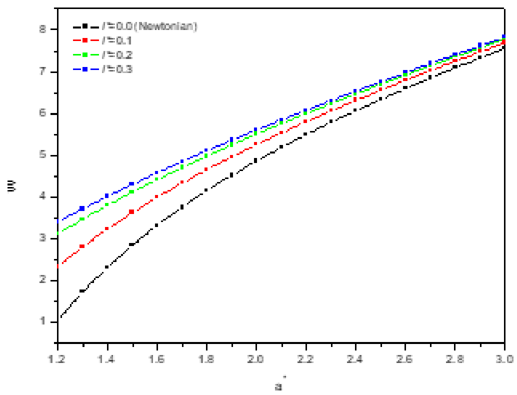

Figure 5 Variation of the non-dimensional load W* with a* for different values of couple stress l^* with s*=0.3, S=0.5, β =0.3, ψ=0.001.

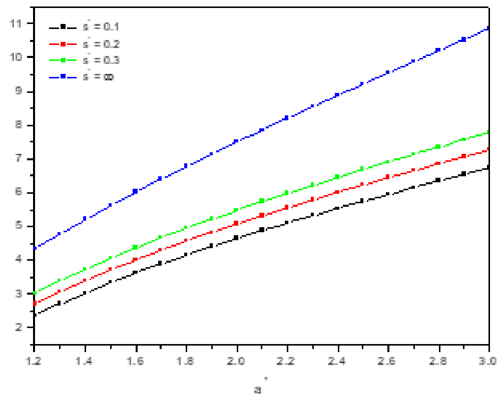

Figure 6 Variation of the non-dimensional load W* with a* for different values of slip velocity *s** with S=0.5, *l** =0.3, β =0.3, ψ=0.001.

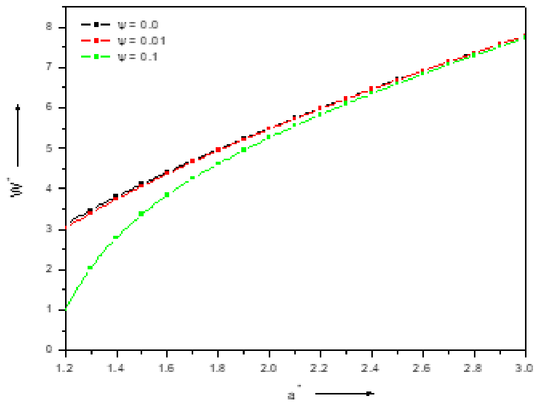

Figure 7 Variation of the non-dimensional load W* with a* for different values of ψ with s*=0.3, S=0.5, *l** =0.3, β =0.3.

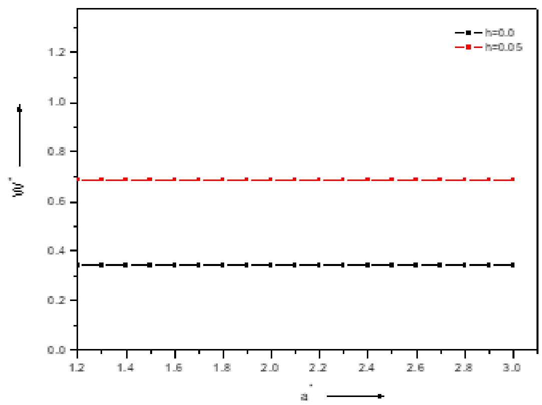

Figure 8 Variation of the non-dimensional load W* with a* for different values of $\dot{h}$ with s*=0.3, S=0.005, *l** =0.3, β =0.3, ψ=0.001, h_0 =0.02, L=0.05 and U=1.0.

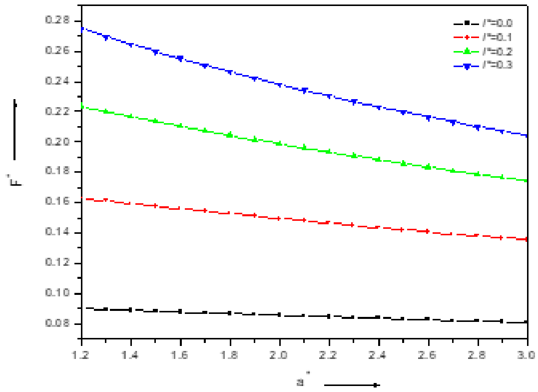

Figure 9 Variation of non-dimensional friction F* with a* for different values of couple stress fluid *l** with S=0.5, *l** =0.3, β =0.3, ψ=0.001.

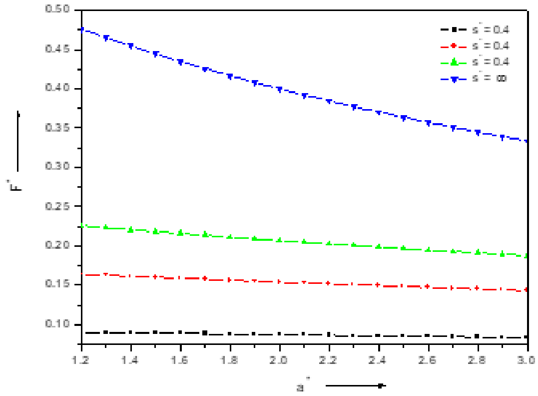

Figure 10 Variation of non-dimensional friction F* with a* for different values of slip velocity s* with S=0.5, *l** =0.3, β =0.3, ψ=0.001.

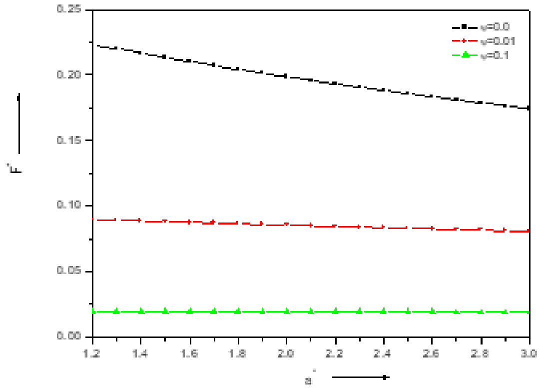

Figure 11 Variation of the non-dimensional friction F* with a* for different values of ψ with S=0.5, *l** =0.3, β =0.3, s*=0.3.

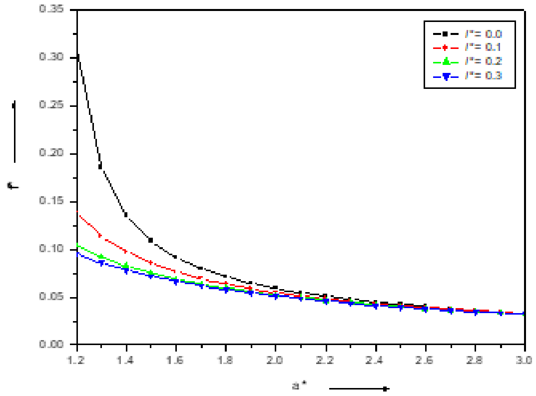

Figure 12 Variation of coefficient friction f* with a* for different values of the couple stress *l** with S=0.5, β =0.3, s*=0.3, ψ=0.001.

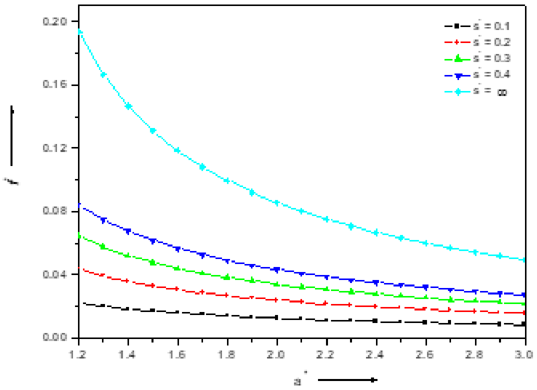

Figure 13 Variation of coefficient friction f* with a* for different values of slip velocity s* with S=0.5, *l** =0.3, β =0.3, ψ=0.001.

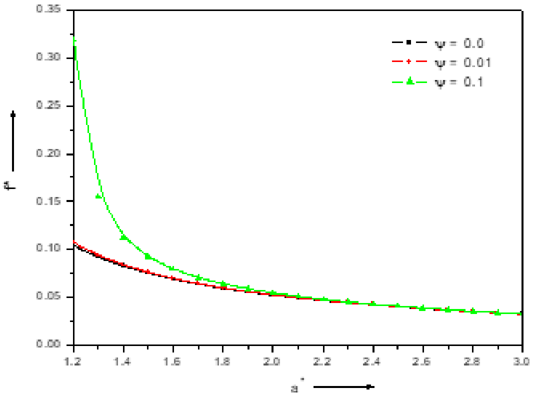

Figure 14 Variation of coefficient friction f* with a* for different values of ψ with S=0.5, *l** = 0.3, β = 0.3, s*=0.3

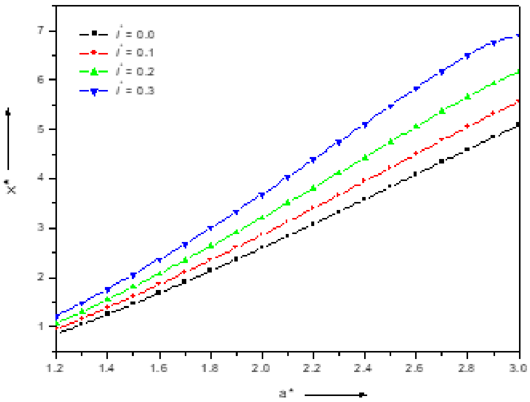

Figure 15 Variation of the centre of pressure x* with a* for different values of couple stress *l** with S=0.5, β =0.3, s*=0.3, ψ=0.001.

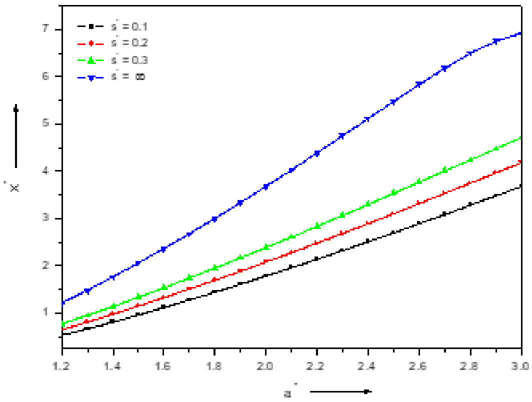

Figure 16 Variation of the centre of pressure f* with a* for different values of slip velocity with s* S=0.5, *l** =0.3, β =0.3, ψ=0.001.

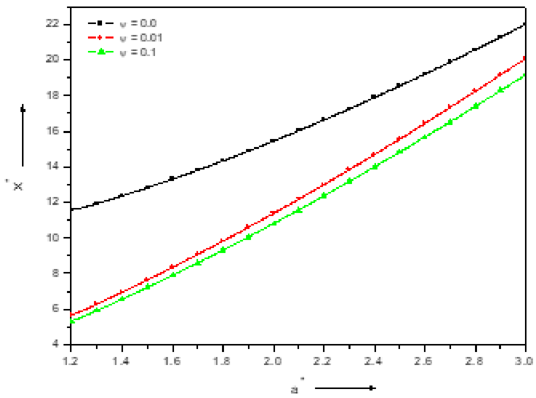

Figure 17 Variation of the centre of pressure x* with a* for different values of ψ with S=0.5, *l** =0.3, β =0.3, s*=0.3

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