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EFFECTS OF VISCOSITY VARIATION IN SQUEEZE FILM LUBRICATION OF CIRCULAR STEPPED PLATES

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ABSTRACT

In this paper an effort has been made to study the squeeze film effects of two circular stepped plates. The generalized form of Reynolds equation governing the flow for two symmetrical surfaces are used to obtain the velocity profiles of the lubricant. The squeeze film pressure and the load carrying capacity are analysed to find the squeeze time. Theoretical results on the effects of velocity slip and viscosity variations are also presented for the circular stepped plates.

Keywords: *squeeze pressure, velocityslip, circular stepped plates.*

1. INTRODUCTION

The squeeze film bearings are found to be very useful because of squeezing action between the surfaces due to which high pressure and more load can be generated. Squeeze film lubrication has several applications such as clutches, breaks, gears, machine tools, etc. A considerable work has been done for the calculation of stresses induced in circular plates due to different loading and boundary conditions. The stepped plates are one of these plates which are widely used in engineering applications. Several researchers studied the squeeze film bearings lubricated with Newtonian fluids. Dowson [1] unified the various attempts in generalizing the Reynolds Equation by considering the variation of fluid properties across as well as along the fluid film thickness by neglecting the slip effects at the bearing surfaces. Rao *et al.* [2] studied the effects of velocity-slip and viscosity variation in squeeze film lubrication of two circular plates. Raghavendra Rao [3] studied the effects of velocity slip and viscosity variation for lubrication of Roller bearings. Rashidi *et al.* [4] Analytical Solution of Squeezing Flow between two circular plates by using homotopy analytical method. Hsu [5] observed the combined effects of surface roughness and rotating inertia on squeeze film characteristics between parallel circular disks. Naduvinamani and Gurubasavaraj [6] analysed the stochastic theory of hydrodynamic lubrication of rough surfaces and studied the effects of surface roughness on the performance of the squeeze film between circular curved plates. Bujurke *et al.* [7] analysed effect of surface roughness on the squeeze film lubrication between curved annular plates. Patel and Deheri [8] investigated the effect of surface roughness on the performance of a rough circular cylinder near a plane considering slip velocity. A theoretical analysis on the squeeze film characteristics between circular stepped plates lubricated with Rabinowitsch fluid is presented by Naduvinamani [13].

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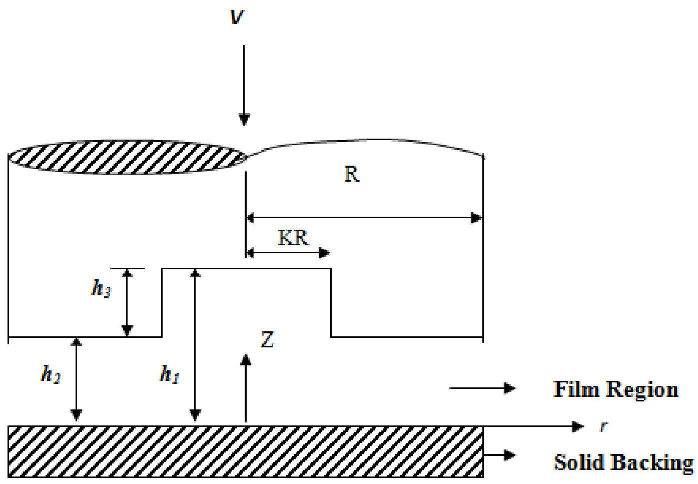

Figure-1

2. NOMENCLATURE

h	Total film thickness
h_f	Final film thickness
k	Ratio of the viscosities
l	Length of the bearing
P	Hydrodynamic Pressure
R	Radius of the surfaces in case of circular plates
T	Squeezing time of for stiff surfaces
V	Squeeze Velocity
W	Load capacity for stiff surfaces
μ	Viscosity of the purely hydrodynamic zone
Q	Volume flux
ρ	fluid density
u, v	velocity components in the x,y direction
η	viscosity
KR	The position of the step $0 < K < 1$
p_1	Fluid film pressure in the region $0 \le r \le KR$
p_2	fluid film pressure in the region $KR \le r \le R$
V	velocity
V, V_1	velocity vector
W	load - carrying capacity
W^*	non-dimensional load-carrying capacity
h_1	maximum film thickness
h_2	minimum film thickness
a	thickness of the peripheral layer
$\overline{h}$	dimensionless film thickness $\left(=\frac{h}{l}\right)$
$\overline{h_1}$	dimensionless film thickness after time Δt $\left(=\frac{h_1}{l}\right)$
$\overline{a}=\frac{a}{l}$	
r^*	non-dimensional radial

3. ANALYSIS

The equations of motion for a Newtonian fluid in Cartesian co-ordinates are,

$$\left.\begin{aligned}
\frac{\partial p}{\partial x}+\rho\frac{Du}{Dt}&=\rho X+\frac{2}{3}\frac{\partial}{\partial x}\eta\left(\frac{\partial u}{\partial x}-\frac{\partial v}{\partial y}\right)+\frac{2}{3}\frac{\partial}{\partial x}\eta\left(\frac{\partial u}{\partial x}-\frac{\partial w}{\partial z}\right)+\frac{\partial}{\partial y}\eta\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\eta\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)\\
\frac{\partial p}{\partial y}+\rho\frac{Dv}{Dt}&=\rho Y+\frac{2}{3}\frac{\partial}{\partial y}\eta\left(\frac{\partial v}{\partial y}-\frac{\partial u}{\partial x}\right)+\frac{2}{3}\frac{\partial}{\partial y}\eta\left(\frac{\partial v}{\partial y}-\frac{\partial w}{\partial z}\right)+\frac{\partial}{\partial x}\eta\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial z}\eta\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)\\
\frac{\partial p}{\partial z}+\rho\frac{Dw}{Dt}&=\rho Z+\frac{2}{3}\frac{\partial}{\partial z}\eta\left(\frac{\partial w}{\partial z}-\frac{\partial u}{\partial x}\right)+\frac{2}{3}\frac{\partial}{\partial z}\eta\left(\frac{\partial w}{\partial z}-\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial y}\eta\left(\frac{\partial w}{\partial y}+\frac{\partial v}{\partial z}\right)+\frac{\partial}{\partial x}\eta\left(\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z}\right)
\end{aligned}\right\} \quad (1)$$

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \quad (2)$$

Assuming that the flow of the fluid is laminar between two symmetric triangular plates. The Navier-Stokes equation as obtained by Dowson [1],

$$\left.\begin{aligned}
\frac{\partial P}{\partial x}&=\frac{\partial}{\partial z}\left[\eta\frac{\partial u}{\partial z}\right]\\
\frac{\partial P}{\partial y}&=\frac{\partial}{\partial z}\left[\eta\frac{\partial v}{\partial z}\right]
\end{aligned}\right\} \quad (3)$$

where P = p(x, y) is the pressure in the film and η is the viscosity. The boundary conditions considering slip at the surfaces (3), (4) are as follows: at $Z=H_1$ we have,

$$\begin{aligned}
u&=(u)_1=(\lambda)_1\left[\frac{\partial u}{\partial z}\right]_1+U_1\\
v&=(v)_1=(\delta)_1\left[\frac{\partial v}{\partial z}\right]_1+V_1 \quad at\ Z=H_1\\
u&=(u)_2=-(\lambda)_2\left[\frac{\partial u}{\partial z}\right]_2+U_2\\
v&=(v)_2=-(\delta)_2\left[\frac{\partial v}{\partial z}\right]_2+V_2 \quad at\ Z=H_2
\end{aligned} \quad (4)$$

where the suffixes 1 and 2 represent the values at $z=H_1$ and $z=H_2$, respectively. Here λ's and δ's are molecular mean of the free path for gas lubrication. They depend upon the lubricant temperature, pressure and viscosity. In liquid lubrication λ and δ depend on viscosity and the coefficient is sliding friction.

From equation (3) and (4) we obtain,

$$\begin{aligned}
u-U_1&=\left[\alpha_1+\int_{H_1}^{z}\frac{dz}{\eta}\right]\left[\frac{U_2-U_1}{F_0}-\frac{F_1}{F_0}\frac{\partial P}{\partial x}\right]+\left[\alpha_1 H_1+\int_{H_1}^{z}\frac{zdz}{\eta}\right]\frac{\partial P}{\partial x}\\
v-V_1&=\left[\beta_1+\int_{H_1}^{z}\frac{dz}{\eta}\right]\left[\frac{V_2-V_1}{F^1_0}-\frac{F^1_1}{F^1_0}\frac{\partial P}{\partial y}\right]+\left[\beta_1 H_1+\int_{H_1}^{z}\frac{zdz}{\eta}\right]\frac{\partial P}{\partial y}
\end{aligned} \quad (5)$$

Where $F_0=\alpha_1+\alpha_2+\int_{H_1}^{Z}\frac{dz}{\eta}$, $F^1_0=\beta_1+\beta_2+\int_{H_1}^{z}\frac{zdz}{\eta}$,

$$F_1=\alpha_1H_1+\alpha_2H_2+\int_{H_1}^{H_2}\frac{zdz}{\eta},\ F^1_1=\beta_1H_1+\beta_2H_2+\int_{H_1}^{z}\frac{zdz}{\eta}$$

$$\alpha_1=\frac{(\lambda)_1}{(\eta)_1},\ \alpha_2=\frac{(\lambda)_2}{(\eta)_2},\ \beta_1=\frac{(\delta)_1}{(\eta)_1},\ \beta_2=\frac{(\delta)_2}{(\lambda)_2} \quad (6)$$

From equation (2)

$$\int_{H_1}^{H_2}\frac{\partial\rho}{\partial t}dz+\int_{H_1}^{H_2}\frac{\partial(\rho u)}{\partial x}dz+\int_{H_1}^{H_2}\frac{\partial(\rho v)}{\partial y}dz+(\rho w)_{H_1}^{H_2}=0 \tag{7}$$

$$\frac{\partial}{\partial x}\left\{\left(F_2+G_1\right)\frac{\partial P}{\partial x}\right\}+\frac{\partial}{\partial y}\left\{\left(F_2^1+G_1^1\right)\frac{\partial P}{\partial y}\right\}+H_1\left\{\frac{\partial}{\partial x}(\rho u)_1+\frac{\partial}{\partial y}(\rho v)_1\right\}$$
$$=H_2\left\{\frac{\partial}{\partial x}(\rho u)_2+\frac{\partial}{\partial y}(\rho v)_2\right\}+\int_{H_1}^{H_2}\frac{\partial\rho}{\partial y}dz+(\rho w)_{H_1}^{H_2} \tag{8}$$

Where $F_2=\int_{H_1}^{H_2}\frac{\rho z}{\eta}\left[z-\frac{F_1}{F_0}\right]dz,\ F_2^{\,1}=\int_{H_1}^{H_2}\frac{\rho z}{\eta}\left[z-\frac{F_1^1}{F_0^1}\right]dz,\ F_3=\int_{H_1}^{H_2}\frac{\rho z}{\eta}dz,$

$$G_1=\int_{H_1}^{H_2}\left[z\frac{\partial\rho}{\partial z}\left\{\alpha_1H_1+\int_{H_1}^{z}\frac{zdz}{\eta}-\frac{F_1}{F_0}\left[\alpha_1+\int_{H_1}^{z}\frac{dz}{\eta}\right]\right\}\right]dz,$$

$$G_1^1=\int_{H_1}^{H_2}\left[z\frac{\partial\rho}{\partial z}\left\{\beta_1H_1+\int_{H_1}^{z}\frac{zdz}{\eta}-\frac{F_1}{F_0}\left[\beta_1+\int_{H_1}^{z}\frac{dz}{\eta}\right]\right\}\right]dz$$

$$G_2=\int_{H_1}^{H_2}\left\{z\frac{\partial\rho}{\partial z}\left[\alpha_1+\int_{H_1}^{z}\frac{dz}{\eta}\right]\right\}dz$$

$$G_2^1=\int_{H_1}^{H_2}\left\{z\frac{\partial\rho}{\partial z}\left[\beta_1+\int_{H_1}^{z}\frac{dz}{\eta}\right]\right\}dz,G_3=\int_{H_1}^{H_3}z\frac{\partial\rho}{\partial z}dz \tag{9}$$

Assuming slip velocities at the bearing surfaces for couple stress fluid film lubrication

$$(\lambda)_1=(\lambda)_2=(\delta)_1=(\delta)_2=0$$
$$\alpha_1=\alpha_2=\beta_1=\beta_2=0$$

Using the concept of multiple layer lubrication,

$$\rho=\rho_1(x,y),\eta=\eta_1(x,y)\ \ H_1\le z\le H_1+h_1$$
$$\rho=\rho_2(x,y),\eta=\eta_2(x,y)\ \ H_1+h_1\le z\le H_1+h_1+h_2$$
$$\rho=\rho_3(x,y),\eta=\eta_3(x,y)\ \ H_1+h_1+h_2\le z\le H_1+h_1+h_2+h_3 \tag{10}$$

Taking, $U_1=U$ $U_2=V_1=V_2=0$

$$\alpha_1=\beta_1\ \ \alpha_2=\beta_2$$
$$\frac{\partial\rho_i}{\partial z}=0\qquad i=1,2,3\ldots \tag{11}$$

From equation (8),

$$\frac{\partial}{\partial x}\left[F_2\frac{\partial P}{\partial x}\right]+\frac{\partial}{\partial y}\left[F_2\frac{\partial P}{\partial y}\right]$$
$$=H_2\left\{\frac{\partial}{\partial x}(\rho u)_2+\frac{\partial}{\partial y}(\rho v)_2\right\}-H_1\left\{\frac{\partial}{\partial x}\left(\rho u\right)_1+\frac{\partial}{\partial y}(\rho v)_1\right\}+U\frac{\partial}{\partial x}\left[\frac{F_3}{F_0}\right]+\left[\rho w\right]_{H_1}^{H_2} \tag{12}$$

where $F_0=\alpha_1+\alpha_2+\frac{h_1}{\eta_1}+\frac{h_2}{\eta_2}+\frac{h_3}{\eta_3}$

$$F_1=\alpha_1H_1+\alpha_2H_2+\frac{h_1(2H_1h_1)}{2\eta_1}+\frac{h_2(2H_1+2h_1+h_2)}{2\eta_2}+\frac{h_3(2H_1+2h_1+2h_2+h_3)}{2\eta_3}$$

$$F_3 = \frac{\rho_1 h_1(2H_1 h_1)}{2\eta_1} + \frac{\rho_2 h_2(2H_1 + 2h_1 + h_2)}{2\eta_2} + \frac{\rho_3 h_3(2H_1 + 2h_1 + 2h_2 + h_3)}{2\eta_3}$$

$$(\rho u)_1 = \rho_1 \alpha_1 \left[H_1 - \frac{F_1}{F_0} \right] \frac{\partial P}{\partial x} + \rho_1 U \left[1 - \frac{\alpha_1}{F_0} \right]$$

$$(\rho u)_2 + \rho_3 \alpha_2 \left[H_2 - \frac{F_1}{F_0} \right] \frac{\partial P}{\partial x} = \rho_3 U \frac{\alpha_2}{F_0}$$

$$(\rho v)_1 = \rho_1 \alpha_1 \left[H_1 - \frac{F_1}{F_0} \right] \frac{\partial P}{\partial y}$$

$$(\rho v)_2 + \rho_3 \alpha_2 \left[H_2 - \frac{F_1}{F_0} \right] \frac{\partial P}{\partial y} = 0 \tag{13}$$

$$[\rho w]_{H_1}^{H_2} + (\rho u)_1 \frac{\partial H_1}{\partial x} + (\rho v)_1 \frac{\partial H_1}{\partial y} + V_s = (\rho u)_2 \frac{\partial H_2}{\partial x} + (\rho v)_2 \frac{\partial H_2}{\partial y}$$

where V_s is the resultant velocity towards the film. Considering three symmetrical incompressible layers between two solid boundaries.

We have, $\eta_1 = \eta_2$ and $\rho_1 = \rho_2 = \rho_3$

$$H_1=0 \qquad H_2 = (h+a) = h, h_1 = h_3 = a/2, h_2 = (h-a)$$

$$\alpha_1 = \alpha_2 = \beta_1 = \beta_2 = 1/\beta \tag{14}$$

Hence,

$$\frac{\partial}{\partial x}\left[F_4 \frac{\partial P}{\partial x} \right] + \frac{\partial}{\partial y}\left[F_4 \frac{\partial P}{\partial y} \right] = U \frac{\partial}{\partial x}(h) - V \tag{15}$$

where $F_4 = \frac{(h-a)^3}{12\eta_2} + \frac{a^3 + 3a^2(h-a) + 3a(h-a)^2}{12\eta_1} + \frac{h^2}{2\beta}$, $\beta = \frac{\eta_1}{\lambda}$ is the slip parameter.

1. SQUUEEZE FILM LUBRICATION OF CIRCULAR STEPPED PLATES

The Volume flux of the lubricant is given by

$$Q = 2\pi r \left[F_4 \frac{dP}{dr} \right] \tag{16}$$

$$F_4 = \frac{l^3}{12\mu} \left\{ \frac{(\bar{h} - \bar{a})(k-1) + \bar{h}^3}{k} + \frac{6\bar{h}^2}{\beta} \right\}$$

Integrating the continuity equation

$$\frac{1}{r}\frac{\partial}{\partial r}(ru) + \frac{\partial w}{\partial z} = 0$$

$$\frac{\partial}{\partial r}(ru) = -r\frac{\partial w}{\partial z}$$

Using the boundary condition w=0 at z=0 & w=-V at z=h

$$\int_0^h \frac{\partial}{\partial r}(ru)dz = -r\int_0^h \frac{\partial w}{\partial z} dz$$

$$\frac{\partial}{\partial r}[r\int_0^h u dz] = -r(w)_0^h$$

$$\frac{\partial}{\partial r}\left[r\frac{Q}{2\pi r}\right] = -r(-V-0)$$

$$\frac{\partial Q}{\partial r} = 2\pi r V$$

$$\int \frac{\partial Q}{\partial r}dr = 2\pi V\left(\frac{r^2}{2}\right) + C_1$$

$$Q = \pi V r^2 + C_1$$

Since Q=0 at r=0

$$\Rightarrow C_1 = 0$$

$$Q = \pi r^2 V \tag{17}$$

From equations (16) & (17) we have

$$\pi r^2 V = -2\pi r\left[F_4 \frac{dP}{dr}\right]$$

$$\frac{\partial p}{\partial r} = -\frac{Vr}{F_4}$$

$$\frac{\partial p_i}{\partial r} = -\frac{Vr}{F_4} \tag{18}$$

where $i = 1, h = h_1$ in the region $0 \le r \le KR$ and $i = 2, h = h_2$ in the region $KR \le r \le R$

In region I: $\left(0 \le r \le KR\right)$

$$\frac{\partial p_1}{\partial r} = -\frac{Vr}{F_5} \tag{19}$$

$$F_5 = \frac{l^3}{12\mu}\left\{\frac{(\bar{h}_1 - \bar{a})(k-1) + \bar{h}_1^{\,3}}{k} + \frac{6\bar{h}_1^{\,2}}{\beta}\right\}$$

In region II: $\left(KR \le r \le R\right)$

$$\frac{\partial p_2}{\partial r} = -\frac{Vr}{F_6} \tag{20}$$

$$F_6 = \frac{l^3}{12\mu}\left\{\frac{(1-\bar{a})(k-1)+1}{k} + \frac{6}{\beta}\right\}$$

Integrating (19) and (20) and using the boundary conditions

$$p_1 = p_2 \;\; at \;\;\; r = KR$$

$$p_2 = 0 \;\; at \;\;\; r = R$$

$$p_1 = -\frac{V}{F_5}\frac{r^2}{2} + C_1 \tag{21}$$

Similarly,

$$p_2 = -\frac{V}{F_6}\frac{r^2}{2} + C_2 \tag{22}$$

Using $p_2 = 0$ at $r = R$ in equation (22) we get

$$C_2 = \frac{V}{F_6}\frac{R^2}{2}$$

Equation (22) changes to

$$p_2 = \frac{V}{2}\frac{(R^2 - r^2)}{F_6}$$

Since $p_1 = p_2$ at $r = KR$

$$C_1 = \frac{V}{2}\left\{\frac{K^2R^2}{F_5} + \frac{R^2(1-K^2)}{F_6}\right\}$$

Substituting the value of C_1 in equation (21) we get

$$p_1 = -\frac{Vr^2}{2F_5} + \frac{V}{2}\left\{\frac{K^2R^2}{F_5} + \frac{R^2(1-K^2)}{F_6}\right\}$$

$$p_1 = \frac{V}{2}\left\{\frac{K^2R^2 - r^2}{F_5} + \frac{R^2(1-K^2)}{F_6}\right\} \tag{23}$$

$$p_1^* = \frac{p_1}{R^2V} = \frac{K^2 - r^{*2}}{2F_5} + \frac{(1-K^2)}{2F_6}$$

$$p_2 = \frac{V}{2}\frac{(R^2 - r^2)}{F_6} \tag{24}$$

$$p_2^* = \frac{p_2}{VR^2} = \frac{(1-r^{*2})}{2F_6}$$

The load carrying capacity w is given by

$$W = 2\pi\int_0^{KR} rp_1 dr + 2\pi\int_{KR}^{R} rp_2 dr$$

$$W = 2\pi\int_0^{KR} r\left[\frac{V}{2}\left\{\frac{K^2R^2 - r^2}{F_5} + \frac{R^2(1-K^2)}{F_6}\right\}\right]dr + 2\pi\int_{KR}^{R} r\left\{\frac{V}{2}\frac{(R^2-r^2)}{F_6}\right\}dr$$

$$W = \pi V\left\{\int_0^{KR}\frac{K^2R^2r}{F_5}dr - \int_0^{KR}\frac{r^3}{F_5}dr + \int_0^{KR}\frac{R^2(1-K^2)r}{F_6}dr + \int_{KR}^{R}\frac{R^2r}{F_6}dr - \int_{KR}^{R}\frac{r^3}{F_6}dr\right\}$$

$$W = \pi V\left\{\frac{1}{F_5}\left(\frac{K^4R^4}{2} - \frac{K^4R^4}{4}\right) + \frac{1}{F_6}\left(\frac{K^2R^4}{2} - \frac{K^2R^2}{2} + \frac{R^4}{2} - \frac{K^2R^4}{2} - \frac{R^4}{4} + \frac{K^4R^4}{4}\right)\right\}$$

$$W = \frac{\pi VR^4}{4}\left(\frac{K^4}{F_5} + \frac{(1-K^4)}{F_6}\right) \tag{25}$$

$$W^* = \frac{W}{P_0 l R^4 \overline{V}} = \frac{1}{4}\left(\frac{K^4}{F_5} + \frac{(1-K^4)}{F_6}\right) \tag{26}$$

Writing $\overline{V} = -\frac{dh_2^*}{dT}$ in equation (25), the time of approach is given by

$$W = \left(-\frac{dh_2}{dT}\right)\frac{1}{4}\left(\frac{K^4}{F_5} + \frac{(1-K^4)}{F_6}\right)$$

$$\frac{dT}{dh_2^*} = -\frac{R^4}{4W}\left(\frac{K^4}{F_5} + \frac{(1-K^4)}{F_6}\right)$$

$$\int dT = -\frac{\pi R^4}{4W}\int_1^{h_f^*}\left(\frac{K^4}{F_5} + \frac{(1-K^4)}{F_6}\right)d\overline{h}_2$$

$$T = -\frac{R^4}{4W}\int_{h_0}^{h_f}\left(\frac{K^4}{F_5} + \frac{(1-K^4)}{F_6}\right)d\overline{h}_2 \tag{27}$$

$$F_5 = \frac{l^3}{12\mu}\left\{\frac{(\overline{h}_2 + \overline{h}_s - \overline{a})(k-1) + (\overline{h}_2 + \overline{h}_s)^3}{k} + \frac{6(\overline{h}_2 + \overline{h}_s)^2}{\beta}\right\}$$

$$F_6 = \frac{l^3}{12\mu}\left\{\frac{(\overline{h}_2 - \overline{a})(k-1) + \overline{h}_2^{\,3}}{k} + \frac{6\overline{h}_2^{\,2}}{\beta}\right\}$$

RESULTS AND CONCLUSION

The non-Newtonian effects of Viscosity Variation in squeeze film lubrication of circular stepped plates are investigated. This paper predicts the influence of couple stresses on the squeeze film characteristics of step bearings on the basis of Stokes couple stress fluid theory.

LOAD CARRYING CAPACITY

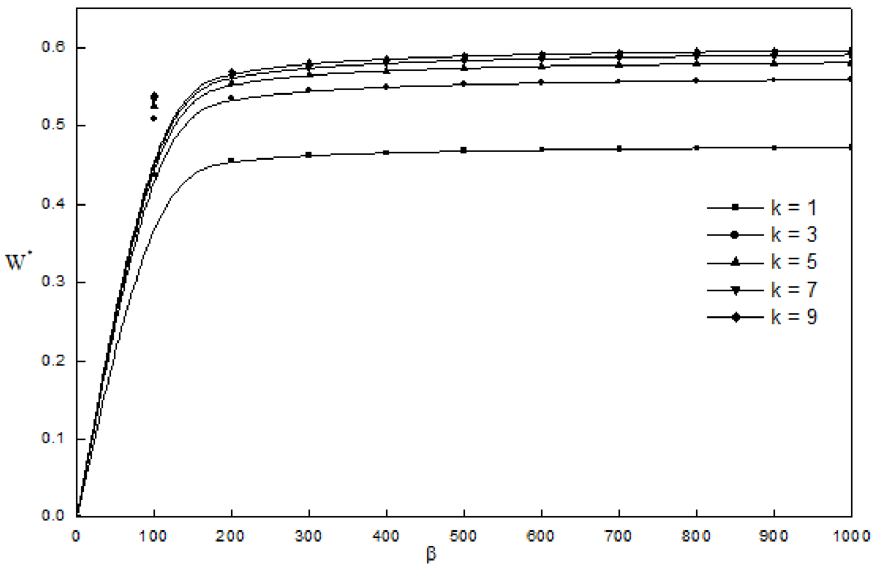

Figure-2: Variation of W^* with β for different values of k with $h = 0.6, a = 0.055, K = 0.6.$

The above figure indicates variation of W^* with β for $k = 1, k = 3, k = 5, k = 7$ and $k = 9$. We observe that for any value of β dimensionless load carrying capacity W^* increases for an increase in k.

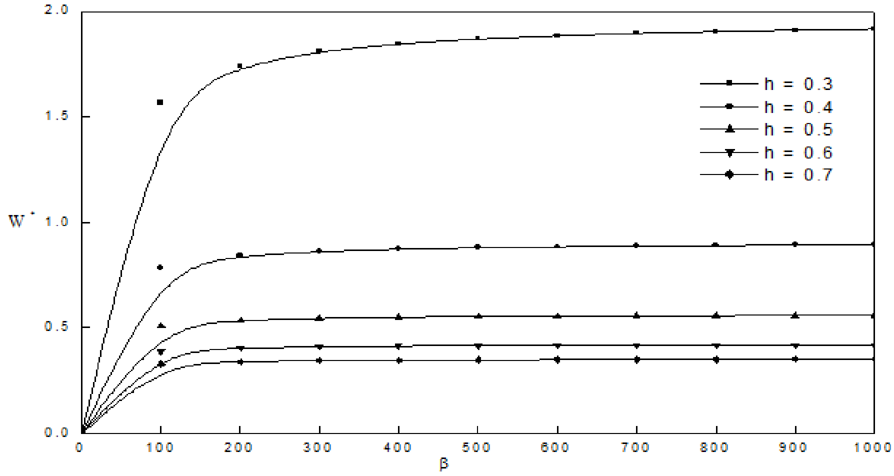

Figure-3: Variation of W^* with β for different values of h with $a = 0.055, k = 3, K = 0.6.$

The above figure indicates variation of W^* with β for $h = 0.3,$ $h = 0.4,$ $h = 0.5,$ $h = 0.6$ and $h = 0.7$. We observe that for any value of β dimensionless load carrying capacity W^* increases for an increase in h.

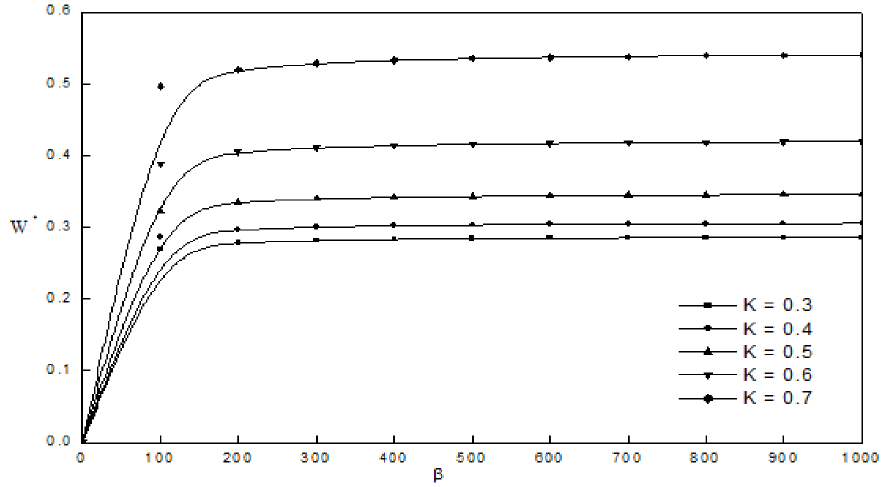

Figure-4: Variation of W^* with β for different values of K with $h = 0.6, a = 0.055, k = 3.$

The above figure indicates variation of W^* with β for $k = 0.3,$ $k = 0.4,$ $k = 0.5,$ $k = 0.6$ and $k = 0.7$. We observe that for any value of β dimensionless load carrying capacity W^* increases for an increase in k.

TIME-HEIGHT RELATIONSHIP

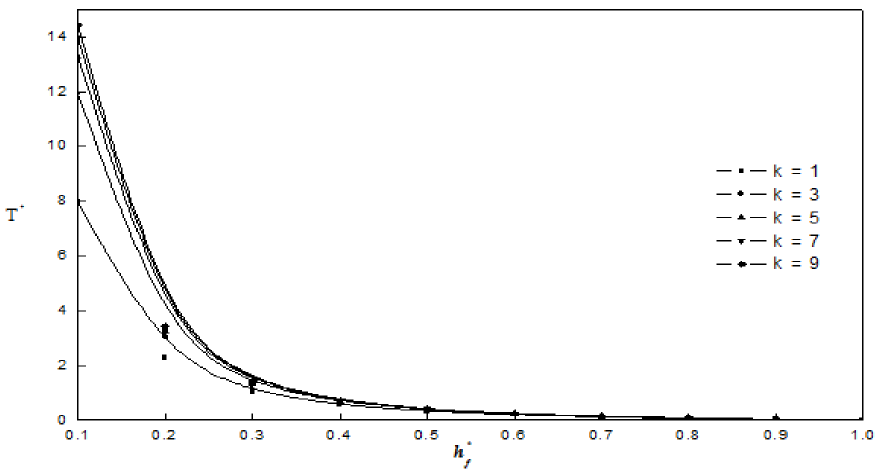

Figure-5: Variation of T^* with h_f^* for different values of k with $h = 0.6, a = 0.055, K = 0.6,$ $\beta = 100,$ $h_3 = 0.15.$

The above figure indicates variation of T^* with β for $k=1,\ k=3,\ k=5,\ k=7$ and $k=9$. We observe that for any value of h_f^* dimensionless load carrying capacity T^* increases for an increase in k.

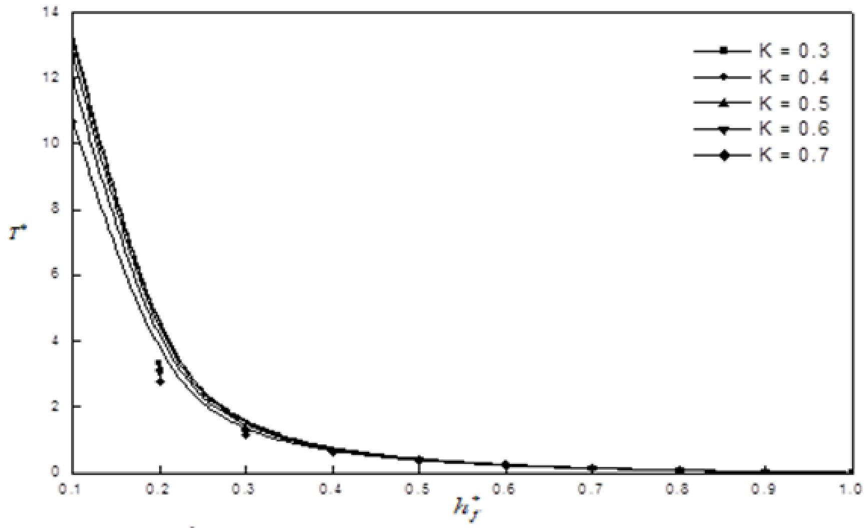

Figure-6: Variation of T^* with h_f^* for different values of K with $k=3, a=0.055, \beta=100, h_f^*=0.15.$

The above figure indicates variation of T^* with h_f^* for $k=0.3,\ k=0.4,\ k=0.5,\ k=0.6$ and $k=0.7$. We observe that for any value of h_f^* dimensionless load carrying capacity T^* decreases for an increase in k.

The dimensionless load carrying capacity increases as ratio of the viscosities increases. Also the dimensionless load carrying capacity increases as the total film thickness increases. The load carrying capacity increases as ratio of the viscosities increases. The dimensionless time increases as the ratio of viscosities increases. Also the dimensionless time decreases when the length of the circular stepped plate decreases.

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