Effect of nanoparticle additives on rough surface cylinder in line contact under TEHL with non-Newtonian lubricant

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Abstract
This paper presents the results of a transient analysis of thermal elastohydrodynamic lubrication (TEHL) of a rough cylinder on a rough flat surface in line contact with non-Newtonian lubricant blended with Al₂O₃ nanoparticles. The simultaneous systems of time-dependent modified Reynolds equation, elasticity equation and energy equation with initial conditions were solved numerically using multigrid multilevel with full approximation technique. In this study, the effect of Al₂O₃ nanoparticle additives, surface roughness and sudden overload on TEHL of two surfaces in line contact were examined. The minimum film thickness and the pressure spike increase slightly with an increase in nanoparticle concentration. For TEHL with Al₂O₃ nanoparticle additives, the film temperature increases very little due to thermal enhancement of nanofluids.

Keywords : Nanoparticle, Transient TEHL, Rough surface, Non-Newtonian lubricant, Multigrid multilevel

1. Introduction

The lubricating film between contacting surfaces is important to the proper functioning of modern machines under severe conditions. Nanoparticle additives have attracted considerable interest in recent years due to their excellent mechanical properties. Dowson and Higginson (Dowson and Higginson, 1959) developed a numerical solution of elastohydrodynamic lubrication in 1959. This concept has been studied in the area ranging from elastohydrodynamic lubrication (EHL) to transient thermoelastohydrodynamic lubrication (TEHL). Newton-Raphson methods were implemented to calculate transient EHL problem under low load conditions (Lee and Hamrock, 1989). Bhattachajee and Dast (Bhattachajee and Dast, 1996) have studied the effect of power law index on the central film thickness, minimum film thickness and load capacity. The modified Reynolds equation and energy equation for non-Newtonian liquid-solid lubricants in line contact have been formulated (Khonsari, et al., 1989) which more significant effects in film thickness, film temperature, load capacity and friction coefficient. Evans and Snidle (Evans and Snidle, 1996) have developed the theoretical analysis of EHL in situations where the nominal oil film thickness is of the same order as the height of roughness asperities on the surfaces in contact region. Mongkolwongrojn, Aiumporsin and Thammakosol (Mongkolwongrojn, et al., 2006) investigated the film temperature and film thickness of liquid-solid lubricants in contact region with non-Newtonian lubricants under sudden overloads and showed the significant effect of solid particles on transient TEHL. Jin, Yang, Cui and Dowson (Jin, et al., 2004 and 2005) have analyzed transient EHL of elliptical contacts with Newtonian lubricant to predict the film pressure and film thickness. The results showed that, transient TEHL are similar to EHL. Mongkolwongrojn, Wongseedakaew and Kennedy (Mongkolwongrojn, et al., 2008) showed the result of a transient analysis EHL in line contact with non-Newtonian lubrication under oscillatory motion and founded that surface roughness, viscosity and power index of non-Newtonian lubricants; have significant effects on film thickness profile and film pressure profile. Wang, Li, Tong and Yang (Wang, et al., 2004) showed that thermal effect can strongly influence the approach and recess points film thickness for involute spur gear with Newtonian
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In this study, the analyses of a rough cylinder on a flat surface under TEHL with non-Newtonian lubricant blended with Al₂O₃ nanoparticle additives have been investigated. Finite difference method and multigrid multilevel method with full approximation scheme techniques were implemented. Transient TEHL with non-Newtonian fluid blended with Al₂O₃ nanoparticle additives were simulated under normal load and overload conditions to obtain the performance characteristics of two surfaces under TEHL.

2. Nomenclature

\( b \) : Semi-width of Hertzian contact under load \( w_0 \)

\( D(X) \) : Dimensionless of combined surface roughness of cylinder and flat surface

\( E_{1/2} \) : Elastic modulus of cylinder (1) and flat surface (2), \( Pa \)

\( E' \) : Effective elastic modulus, \( Pa \)

\( h \) : Lubricant film thickness, \( m \)

\( h_0 \) : Rigid central film thickness, \( m \)

\( H \) : Dimensionless film thickness, \( H = h(R_0/b^2) \)

\( H_0 \) : Dimensionless rigid central film thickness, \( H_0 = h_0(R_0/b^2) \)

\( K \) : Constant in Reynold equation

\( k \) : Thermal conductivity of lubricant, \( W/m \cdot K \)

\( k_0 \) : Thermal conductivity of lubricant at ambient pressure, \( W/m \cdot K \)

\( \bar{k}_p \) : Dimensionless Thermal conductivity of nanofluids

\( K_{T1} \) : Constant in Energy equation

\( K_{T2} \) : Constant in Energy equation

\( K_{T3} \) : Constant in Energy equation

\( m_0 \) : Apparent viscosity at the shear rate of unit, \( Pa \cdot s \)

\( n \) : Power law index

\( P \) : Pressure, \( Pa \)

\( P_0 \) : Maximum Hertzian pressure, \( Pa \)

\( P_H \) : Dimensionless pressure, \( P = p/P_H \)

\( P_H \) : Maximum Hertzian pressure, \( Pa \)

\( R_1 \) : Radii of curvature of cylinder, \( m \)

\( R_2 \) : Radii of curvature of flat surface, \( m \)

\( R_0 \) : Curvature sum, \( 1/R_X = 1/R_1 + 1/R_2 \)

\( S_0 \) : Slip ratio, \( S_0 = (u_2 - u_1)/\bar{u} \)

\( t \) : Time, \( s \)

\( \tilde{t} \) : Dimensionless time, \( \tilde{t} = t(u_0/b) \)

\( T \) : Temperature, \( K \)

\( T_1 \) : Surface temperature of cylinder, \( K \)

\( T_2 \) : Surface temperature of flat surface, \( K \)

\( T_0 \) : Inlet temperature, \( K \)

\( u \) : Film velocity in x direction, \( m/s \)

\( u_1 \) : Cylinder surface velocity, \( m/s \)
\( u_z \): Flat surface velocity, \( m/s \)
\( \bar{u} \): Entrainment velocity, \( m/s, \bar{u} = (u_z + u_0)/2 \)
\( u_0 \): Reference velocity, \( m/s \)
\( u^* \): Dimensionless film velocity, \( u^* = u/\mu_0 \)
\( v \): Film velocity in \( y \) direction, \( m/s \)
\( x \): Coordinate, \( m \)
\( X \): Dimensionless coordinate, \( X = x/b \)
\( W_Z \): Transient load, \( N/m \)
\( z \): Coordinate, \( m \)
\( Z \): Dimensionless coordinate, \( Z = z/h \)
\( Z_1 \): Viscosity-Pressure index
\( \theta \): Dimensionless film temperature, \( \theta = T/T_0 \)
\( \theta_1 \): Dimensionless cylinder surface temperature, \( \theta_1 = T_1/T_0 \)
\( \theta_2 \): Dimensionless flat surface temperature, \( \theta_2 = T_2/T_0 \)
\( \mu \): Equivalent viscosity, \( Pa \cdot s \)
\( \bar{\mu} \): Dimensionless equivalent viscosity, \( \bar{\mu} = \mu/\mu_0 \)
\( \mu_0 \): Inlet viscosity, \( Pa \cdot s \)
\( \tau \): Shear stress of lubricant, \( Pa \)
\( \rho \): Density of lubricant, \( kg/m^3 \)
\( \rho_0 \): Inlet density of lubricant, \( kg/m^3 \)
\( \rho_p \): Inlet density of nanoparticles, \( kg/m^3 \)
\( \bar{\rho} \): Dimensionless density of nanofluid
\( \beta \): Coefficient of thermal expansively, \( 1/K \)
\( \gamma \): Viscosity-Temperature coefficient, \( 1/K \)
\( \phi \): Volume fraction of nanoparticles

3. Governing equations

The governing equations; modified Reynolds equation, elasticity equation, and energy equation for transient thermal elastohydrodynamic lubrication of rough surfaces in line contact have been formulated. The finite difference method and multigrid multilevel with full approximate have been implemented to obtain the film pressure profile, film temperature profile and film thickness profile.

The equation of viscosity can be expressed using relationship between shear stress and shear rate of non-Newtonian fluids. The model of viscosity in this work can be approximated as a power-law viscosity model.

\[
\tau_{xz} = \mu^* \frac{\partial u}{\partial z} \quad \text{and} \quad \tau_{yz} = \mu^* \frac{\partial v}{\partial z} \tag{1}
\]

where the equivalent viscosity

\[
\mu^* = m_0 \left[ \left( \frac{\partial u}{\partial z} \right)^2 + \left( \frac{\partial v}{\partial z} \right)^2 \right]^{(n-1)/2} \tag{2}
\]

3.1 Time-dependent modified Reynolds equation

The time-dependent dimensionless modified Reynolds equation with non-Newtonian lubricant can be written (Khonsari, et al., 1989):

\[
\frac{\partial}{\partial X} \left( \rho H \frac{\partial p}{\partial X} \right) = K \left\{ \frac{\partial}{\partial X} \left( \bar{\rho} H \right) + \left( \frac{S_0}{2} \right) \frac{\partial}{\partial X} \left( \bar{\rho} H \left( 1 - 2 \frac{\bar{\mu}_e}{\bar{\mu}_e^*} \right) \right) \right\} \tag{3}
\]
where

\[
K = \frac{u_0\mu_0 R_0^2}{b^3 P_H} \tag{4}
\]

\[
\varepsilon = \tilde{\rho} H^3 \left( \frac{1}{\mu_{e2}} - \frac{\tilde{\mu}_{ei}}{\mu_{e1}} \right) \tag{5}
\]

\[
\frac{1}{\tilde{\mu}_{ei}} = \int_0^{Z_i} \frac{1}{\mu^*} dZ, i = 0,1,2 \tag{6}
\]

Boundary conditions are

\[
X = X_{\text{inlet}}, P = 0 \quad ; \quad X = X_{\text{exit}}, P = \frac{\partial P}{\partial X} = 0 \tag{7}
\]

The effect of nanoparticles on viscosity can be expressed using Batchelor model (Chandrasekar, et al., 2010) for dilute fluid dispersed with solid sphere nanoparticles. The apparent viscosity in power-law viscosity model needs to include the correction factor for viscosity-pressure-temperature by Roelands (1966) and the correction factor for nanoparticles in the lubricant according to Rylander (Rylander, 1966). The dimensionless apparent viscosity can be written as

\[
\tilde{\mu}^* = \tilde{\mu}_R \tilde{\mu}_S^* \tag{8}
\]

where

\[
\tilde{\mu}_R = (1 + (2.5\phi) + (2.5\phi)^2) \exp \left( \ln(\mu_0) + 9.67 \times (-1 + (1 + 5.1 \times 10^{-9} P_H P)^{21}) - \gamma T_0 (\theta - 1) \right) \tag{9}
\]

\[
\tilde{\mu}_S^* = m_0 \mu_0 R_0 \frac{b^2}{[u_0 R_0^2]^{n-1} \left| \frac{1}{H} \frac{\partial u^*}{\partial Z} \right|^{n-1}} \tag{10}
\]

The dimensionless density of liquid-solid lubricant according by Dowson and Higginson(1966) obeys the following relation

\[
\tilde{\rho} = \frac{\left(1 + \frac{0.6 \times 10^{-9} P_H P}{1 + 1.7 \times 10^{-9} P_H P} \right) \left(1 - \beta T_0 (\theta - 1)\right)}{(1 - \phi) + \frac{\rho}{\rho_0}} \tag{11}
\]

The dimensionless film thickness, including the deformation of rough surfaces under line contact can be written as:

\[
H = H_0 + \frac{X^2}{2} + D(X) - \frac{1}{\pi} \int_{X_{\text{inlet}}}^{X_{\text{exit}}} P(X') \ln |X - X'| dX' \tag{12}
\]

Where $D(X)$ is the dimensionless combined surface roughness of two surfaces with random roughness amplitude distribution.

### 3.2 The load balance equation

The dimensionless load balance equation is

\[
\int_{X_{\text{inlet}}}^{X_{\text{exit}}} P dX - \frac{\pi}{2} = 0 \tag{13}
\]

### 3.3 Energy equation

The time-dependent dimensionless energy equation under line contact can be written as (Mongkolwongrojn, et al., 2006):
\[
\frac{\partial^2 \theta}{\partial Z^2} = K_{T1} \left( \frac{\partial H^2}{k_p} \left( \frac{\partial \theta}{\partial t} + u^* \frac{\partial \theta}{\partial X} \right) \right) - K_{T2} \left( \frac{\mu}{k_p} \left( \frac{\partial u^*}{\partial t} \right) \right) - K_{T3} \left( \frac{\theta H^2}{k_p} \left( \frac{\partial P}{\partial t} + u^* \frac{\partial P}{\partial X} \right) \right)
\]

(14)

where

\[
K_{T1} = \frac{u_0 \rho_0 c_p b^3}{k_0 R_0^2}
\]

(15)

\[
K_{T2} = \frac{\mu_0 u_0^2}{k_0 T_0}
\]

(16)

\[
K_{T3} = \frac{\beta u_0 b^3 p_H}{k_0 R_0^2}
\]

(17)

The boundary conditions of the energy equation introduced by Carslaw and Jaeger (1959)

\[
\theta_{1/2} = 1 \pm \frac{k_0 R_0}{\pi \rho_1 c_{p1/2} k_1/2 b^3 u_0 \left( 1 - \frac{\omega}{2} \right)} \int_{X_{inlet}}^{x_{exit}} \frac{\partial \theta}{\partial Z} dX'
\]

(18)

\[
\theta(X_{inlet}) = 1
\]

(19)

The dimensionless thermal conductivity of nanofluids is given by Xuan and Roetzel (Xuan and Roetzel, 2000) and Wang and et al. (Wang, et al., 2002)

\[
k_p = \frac{k_p + 2k - 2\Phi(k - k_p)}{k_p + 2k + \Phi(k - k_p)}
\]

(20)

Where \( k_p \) is the thermal conductivity of nanoparticles, \( W/m \cdot K \).

The thermo-physical properties of nanofluids in this research work are assumed for well dispersed of nanoparticles within the base lubricant and can be written as (Chandrasekar, et al., 2010):

\[
\overline{\rho c_p} = (1 + \Phi) + \frac{\Phi \rho_p c_{pp}}{\rho c_p}
\]

(21)

4. Numerical Procedure

The time-dependent modified Reynolds equation, elasticity equation and energy equation of TEHL with non-Newtonian lubricants were calculated using multigrid multilevel with full approximation scheme technique. The convergence criteria of pressure, temperature, and hydrodynamic load are adopted as follows:

\[
\sum_{i=0}^{N} |p_i^{k+1} - p_i^{k}| / \sum_{i=0}^{N} p_i^{k+1} \leq 0.0001
\]

(22)

\[
\sum_{i=0}^{N} |\theta_i^{k+1} - \theta_i^{k}| / \sum_{i=0}^{N} \theta_i^{k+1} \leq 0.0001
\]

(23)

Where \( k^* \) is the number of iteration cycles.
\[ \int_{x_{\text{inlet}}}^{x_{\text{exit}}} P \, dx \leq 0.0001 \]  

(24)

During each time interval, the modified Reynolds equation, elasticity equation, and energy equation were calculated simultaneously under boundary conditions and initial conditions to obtain film pressure profile, film thickness profile and film temperature profile. In this paper, \( x_{\text{inlet}} \) and \( x_{\text{exit}} \) were obtained from the calculation as; \( x_{\text{inlet}} = -5.0 \) and \( x_{\text{exit}} = +2.0 \).

5. Results and discussion

The mechanical properties of the two surfaces, lubricant and nanoparticle used in this analysis are given in table 1 and table 2. In this research, a line contact between steel cylinders on a flat steel surface under TEHL with non-Newtonian lubricant blended with Al\(_2\)O\(_3\) nanoparticles have been examined through numerical simulation. In order to illustrate the effect of Al\(_2\)O\(_3\) nanoparticle additives on transient TEHL of rough surfaces under sudden overloads with non-Newtonian lubricant were investigated as;

1. EHL and TEHL with non-Newtonian lubricant and non-Newtonian lubricant blended with Al\(_2\)O\(_3\) nanoparticles as shown in Fig. 1 and Fig. 2.

2. Smooth surfaces with non-Newtonian lubricant and non-Newtonian lubricant blended with Al\(_2\)O\(_3\) nanoparticles under load 200 kN/m at steady state condition as shown in Fig. 3, Fig. 4, and Fig. 5.

3. Rough surfaces with non-Newtonian lubricant and non-Newtonian lubricant blended with Al\(_2\)O\(_3\) nanoparticles under load 200 kN/m at steady state condition as shown in Fig. 6, Fig. 7, Fig. 8, Fig. 9 and Fig. 10.

4. TEHL for non-Newtonian lubricant and non-Newtonian lubricant blended with Al\(_2\)O\(_3\)nanoparticles under sudden load change from 200 kN/m to 240 kN/m at transient condition as shown in Fig. 11(a), (b) and (c).

| Property | Value |
|----------|-------|
| Elasticity modulus, GPa | 205 |
| Density, kg/m\(^3\) | 7850 |
| Poisson’s ratio | 0.30 |
| Specific heat, J/(kg-K) | 475 |
| Thermal conductivity, W/(m-K) | 50.20 |
| Combined surface roughness amplitude \( (R_{rms}) \), \( \mu m \) | 0.1 |
| Average velocity, m/s | 1.92 |
| Slip Ratio | 0.75 |
| Inlet density of the lubricant, kg/m\(^3\) | 892.80 |
| Inlet viscosity of the lubricant, Pa-s | 0.195 |
| Viscosity-Pressure index \( (Z_1) \) | 0.5685 |
| Specific heat of the lubricant, J/(kg-K) | 1870 |
| Thermal conductivity of the lubricant, W/(m-K) | 0.126 |
| Inlet temperature of the lubricant, K | 313.15 |
| Power law index \( (n) \) | 0.985 |

| Property | Alumina |
|----------|---------|
| Density, kg/m\(^3\) | 3890 |
| Specific heat, J/(kg-K) | 729 |
| Thermal conductivity, W/(m-K) | 36 |

Table 2 Physical property of alumina (Al\(_2\)O\(_3\)) (Javadiand Tadari, 2006)
Fig. 1 Film pressure profile under EHL and TEHL for smooth surface at load 800 kN/m at steady state condition.

Fig. 2 Film thickness profiles under EHL and TEHL for smooth surface at load 800 kN/m at steady state condition.

Fig. 3 Film pressure, film thickness and film temperature profiles under TEHL with non-Newtonian lubricant for smooth surface at load 200 kN/m.
For smooth surface at load 800 kN/m, average velocity at 1.92 m/s and slip ratio at 0.75, the film pressure profiles and film thickness profiles for EHL and TEHL with non-Newtonian lubricant and with non-Newtonian lubricant blended with Al₂O₃ nanoparticles at steady state are shown in Fig. 1 and Fig. 2 respectively. In Fig. 1, for TEHL with non-Newtonian lubricant and for TEHL with non-Newtonian lubricant blended with Al₂O₃ nanoparticles, the pressure spikes are higher than the pressure spikes under EHL for non-Newtonian lubricant. A small pressure spike appears for EHL with non-Newtonian lubricant because temperature of fluid film has significantly affected on viscosity and density of the lubricant. The film temperature for TEHL line contact with non-Newtonian lubricant is higher than the film temperature for EHL result in higher pressure spike for TEHL when compared with the pressure spike for EHL. For TEHL with non-Newtonian lubricant blended with Al₂O₃, the film thickness is larger slightly than the film thickness for TEHL with non-Newtonian lubricant because nanoparticles increase film viscosity. In the simulation results, the film thickness for EHL is larger than that for TEHL due to the decreasing in lubricant viscosity as shown in Fig. 2. It can be observed that addition of nanoparticles increases the minimum film thickness in the contact region. For EHL, the minimum film thickness for non-Newtonian lubricant, non-Newtonian lubricant blended with Al₂O₃ 1 % and non-Newtonian lubricant blended with Al₂O₃ 2 % are 1.80\mu m, 1.83\mu m and 1.86\mu m respectively. For TEHL, the minimum film thickness for non-Newtonian lubricant, non-Newtonian lubricant blended with Al₂O₃ 1 % and non-Newtonian lubricant blended with Al₂O₃ 2 % are 1.00\mu m, 1.03\mu m and 1.06\mu m respectively.

Fig. 4 Film pressure, film thickness and film temperature profiles under TEHL for smooth surface at load 200 kN/m. with non-Newtonian lubricant blended with Al₂O₃ 1 %.

Fig. 5 Film thickness and film temperature profiles under TEHL for smooth surface at load 200 kN/m with non-Newtonian lubricant blended with Al₂O₃ 0 %, 0.50 %, 0.75 %, and 1 %.
For smooth surfaces under TEHL at 200 kN/m load, at average velocity of 1.92 m/s and slip ratio 0.75, film pressure profile, film thickness profile and film temperature profile with non-Newtonian lubricant (n = 0.985) are shown in Fig. 3. It can be seen that both the maximum film pressure and the maximum film temperature increase to its maximum value near the center in the contact region, the minimum film thickness occurs near the exit in the contact region. The maximum film pressure, the minimum film thickness and the maximum film temperature are 0.52 GPa, 1.83 μm and 92.35°C respectively. Figure 4 illustrates the effect of Al₂O₃ nanoparticles on film pressure, film thickness and film temperature under TEHL. For non-Newtonian lubricant blended with Al₂O₃1.0 % nanoparticles, the maximum film temperature is 92.40°C and the minimum film thickness is 1.87 μm as shown in Fig. 4. In Fig. 5, for TEHL with non-Newtonian lubricant, the maximum film temperature is 92.39°C and the minimum film thickness is 1.83 μm. Therefore, the addition of nanoparticles increases in film thickness due to the increasing of viscosity. The film temperature for TEHL non-Newtonian lubricant blended with nanoparticles is only little higher when compared with the film temperature for TEHL with non-Newtonian lubricant. The increasing of temperature in nanofluids can be reduced for high value of \( \rho c_p \) but the heat generated is slightly large in nanofluids due to slightly large value of fluid viscosity when compared with that for non-Newtonian lubricant. Therefore, the film temperature increases only little for non-Newtonian lubricant with Al₂O₃ nanoparticle. For rough surface (\( R_{rms} = 0.10 \mu m \)) at steady state condition, the influence of roughness on film pressure, film thickness and film temperature are found to be significant as shown in Fig. 6 and Fig. 7.

![Fig. 6 Film pressure, film thickness and film temperature profiles at applied load 200 kN/m for rough surface \( R_{rms} = 0.10 \mu m \) under TEHL with non-Newtonian lubricant at steady state condition.](image1)

![Fig. 7 Film pressure under applied load 200 kN/m with smooth surface and rough surface \( R_{rms} = 0.10 \mu m \) under TEHL for non-Newtonian lubricant and non-Newtonian lubricant blended with Al₂O₃ nanoparticles.](image2)
The surface roughness reduces flow area. Therefore, the pressure rises to very high value caused the fluctuating of film pressure. The results show that the minimum film thickness for smooth surface is 1.83 µm but for rough surface $R_{rms} = 0.10 \mu m$, the minimum film thickness reduces to 1.66 µm. It can be seen that the minimum film thickness decreases with the increasing in roughness amplitude. For smooth surface under TEHL with non-Newtonian lubricant at steady state condition, the maximum film pressure is 0.52 GPa near the central region of the contact area but for rough surface under TEHL with non-Newtonian lubricant blended with $Al_2O_3$ 2.5% nanoparticles, film pressure fluctuate in the contact region and the maximum pressure is 0.54 GPa as shown in Fig. 8. For rough surface under TEHL at steady state condition, the film pressure for non-Newtonian lubricant blended with nanoparticles is larger than the film pressure for non-Newtonian lubricant due to the increasing of viscosity in nanofluids.

![Fig. 8 Effect of $Al_2O_3$ 2.5 % nanoparticle additives on film pressure profile, film thickness profile and film temperature profile under TEHL at applied load 200 kN/m at steady state condition.](image)

Figure 9 shows that for TEHL with non-Newtonian lubricant blended with nanoparticles, the film thickness is significantly larger than the film thickness for non-Newtonian lubricant. For smooth surface TEHL with non-Newtonian lubricant blended with $Al_2O_3$ 1.0 % nanoparticles, the minimum film thickness is 1.86 µm when compared with the minimum film thickness of 1.83 µm for non-Newtonian lubricant. For rough surface, TEHL with non-Newtonian lubricant blended with $Al_2O_3$ 2.5 % nanoparticles; the minimum film thickness is 1.74 µm that is larger than the minimum film thickness of 1.66 µm for non-Newtonian lubricant.

For rough surfaces under TEHL with non-Newtonian lubricant blended with $Al_2O_3$ 2.5 % nanoparticles, the maximum film temperature is 96.54°C when compared with the maximum film temperature of 96.35°C for non-Newtonian lubricant as shown in Fig. 10. For smooth surface under TEHL with non-Newtonian lubricant blended with $Al_2O_3$ 1 % nanoparticles, the maximum film temperature is 92.40°C when compared with the maximum film temperature of 92.39°C for non-Newtonian lubricant. For both smooth and rough surfaces under TEHL, the minimum film thickness and the maximum film temperature for non-Newtonian lubricant with $Al_2O_3$ nanoparticles are slightly higher than for non-Newtonian lubricant. Since the values of specific heat and thermal conductivity of nanoparticles are large when compared with that for non-Newtonian lubricant. Thermal characteristics of nanoparticles such as density, specific heat, thermal conductivity and viscosity have major influence on film temperature, film pressure and film thickness in TEHL.
Fig. 9 Effect of Al₂O₃ nanoparticle additives on film thickness profiles under applied load 200 kN/m at steady state condition.

Fig. 10 Effect of Al₂O₃ nanoparticle additives on film temperature profiles under applied load 200 kN/m at steady state condition.
Fig. 11 Transient response of maximum film pressure, minimum film thickness and maximum film temperature under load change from 200 kN/m to 240 kN/m.
The characteristics of two rough surfaces in line contact under transient TEHL were investigated when subjected to a sudden overload of 20% from normal load at 200 kN/m and overload duration of 1.0 ms with non-Newtonian lubricant and with non-Newtonian lubricant blended with Al$_2$O$_3$ 2.0% nanoparticles as shown in Fig. 11(a), (b) and (c). The maximum film pressure for non-Newtonian lubricant and for non-Newtonian lubricant blended with nanoparticles increase to the peak maximum film pressure in approximately 0.2 ms and then the film pressure for both cases decrease rapidly followed to the normal applied load as shown in Fig. 11(a). The maximum film pressure for non-Newtonian lubricant is almost the same as the maximum film pressure for non-Newtonian lubricant blended with nanoparticles. During sudden overload, the minimum film thickness decreases rapidly with an increase in overload and then, the film thickness increases to the minimum film thickness under normal load condition due to squeeze effect. The minimum film thickness for non-Newtonian lubricant blended with Al$_2$O$_3$ 2.0% nanoparticles and for non-Newtonian lubricant approximately equal to 1.79 µm and 1.73 µm respectively as shown in Fig. 11(b). Under sudden overload conditions, both the maximum film temperature for non-Newtonian lubricant and the maximum film temperature for non-Newtonian lubricant blended with Al$_2$O$_3$ 2.0% nanoparticles are 105.81°C as shown in Fig. 11(c). For non-Newtonian lubricant, the maximum film temperature is almost the same as the film temperature for non-Newtonian lubricant blended with Al$_2$O$_3$ 2.0%. The minimum film thickness and the maximum film pressure for non-Newtonian lubricant with nanoparticles are slightly larger than those for non-Newtonian lubricant because of the thermal enhancement on specific heat, thermal conductivity and viscosity of nanofluids.

6. Conclusions

The transient TEHL of two parallel rough surface cylinders line contact was solved to obtain film pressure, film thickness and film temperature. The lubricant is non-Newtonian fluid blended with Al$_2$O$_3$ nanoparticle additives with various volume concentrations. The TEHL characteristics under normal load and sudden overload conditions were examined. The following can be concluded as:

1. Under EHL, line contact and smooth surface, maximum film pressure reaches its maximum near the center in the contact region but for TEHL with non-Newtonian lubricant and non-Newtonian lubricant blended with Al$_2$O$_3$ nanoparticles, the maximum film pressure reaches its maximum near the exit in the contact region. Pressure spike for non-Newtonian lubricant is almost the same as pressure spike for non-Newtonian lubricant blended with Al$_2$O$_3$ nanoparticles.

2. Under TEHL line contact, the addition of Al$_2$O$_3$ nanoparticles increases significantly the film thickness but the addition of Al$_2$O$_3$ nanoparticles has almost no effect on film pressure and film temperature.

3. In the case of rough surface, the addition of Al$_2$O$_3$ nanoparticles has no effect on both pressure spike and film temperature.

4. For transient TEHL, line contact and smooth surface under sudden overloads, higher film thickness for non-Newtonian lubricant blended with Al$_2$O$_3$ nanoparticles when compared with film thickness for non-Newtonian lubricant.

Recently, nanoparticles exhibit good tribological properties to protect the solid surface of machine parts. This study has shown that nanoparticles can have significant effect on thermal elastohydrodynamic performance, particularly under transient conditions.

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