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Simulating tribological characteristics of Palm Methyl Ester (PME) lubricated contact

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Abstract. The study simulates the lubricant Stribeck curve for Palm Methyl Ester (PME) by coupling modified Reynolds solution with Greenwood and Tripp's rough surface contact model. The predicted lubricant Stribeck curves for PME is validated with measured data from a pin-on-disc tribometer. The Reynolds equation is modified to accommodate for the lubricant properties of PME (e.g. viscosity and density), which is mathematically described using Gibbs energy additivity approach. Solving the modified Reynolds equation would then provide the fluid film formation behaviour of PME, such as the contact pressure and film thickness. These fluid film parameters are then used as the input to determine the boundary and viscous friction of the investigated lubricated contact using Greenwood and Tripp's rough surface contact model. The proposed mathematical solution correlates well with experimental data and is shown to be capable of predicting lubricant Stribeck, capturing the frictional behavior for the whole range of lubrication regimes. The findings of the present study prepare for a mathematical foundation to further explore the use of biodiesel as an alternative biodegradable lubricant to mineral-based ones.

1. Introduction

The global energy demand is predicted to increase significantly from 557 quadrillion BTU in the year 2014 to 703 quadrillion BTU in the year 2040. This could lead to environmental concerns related to greenhouse gas (GHG) emissions [1, 2]. It is now required that vehicle manufacturers develop more efficient components and system to counter such concern. One of the ways to improve efficiency of vehicles and at the same time rectify the concerns related to emissions of GHG is to have a better lubrication system, which is less dependent on mineral oil-based lubricant. A type of biodegradable lubricant that could be considered is biodiesel, namely the mono-alkyl esters of vegetable oils or animal fats or triacylglycerol-containing feedstock [3]. Biodiesels can be derived from many sources either from vegetable oil or animal fat such as palm oil, soybean oil, coconut oil and canola oil [4, 5]. Biodiesel is known to have low or no sulfur content with no aromatics content, high flash point, good lubricity and biodegradability [2, 6]. Usage of biodiesel in compression ignition engine is also known to be able to significantly reduce most regulated exhaust emissions [7].

Friction behavior of a lubrication system can be typically assessed using the classical lubricant Stribeck curve [8]. There are four main lubrication regimes in a Stribeck curve, namely hydrodynamic lubrication (HL), elastohydrodynamic lubrication (EHL), mixed lubrication (ML) and boundary lubrication (BL) regimes. Transitions between these lubrication regimes are affected by the relative sliding speed between the rubbing opposing surfaces, applied normal load, contact geometry and also lubricant properties. Stribeck curves are usually measured using tribometers [8], which proved to be costly, with limited predictive tools available in generating such curve, especially for biodiesel [9]. Therefore, the current study intends to simulate the lubricant Stribeck curve and also to predict frictional behaviour of palm oil derived biodiesel or palm methyl ester (PME). The simulation is conducted by solving for the Reynolds equation and Greenwood and Tripp's rough surface contact model. To validate the derived mathematical model, a pin-on-disk type tribometer is used to measure the friction generated by PME.

2. Methodology

2.1 Mathematical approach

2.1.1 Modified Reynolds equation

Reynolds equation is used to predict fluid film formation of PME. The equation relates sliding velocity of two surfaces, contact geometry, lubricant properties (density and viscosity) and applied normal load with lubricant fluid film formation properties, such as contact pressure distribution and lubricant film thickness. The contact pressure distribution is governed by the partial differential equation along the lubricated conjunction. The modified Reynolds equation is given as follow [10]:

$$\frac{\partial}{\partial x}\left(\frac{h^3}{\eta}\frac{\partial P}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{h^3}{\eta}\frac{\partial P}{\partial y}\right)=12\,\chi\left\{\frac{\partial}{\partial x}[(U)\rho h]+\frac{\partial}{\partial y}[(V)\rho h]+\frac{\partial(\rho h)}{\partial t}\right\} \tag{1}$$

Where U represents the entrainment motion along the sliding direction and V is the speed of lubricant side leakage. The term χ is introduced to the modified Reynolds equation as a correction factor in considering methyl ester type lubricants. This term will be determined by correlating the simulation results with experimentally measured data. The film profile, h is determined using the following equation:

$$h = h_o + h_s + \delta \tag{2}$$

Where h_o refers to the initial undeformed central separation gap, h_s refers to the contact geometry and δ refers to the surface deflection as a result of generated fluid film contact pressure. The deflection is computed as given in reference [20]. For biodiesel, Chum-in et al. [11] and Phankosol et al. [12] showed that the lubricant rheological properties of methyl ester (viscosity and density) can be described using Gibbs energy additivity approach. This viscosity and density relation with pressure and temperature can be calculated using the average carbon number (z_{ave}) and the average number of double bonds (nd_{ave}). The relevant equations are given below for the dynamic viscosity and the density:

$$\ln\eta = \ln\eta_o + \frac{P}{P_{atm}}\left[0.0006 - 0.000011.z_{ave} - 0.00022.nd_{ave} + \frac{0.0415 + 0.0103.z_{ave} + 0.054.nd_{ave}}{T}\right] \tag{3}$$

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$$\ln \rho = \ln \rho_o + \frac{P}{P_{atm}}\left[0.000228 - 0.0000026.z_{ave} - 0.000006.nd_{ave} + \frac{0.003171.z_{ave} + 0.00223.nd_{ave} - 0.0416}{T}\right] \tag{4}$$

The above-mentioned Reynolds equation is then solved numerically based on the method described in reference [13].

2.1.2 *Friction modelling*

The solution from the modified Reynolds equation provides the information with relation to the contact pressure distribution and the lubricant film thickness. These are then used as the input to predict the friction force along the tribological conjunction lubricated with PME. The total friction is assumed to consist of boundary friction (F_b) and viscous friction (F_v) components. Boundary friction is due to a direct surface asperity contact interaction while lubricant shearing leads to viscous friction along a lubricated conjunction [14]. Hence, the total friction can be expressed as follow:

$$F_f = F_b + F_v \tag{5}$$

The viscous friction force can be computed as:

$$F_V = \int \tau_v \, dA = \sum \tau_v \, (A - A_a) \tag{6}$$

Where τ_v is the viscous shear stress ($\tau_v = \frac{\eta_o U}{h}$). The boundary shear can then be calculated using:

$$F_b = \sum A_a \, (\tau_b) \quad ; \quad \tau_b = \tau_o + m\left(\frac{W_a}{A_a}\right) \tag{7}$$

Where τ_o is the Eyring shear stress of the lubricant and m is the pressure coefficient of the boundary shear strength. The term W_a is the load carried by the asperities, A is the apparent contact area and A_aa is the actual contact area. These parameters are determined using Greenwood and Tripp's rough surface contact model [14].

2.2 *Friction measurement*

In order to characterize the frictional properties of PME, an experimental friction test has been conducted under pure sliding motion that covers the range of three main lubrication regimes such as, EHL, ML and BL. This test is carried out using a tribometer pin-on-disc machine. A stainless-steel wear disc is rotated against a stationary cast iron pin with spherical cap of 10 mm diameter. The friction tests are conducted under room temperature condition. Throughout the test, the wear disc and pin are loaded with a constant normal load of 20 N, where the wear disc is rotated at a speed ranging from 2000 rpm to 20 rpm. The wear track is set at 20mm, giving sliding velocities of wear disc between 4.2ms^{-1} to 0.042 ms^{-1}. The friction test is conducted for three minutes for each of the set speed, which is in accordance to the method proposed in reference [5].

2.3 *Biodiesel production*

Transesterification process is used to derive PME from commercially available palm oil. This process requires the chemical reaction between triglyceride reactants and short-chain alcohol at sufficiently high temperature in the presence of acid, alkaline or lipase catalysts. By the end of this process, methyl esters are obtained with crude glycerol as the by-product. Among the types of catalysts, alkaline catalyst is a better option when high yield of the biodiesel is required [15]. The production of PME is based on the method proposed by Hamdan et al. [5]. Table 1 shows the measured rheological properties of the produced PME at the simulated room temperature of 25°C.

Table 1. Experimentally measured rheological properties of Palm Methyl Ester (PME).

Type of Methyl Ester	Bulk viscosity, η_o (mPa.s)	Bulk density, η_o (g/m^3)
PME	5.1459	873.0

3. Result and discussion

Using the derived numerical scheme for solving Modified Reynolds equation mention earlier, the frictional behaviour for the pin-on-disc tribometer tribological conjunction lubricated with PME is simulated. Figure 1 shows the simulated Stribeck curve for PME lubricated conjunction. By using χ value of 53, the simulated curve is depicted to correlate well with experimental data. It is to note that the simulated curve is capable of capturing the transitions of lubrication regimes with R^2 equal 88.8%, following the ones observed experimentally with R^2 equal 86.6%.

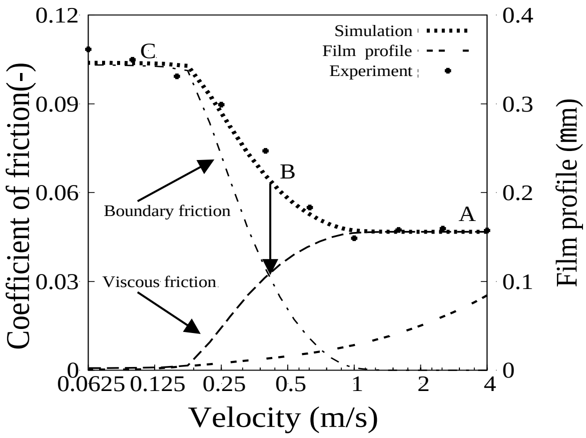
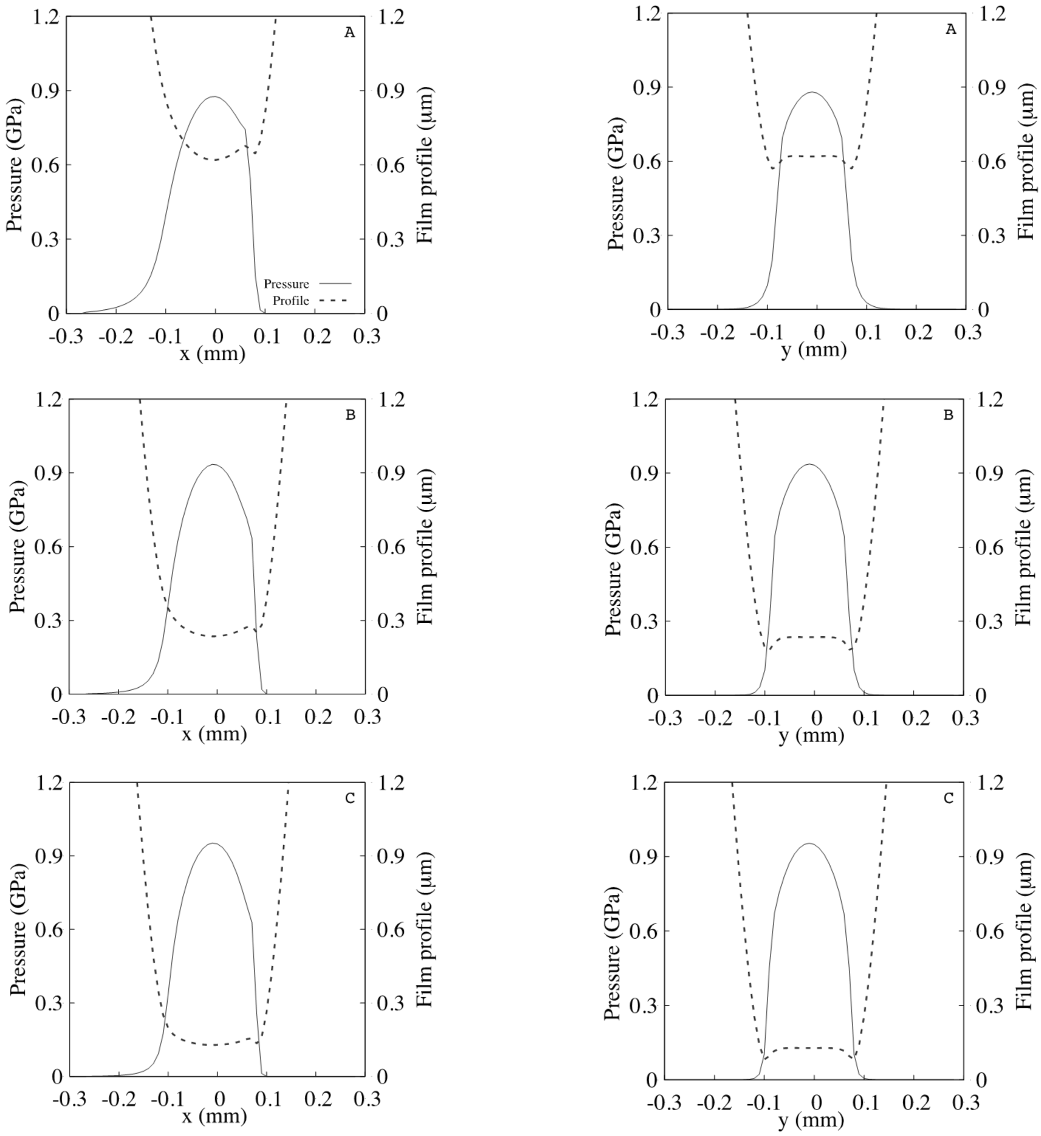


Figure 1. Comparison of simulated and experimentally measured Stribeck curve for PME

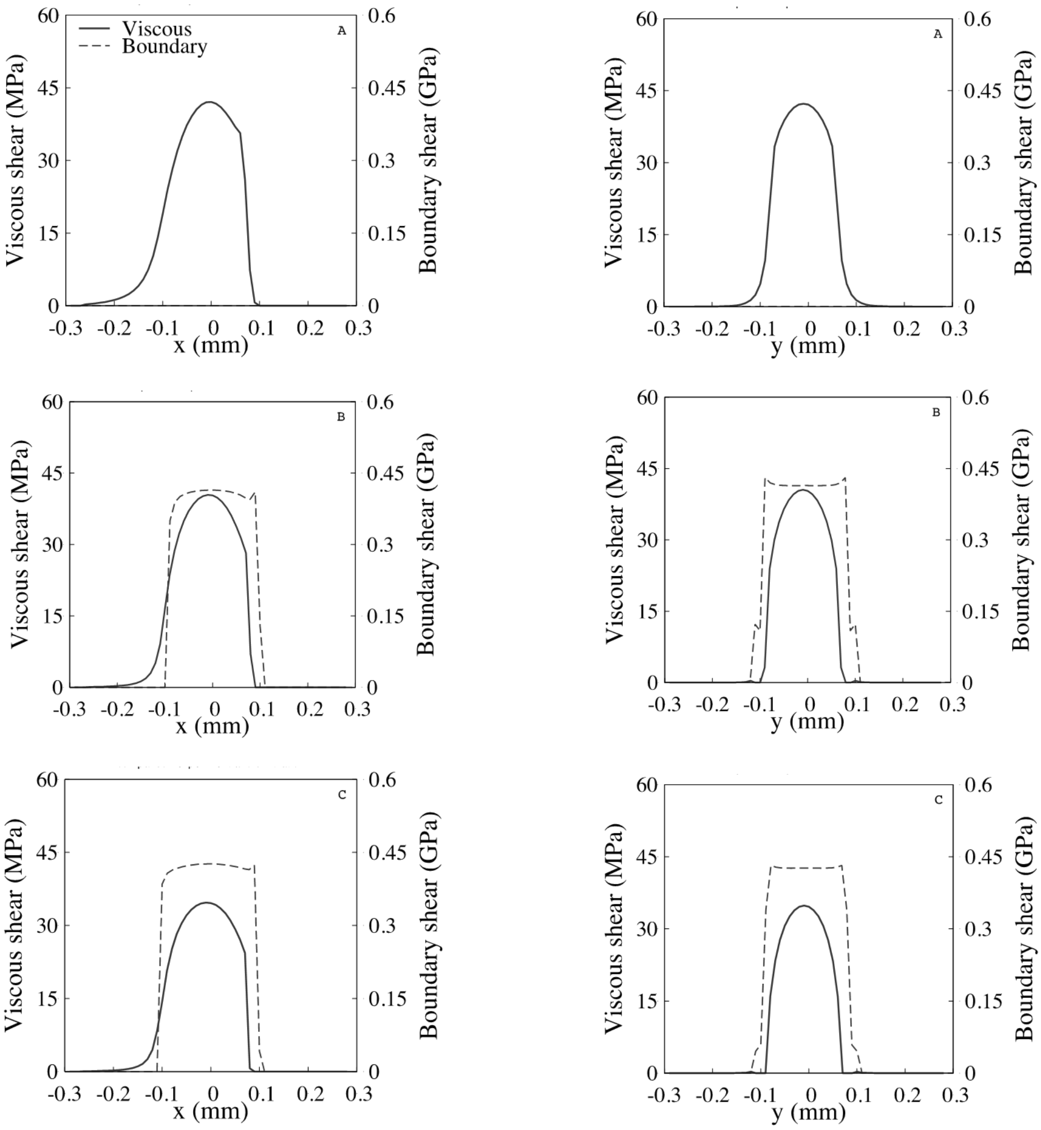
To investigate further the simulated properties of the PME lubricated conjunction, Figure 2 shows the contact pressure distribution and contact film profile for the investigated lubrication system. Three different sliding velocities was chosen at locations A, B and C (refer Figure 1), representing the sliding velocity at 4 ms^{-1}, 0.4 ms^{-1} and 0.1 ms^{-1}, respectively. The contact pressure resembles the Hertzian contact pressure at location A with the contact pressure being in the range of GPa but with a secondary peak. As the magnitude of film profile becomes smaller at location B and C, the probability of having surface asperity contact increases between the rubbing surfaces. Thus, this could lead to boundary friction.



(a) X-axis (b) Y-axis

Figure 2. Distributed contact pressure and fluid film profile simulated for PME at three different sliding velocities at locations A, B and C (refer Figure 1)

Figure 3 shows that the frictional property at location A is dominated by viscous shearing of PME fluid film with no boundary component observed. This is synonymous to the lubrication regime indicated in Figure 1 at location A, where fluid film lubrication of elastohydrodynamic nature is expected. It is observed that shear properties at location B indicate a fair mix of boundary shear and viscous shear components. This corroborates with the transition of lubrication regime, which is expected to occur as being highlighted in Figure 1, giving rise to the ML regime. Finally, at location C, the simulated contact shows that the boundary shear component begins to significantly dominate over the viscous shear component, indicating BL regime. By reviewing the shear properties of these selected locations, it is demonstrated that the proposed numerical scheme is capable of capturing its tribological behaviour at various lubrication regimes for the investigated PME lubricated contact, similar to the measured regimes given in Figure 1.



(a) X-axis (b) Y-axis

Figure 3. Simulated viscous shear and boundary shear of PME at three different sliding velocities at locations A, B and C (refer to Figure 1).

4. Conclusion

A lubrication Stribeck curve has been simulated and validated with measured friction using a pin-on-disc tribometer. The proposed mathematical tool is demonstrated to be capable of capturing the lubrication behavior of PME using a correction factor, χ. The present study sets in place a mathematical foundation to further investigate the relevance of the introduced correction factor, χ in the Reynolds equation for biodiesel derived from other feedstocks with varying fatty acid compositions. This is in hope that the correction factor could then be correlated to the average carbon number (z_{ave}) and average number of double bonds (nd_{ave}), providing an effective predictive tool to better explore the use of biodiesel as an alternative lubricant.

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