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Short Communication

On the reduction of heat generation in lubricants using microscale additives

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ABSTRACT

This work is concerned with the identification of microscale properties of additives for base lubricants in order to reduce heat generation. An application of specific interest is the thin film lubrication of bearings. In order to isolate the thermal effects in the fluid film, we assume that the bearing and housing are insulated. A relation for the temperature rise in the fluid film between the bearing and housing is developed as a function of the rotation speed, the viscosity of the base lubricant and properties of the additives, namely (1) their viscosities, (2) their mass density, (3) their heat capacity and (4) volume fraction, which are free design parameters. Nondimensionalization of the developed relations allows for the construction of a design parameter space which can identify desirable parameter combinations that deliver a target value of heat generation reduction and simultaneously deliver the appropriate overall viscosity of the modified lubricant mixture.

1. Simple fluid profiles

The "functionalization" or "tailoring" of solid and fluid materials by the addition of fine-scale material is a process that has a long history in engineering. The usual approach is to add particulates that possess a desired property to modify (enhance) a base (binder) material. There exist several methods to predict the resulting effective properties of materials with embedded particulates, dating back to well over a century to, for example, Maxwell (1867, 1873), Rayleigh (1892) and, specifically for effective viscosity characterizations, to Einstein (1906, 1911). For a thorough analysis of many of such methods, see Torquato (2001), Jikov, Kozlov, and Olenik (1994), Hashin (1983) and Nemat-Nasser and Hori (1999) for mechanics oriented treatments and (Ghosh, 2011a; Ghosh & Dimiduk, 2011b; Zohdi & Wriggers, 2008) for computational aspects. For a recent review of general effective viscosity models, see Abedian and Kachanov (2010) and Sevostianov and Kachanov (2012). We note that a wide range of additives are possible to modify lubricant properties; for example, see Wu, Tsui, and Liu (2007) for extensive experiments.

Our interest in this work is to identify material parameters for additives in order to modify lubricant properties with the goal of reducing heat generation in fluid films. An application of specific interest is the lubrication of bearings. Since the clearance between the bearing and housing are extremely small, the fluid flow profile is assumed to be spatially linearly-varying (radially, see Fig. 1, driven by the bearing, assuming concentric circular Couette flow)

$$v_x = \frac{R\omega}{\delta} y, \tag{1.1}$$

where δ is the film thickness and the other velocity components are zero, $v_y = v_z = 0$. We focus only on the viscous stresses, and ignore all other contributions, thus the stress tensor reduces to (assuming a Newtonian fluid)

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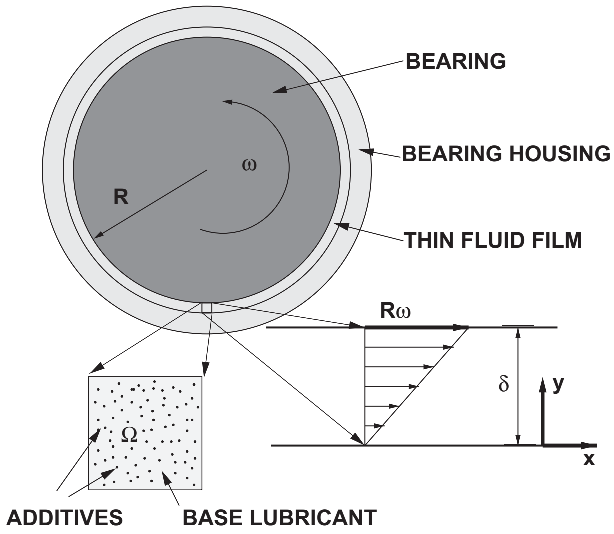

Fig. 1. Idealized fluid profile in a thin film.

$$\boldsymbol{\sigma} = 2\mu^*\boldsymbol{D} = \begin{bmatrix} 0 & \mu^*\frac{R\omega}{\delta} & 0 \\ \mu^*\frac{R\omega}{\delta} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \tag{1.2}$$

where $\boldsymbol{D} = \frac{1}{2}(\nabla_{\boldsymbol{x}}\boldsymbol{v} + (\nabla_{\boldsymbol{x}}\boldsymbol{v})^T)$ and $\boldsymbol{\sigma}$ is Cauchy stress.

2. Heat generation

In order to focus on the properties of the lubricant, we assume that there is no heat transfer between the lubricant and the bearing and bearing housing. The key quantity of interest here is the amount of heat generated, calculated from first law of thermodynamics,

$$\rho^*\dot{w} - \boldsymbol{\sigma} : \nabla\boldsymbol{v} + \nabla\cdot\boldsymbol{q} = 0. \tag{2.1}$$

In Eq. (2.1), ρ^* is effective mass density, w is the stored energy per unit mass and $\boldsymbol{q}$ is heat flux, for example, due to conduction. If we assume that the temperature, T, is uniform in the film, throughout the thickness, with $w = C^*T$, where C^* is the effective heat capacity, volume averaging yields

$$\langle\rho CT\rangle_\Omega = \langle\rho C\rangle_\Omega\langle T\rangle_\Omega = \rho^*C^*T, \tag{2.2}$$

where

$$\langle(\cdot)\rangle_\Omega = \frac{1}{V_\Omega}\int_\Omega(\cdot)\,d\Omega, \tag{2.3}$$

where Ω is the domain over which the averaging takes place (Fig. 1), V_Ω is the corresponding volume and $\langle T\rangle_\Omega = T$, due to the uniformity of T. Furthermore, the heat capacity can be written as

$$\langle\rho C\rangle_\Omega = \rho^*C^* = v_1\rho_1C_1 + v_2\rho_2C_2, \tag{2.4}$$

where subscript 1 denotes the base lubricant (phase 1) and subscript 2 indicates the additives (phase 2). Also, due to the linear velocity profile, $\boldsymbol{D}$ is uniform, thus $\langle\boldsymbol{D}\rangle_\Omega = \boldsymbol{D}$ and

$$\langle 2\mu\boldsymbol{D}\rangle_\Omega = \langle 2\mu\rangle_\Omega\langle\boldsymbol{D}\rangle_\Omega = 2\mu^*\langle\boldsymbol{D}\rangle_\Omega = 2\mu^*\boldsymbol{D} = \langle\boldsymbol{\sigma}\rangle_\Omega, \tag{2.5}$$

where

$$\mu^* = v_1\mu_1 + v_2\mu_2, \tag{2.6}$$

where μ_1 and μ_2 are the dynamic viscosities of the two phases, and v_1 and v_2 are the corresponding volume fractions ($v_1 + v_2 = 1$). Since we have assumed uniformity of the temperature field, there is no angular dependence nor temperature variation through the film thickness, and if we further assume Fourier's law of conduction ($\boldsymbol{K}$ is the conductivity) holds, $\boldsymbol{q} = -\boldsymbol{K}\cdot\nabla_{\boldsymbol{x}}T$, then $\boldsymbol{q} = \boldsymbol{0}$, and we have