GRANULAR COLLISION LUBRICATION

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ABSTRACT

The study of powder flow has become a fascinating topic in recent years. Powder lubricants are capable of withstanding extreme temperatures as compared to conventional liquid lubricants that are completely ineffective beyond a certain operating temperature. The motivation for this is the development of Integrated High Performance Turbine Engine Technology (IHPTET) where the engine is operated at very high temperatures.

The behavior of granular material in motion is studied and compared with the conventional fluid-mechanical phenomenon. The individual grains are treated as the molecules of a granular fluid. The main difference between molecules and grains is that collisions of the latter are inevitably inelastic. Haff (1983) wrote down a set of complete equations, which are modeled based on the usual equations of hydrodynamics. The appropriate conservation laws are expressed in terms of macroscopic variables and a complete model were formulated by direct appeal to the nature of grain-grain collisions. The formulation of the problem starts with the first principles of fluid mechanics, i.e., conservation of mass, momentum and pseudo-temperature. For a discussion of the range of applicability of this model, the reader should refer to Johnson and Jackson (1986) and a review paper by Elrod (1988).

\[
\frac{\partial \rho}{\partial t} + \nabla (\rho U) = 0
\]

\[
\rho \frac{DU}{Dt} = \rho g - \nabla \sigma_r
\]

\[
\frac{3}{2} \rho \frac{DT}{Dt} = -\nabla q_{fr} - \sigma_r : \nabla U - \gamma
\]

Dai and Khonsari (1994) addressed the variable geometry boundary problem by applying Haff's constitutive relations and energy and momentum equations to the powder flow of a slider bearing. They acknowledged the complexities of grain boundary conditions across the slider's length. Their theory replicated the pressure profile trends of the Heshmat experiment (1992). Yu et al (1994) proposed the concept of granular collision lubrication by considering the collisional normal stress generated by kinetic energy of the granules and the lubrication normal stress due to converging surfaces. They developed an approximate theory from momentum considerations for interpreting the experimental results. McKeague and Khonsari (1996) generalized the boundary interactions for powder lubricated Couette flows, and they found that the results are in good agreement with other authors who have investigated granular Couette flows using direct computer simulations of granular collisions. The trends are in agreement with Campbell (1993) and with Elrod and Brewe (1992), whose interest was in establishing the lubrication characteristics of grain flows. They found that the boundary conditions could be extended to accommodate variable geometry bearings. The recent powder lubrication theory published by Zhou and Khonsari (2000) and Pappur and Khonsari (2002) predict that powders are capable of generating a lifting force even if placed in a configuration of two parallel discs in relative motion. This is intriguing because the hydrodynamic theory of Newtonian fluids – such as most conventional lubricating oils – predicts that this system is incapable of generating any load-carrying capacity. This work is expected to lead a fundamentally important contribution to the science of tribology with application to a wide-variety of machine components, particularly bearings. It is also likely that once developed it will lead to creation of a new generation of bearings.

In this paper we utilize more comprehensive constitutive equations by Lun et al (1984) in the analysis of the granular material. The constitutive equations of the present paper include taking the viscous dissipation into consideration as deemed necessary by Zhou and Khonsari (2000). In contrast, the work of McKeague and Khonsari (1996) was entirely based on Haff's continuum theory, Haff (1983), with considerably simplified granular constitutive equations. In that paper, the viscous dissipation was neglected. Another feature of the present paper is that the granule volume fraction appears naturally in the formulation and is predicted as part of the solution.

Following the work of Johnson and Jackson (1987), we consider the flow of a granular lubricant sheared between two parallel plates where the pressure is constant, and the
volume fraction and associated flow velocity remain uniform in the direction of motion. The bottom plate moving at a velocity $u_L$ in the positive x direction, and the top plate is stationary with a constant gap width $H$. The flow is considered to be steady, two-dimensional and fully developed. The appropriate conservation laws, constitutive equations, and boundary conditions are derived. An efficient numerical scheme is developed to solve the problem. Verification of the solution methodology were done by using the same benchmark used in different published papers to compare the velocity, temperature, volume fraction, friction coefficient, and volumetric flow rate.

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\[
\frac{\partial}{\partial y} \left[ \rho_y d \sqrt{T} \left( \frac{\partial u}{\partial y} \right) \right] = 0
\]
\[
\frac{\partial}{\partial y} \left( \rho_y T f_T \right) = 0
\]
\[
\frac{\partial}{\partial y} \left[ \rho_y d \sqrt{T} \left( \frac{\partial T}{\partial y} + \rho_y d f_T \sqrt{T} \frac{\partial u}{\partial y} \right) \right] + \rho_y d f_T \sqrt{T} \left( \frac{\partial u}{\partial y} \right)^2 - \frac{\rho_y f_T}{T} T \sqrt{T} = 0
\]

Figure 1 shows the velocity, pseudo-temperature, and solid fraction distribution for TiO2 powder. For a liquid lubricated system, there would have been no slip velocity at the boundaries. Instead, when powder is used, the theory predicted a slip velocity at both boundaries. Granular slippage is one of the important characteristics of granular lubrication. During shearing, it provides energy from the boundaries into the granules contained within the gap. The powder fluctuation velocity (granular temperature) decreases gradually from the boundaries to the center of the gap, due to loosely packing of grains near the boundaries where the energy is being supplied (due to inelastic collision between the granules). This behavior of the fluctuation velocity can be explained by examining the volume fraction profile, which shows that the grains are densely packed in the middle of the gap, while their bulk density decreases towards the boundaries.

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**REFERENCES**