Heat and Mass Transfer in Confined Lubricated Films

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ABSTRACT

Nowadays the accurate prediction of the actual tribological parameters that characterize lubricated systems requires the development of more and more advanced tools. Concerning the numerical ones, this leads to new challenges to model and predict in a proper way the strong couplings between mass (lubricant flow) and heat (dissipation, friction) transfer that appear within and around highly confined lubricating films. This paper presents some recent advances achieved in modeling TEHL problems where shear heating and its consequences can dominate other effects.

1. Introduction

Nowadays the prediction of the actual tribological parameters that characterize lubricated systems requires the development of more and more advanced tools, experimental or numerical. This demand is mainly motivated by the increasing severity of the operating conditions that occur within lubricated contacts. More precisely, this trend comes with the significant rise of the power density experienced by lubricated contacts and simultaneously with the continuous film thickness drop towards the nanometer scale.

Concerning the numerical approach, new challenges emerge to model and predict in a proper way the strong multi-physics couplings between mass (lubricant flow) and heat (dissipation, friction) transfer that appear within and around the contact. This perspective represents a real breakthrough regarding the current knowledge and tools available for mechanical designers and engineers, mostly based on isothermal models.

2. Context and background

Thin lubricated films are formed under the thermo-elastohydrodynamic (TEHD) lubrication regime that is encountered in non-conforming mechanical lubricated contacts of many machine elements. The expression thermo-elastohydrodynamic means that a strong coupling occurs between three main effects: elastic deformations of the solid surfaces subjected to relatively high pressures, hydrodynamic effect due to the fluid entrainment through the contact inlet and finally shear and compressive heating. Thus, the lubricant undergoes extreme operating conditions:

- high pressures, typically between 0.5 to 3 GPa,
- large shear rates up to 10^5-10^8 s^{-1},
- short transit times, usually much less than 1 ms,
- temperature elevation of some tens of degrees,
- very thin lubricant film thickness, from initially about 1 µm to nowadays some tens of nanometers.

Controlling such conditions and ensuring reliable operation of lubricated mechanisms has been possible thanks to numerous contributions – both experimental and numerical – on film thickness build-up mechanisms and friction in TEHD lubricated contacts published over the last 30 years. In this work, we focus on a brief description of a full-system finite element approach of TEHD lubrication and on the use of numerical models to highlight the important couplings between heat and mass transfers that occur in these confined interfaces.

3. Numerical approach

The first solutions of the elastohydrodynamic (EHD) problem were provided by the pioneering works of Dowson and Higginson [1] and then Hamrock and Dowson [2]. Their approach called "iterative semi-system approach" consisted in solving the different equations separately and establishing an iterative scheme to reach the problem solution. This methodology has been regularly improved by numerous contributors, but the vast majority of the literature remained focused on isothermal approaches that make these works unable to address the TEHD problem.

An alternative method to the iterative semi-system approach has recently emerged based on the FEM and a full-system approach. It was driven by the need:

- to overcome the restrictive assumptions specific to the semi-system approach,
- to improve the convergence rate and thus the computing effort,
- to use more general equations,
- to take into account important issues such as the non-Newtonian behavior of the lubricant and / or heat dissipation by fluid shearing and compression.

This was successfully achieved by Habchi et al. [3-4] who solved the generalized Reynolds equation, the film thickness equation (that includes the elastic deformation of the solid bodies) and the load balance equation in a fully coupled Newton-Raphson procedure, for a given temperature distribution. Then the energy equation (applied to both the solid bodies and the lubricating film) is solved for a given pressure and film thickness profiles provided by the solution of the EHD problem. An iterative procedure is thus established between the respective solutions of the EHD and thermal problems until convergence of both the temperature and pressure fields is attained. Two steps further were accomplished in order to provide more physical insight on TEHL:

- The pressure and temperature dependence of the thermo-physical properties of the lubricant was implemented [5] in the generalized Reynolds-based model. This offered the opportunity to carry out a detailed analysis on how heat transfer~~s~~ can take place at different locations within a TEHL contact.

- Navier-Stokes, full elasticity and full energy conservation equations have been used [6] to reduce the number of assumptions classically considered in TEHL. High SRR cases have been computed, showing thermal effects dominating rheological ones. The occurrence of dimples was explained with the viscosity wedge theory by analyzing the gradients of viscosity, pressure and temperature.

4. Results and Discussion

Regarding energy conservation, two heat sources are active in the contact (see fig. 1), the compression of the fluid and its shearing. Convection in the film thickness and conduction in the plane are usually neglected compared to convection in the film plane and conduction in the film thickness, due to the Reynolds thin film assumption.

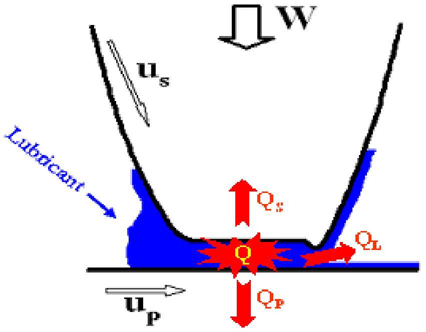

Fig. 1 Energy source terms in a TEHL case, lubricant enters the contact at the left side

A classical result in TEHL lies in the inflexion of traction curves beyond a certain amount of relative slip. This is illustrated in fig. 2: when shear heating becomes important a significant drop of friction is observed.

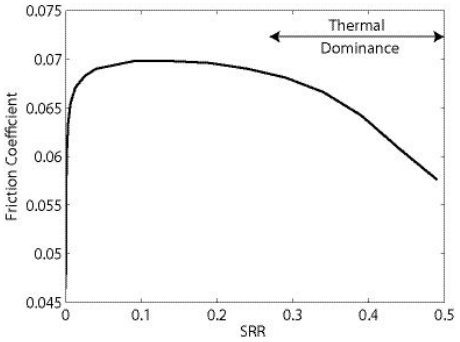

Fig. 2 Typical friction curve obtained in TEHL regime

Fig. 3 shows the heat source distribution for a pure sliding case. A strong dissymmetry is observed across the film thickness, the stationary upper surface—witnesses much larger heat dissipation. In addition, the heat flux through that surface is much smaller than the one going through the lower moving surface as heat is removed from the film only by conduction. For the lower surface, heat is removed by both conduction and advection. Consequently, the temperature elevation at the moving surface will be significantly lower than the one at the upper surface. These results were obtained by solving the Navier-Stokes equations, meaning that the consequences of viscosity or temperature gradients appearing across the film thickness are well described. Two extreme cases are presented in fig. 4 and 5, where both surfaces are moving but in opposite directions and where the upper surface is moving according a spinning motion, respectively. In both cases, the lubricant heats up at the contact inlet due to thermal conduction in the solids produced by its shearing in the central area. This sheds light another type of coupling, between the contact central zone where friction is generated and the inlet area where film thickness is built-up.

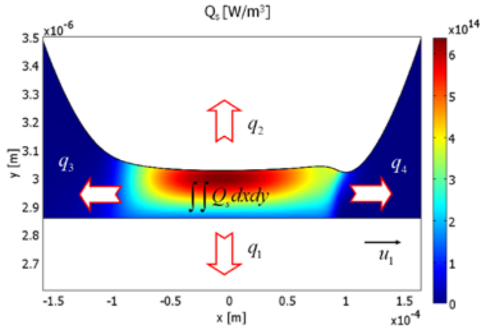

Fig. 3 Energy source term and thermal fluxes for a pure sliding case, lubricant enters the contact at the left side.

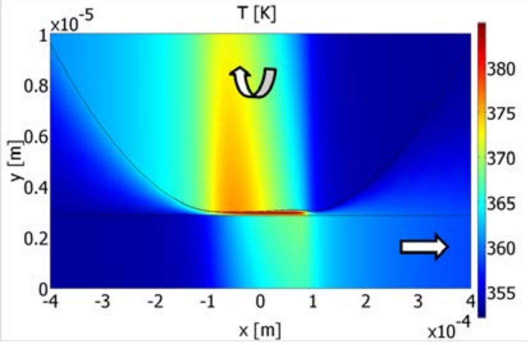

Fig. 4 Temperature distribution in the fluid and the two solids for a high sliding case, lubricant enters the contact from both sides.

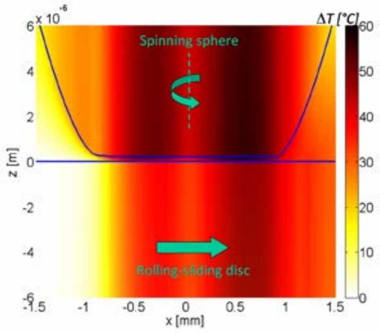

Fig. 5 Temperature rise in a longitudinal cross section of a spinning contact.

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