엔진 밸브 트레인 접촉에서의 유막 감소 효과
(Shear Thinning Effects on Engine Valve Train Contacts)

장 시 열 (Siyoul Jang)
School of Mechanical and Automotive Engineering
Kookmin University

ABSTRACT

최근의 자동차엔진에서 사용되는 윤활유에는 여러 가지 첨가물이 (additives) 사용된다. 특히 고분자량 폴리머계의 (high molecular weight polymer) 점도 지수 향상제를 (viscosity index improver) 윤활유의 원유에 (base oil) 첨가함으로써 온도 증가에 따른 점도 불안정성을 방지하는 다등급 (multigrade oil) 윤활유 성격을 얻을 수 있다. 그러나 이러한 고분자량 폴리머계의 첨가물은 고온의 엔진 운전 조건에서 윤활유의 점도 안정성을 보장해줌에도 불구하고 엔진 부품들의 정상적인 운동 속도에서도 (10^6 s^{-1}) 고 전단 변형율 속도로 (high shear strain rate) 인하여 유막 감소 효과를 (shear thinning effect) 발생 시킨다. 또한 이 첨가제들은 엔진 부품의 마찰 표면에 큰 전단 응력을 (high shear stress) 지닌 끈끈한 형태의 경계막을 (boundary film) 형성한다. 고분자량 폴리머계의 점도 지수 향상제에 대한 예기치 못한 영향은 유막 감소 효과로 인하여 엔진 부품간의 마모를 증가 시키고 점도의 감소로 마찰을 감소 시키는 반면 경계막으로 인하여 고체면이 보호를 받는데 있다.

이러한 유막 형성의 물리적인 개념에 대하여 고체면의 끈끈한 경계막의 존재 효과와 두 경계막 사이에서 일어나는 유막 감소 효과를 표현할 수 있는 현실적인 해석의 필요성이 제기된다.

본 연구는 최근에 많이 쓰이고 있는 점도 지수 향상제가 첨가된 윤활유가 자동차 밸브 트레인 시스템에서 유막 형성에 미치는 영향을 마찰 효율과 마모 방지의 입장에서 고찰하였다.

INTRODUCTION

Thin film lubrication occurs in moving components in many engine components. For example, cam and follower undergo cyclic fluctuating loads and speeds which cause mixed and boundary lubrication during the cycle. Abnormally thin film thickness (0.01~0.1 μm) can happen at intervals during the cycle and such conditions should be analyzed for the viewpoint of either mixed or boundary lubrication.

Lubricants for modern engines have various kinds of additives such as viscosity index (VI) improvers, anti-wear additives, rust-corrosion inhibitors, antioxidants, etc. In particular, VI improver containing high-molecular weight polymer is often added to reduce viscosity changes of the lubricant with temperature. The additive causes thickening at high temperature, giving the oil multigrade characteristics. However, these polymeric VI improvers produce measurable non-Newtonian behavior in the lubricant. One such non-Newtonian effect is the presence of fluid viscoelasticity and another is purely viscous shear thinning. However, no significant viscoelastic effect is found by Paranjpe and Han [1992]. When the shear rate is high, the multigrade lubricant shows a considerable shear thinning effect, Chynoweth *et al.* [1994]. Many researchers have investigated this effect experimentally and analytically. Under high shear rate conditions above 10^6 s^{-1}, which is typical under normal conditions in contact behavior of automobile valve train system, the effective thickening (viscosity increase) provided by the polymer is reduced considerably. This may lead to the reduction of friction and oil film thickness on the critical contacts of the automobile valve train system. Therefore, in this proposal we will analyze the balance between such frictional efficiency and wear protection by VI improvers.

In conditions of very thin film thickness, polymeric molecules stick to the solid surface in the form of high shear resistant layer, as suggested by the experiments of Chan and Horn [1985] and Guangteng *et al.* [1996]. The layer thickness is the same order as the minimum film thickness under severe sliding conditions. In this kind of polymer layer, an abnormal increase of effective viscosity occurs by several orders of magnitude. This kind of molecular microstructure can be simulated by regarding it as an immobile porous medium layer attached to the contact surface. Jang and Tichy [1995, 1997] perform calculations of thin film elastohydrodynamic lubrication (EHL) with elastic deformation of contacting surfaces, modeling the layers by Darcy's law. In their work, a material parameter related to the porosity of the layer is included.

Away from the sticking layer the bulk lubricant is influenced by VI improvers, Gecim [1990] and Paranjpe and Han [1992] analyzed non-Newtonian effects, especially the shear thinning effect on the power loss and load capacity with a constitutive equation for the effect of shear rate on viscosity. Measurement and modeling boundary film property with polymeric lubricant additives are performed by Guangteng *et al.* [1996] and Cooper [1994] by regarding the viscosity to vary as a function of distance from the solid surface.

While the shear thinning effect by the viscosity index polymer reduces viscous forces, the polymer molecular layer of very high effective viscosity near the solid surface increase traction. For a given applied load, the shear thinning effect causes reduced film thickness and load capacity; while the presence of high shear resistant polymeric layer greatly increases these quantities. For better design of valve train system and selection of lubricant, it is inevitable to investigate the competing effects of high shear resistant polymer layers and shear thinning viscosity on load capacity.

MODELING OF FILM FORMATION

During the cycle of contact mechanism between cam and follower, a fluid lubricating film thickness often falls below a thickness of about 15 molecular layers, which is of 0.05 μm order depending on the type of lubricant. High molecular weight polymers in the lubricant stick or absorb on solid surfaces due to polarization and other reasons forming a relatively sticky layer. Under this circumstance, the "apparent" or "effective" viscosity of the layer increases by some ten times that of the bulk viscosity.

The finding of a layered structure is simulated with a 'step function' by Guangteng, *et al.* [1996] which depicts effective viscosity variation with the respect to gap distance for thin film EHL calculations. Although this study simulates the irregular increase of viscosity for the high shear resistant layer where the gap distance is below a certain value of 30 *nm*, it does not reflect the shear thinning effect in the bulk fluid region away from the surface.

In the proposed model a three layered fluid film which consists of two high shear resistant layers and a non-Newtonian (shear thinning) bulk fluid film is to be analyzed (see Fig. 1). In the layer regime, it is likely that the fluid behaves in a complex manner that cannot be portrayed by a purely viscous fluid. For the purely viscous fluid, stress is only a function of rate-of-strain, and viscosity may be a function of the second invariant of the rate-of-strain tensor. The effective viscosity is simply the ratio of one component of shear stress to one component of shear rate in steady flow, and may not have predictive value in other situations. The viscosity η and thickness $\delta_i(x,y)$ of the high shear resistant layer may vary depending on the lubricant characteristics. From this physical feature, the microstructure of polymer molecules on the surface is simulated by porous layer attached to the contact surfaces, Jang and Tichy [1995, 1997].

In addition, viscosity is influenced by the applied pressure and the contact behavior of cam and follower is under high concentrated pressures due to the geometrically nonconforming characteristics.

As far as the apparent viscosity is concerned in thin films occurring in the valve train contact mechanism, it is therefore appropriate to formulate the viscosity as a function of shear strain rate, pressure, density and boundary layer characteristics from the experimental and analytical findings (Figure 1).

With the explained mathematical formulation including the behaviors of mixed elastohydrodynamic lubrication and boundary lubrication, the contact behaviors of automobile valve train system will be analyzed with more practical respects under the circumstances of VI improvers in lubricant.

RESULTS

We have investigated the effects of viscosity index improvers by comparing the Newtonian fluid (figure 2) of pressure-viscosity variation with the proposed model (figure 2, 3 and 4). Some differences in the film shapes, minimum film thicknesses and load capacities reflects the characteristics of viscosity index improver's functions under the high load and high speed conditions such as in the contact mechanism of automobile cam and follower.

CONCLUSIONS

The shear thinning in the bulk region causes viscosity reduction that reflects the decreased load capacity, while the sticky boundary films on the solid surface which have the characteristics of high shear resistance increase the load capacity. The spike patterns in the film shape are influenced by the viscosity change gradient, which is closely related to the minimum film thickness between cam and follower. It is therefore necessary to find the incorporating factors due to the existence of viscosity index improvers. Better design of lubricant characteristics under the high load and high shear rate will provide high load capacity with low shear rate effects. The guidance will give more protection on the cam and follower contact and low frictional behaviors.

REFERENCES

1. Paranjpe, R. S. and Han, T., 1995," A Transient Thermohydrodynamic Analysis Including Mass Conserving Cavitation for Dynamically Loaded Journal Bearings," *ASME Journal of Tribology*, Vol. 117, pp369-378.
2. Chynoweth, S., Coy, R. C. and Michipoulos, Y., 1995," Simulated Non-Newtonian Lubricant Behavior Under Extreme Conditions," *Proceedings of the Institute of Mechanical Engineers*, Ser.J, Vol. 209, pp243-254.
3. Guangteng, G. and Spikes, H.," Boundary Film Formation by Lubricant Base Fluids," *STLE Tribology Transactions*, 1996, Vol. 29, pp448-454.
4. Tichy, J.," Rheological Models for Thin Film Lubrication," *Journal of Tribology*, 1995, Vol. 117, pp22-28.
5. Jang, S. and Tichy, J.," Rheological Models for Thin Film EHL Contacts," 1995, *Journal of Tribology*, Vol. 117, pp22-28
6. Jang, S. and Tichy, J.," Modeling of Mixed Hydrodynamic and Boundary Lubrication: Layered Structures and Shear Thinning," *World Tribology Congress*, 8-12 Sep. 1997, Lodon.
7. Taylor, C. M.," Fluid Film Lubrication in Automobile Valve Train," *Journal of Engineering Tribology*, 1994, Vol. 208, pp208-234.

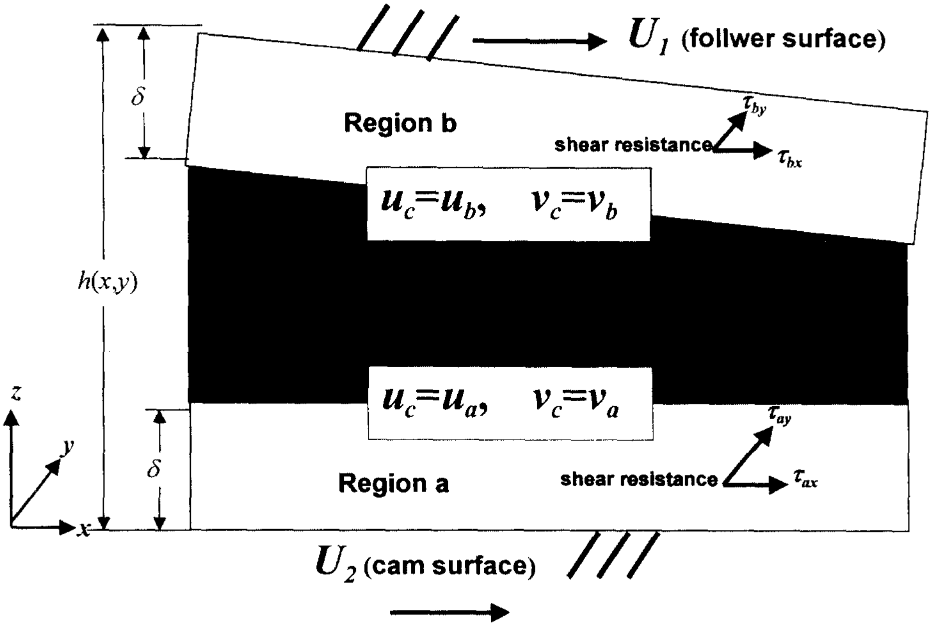

Figure 1. Boundary Film Formation with Sticky and Absorbed Layers on the Solid Surfaces

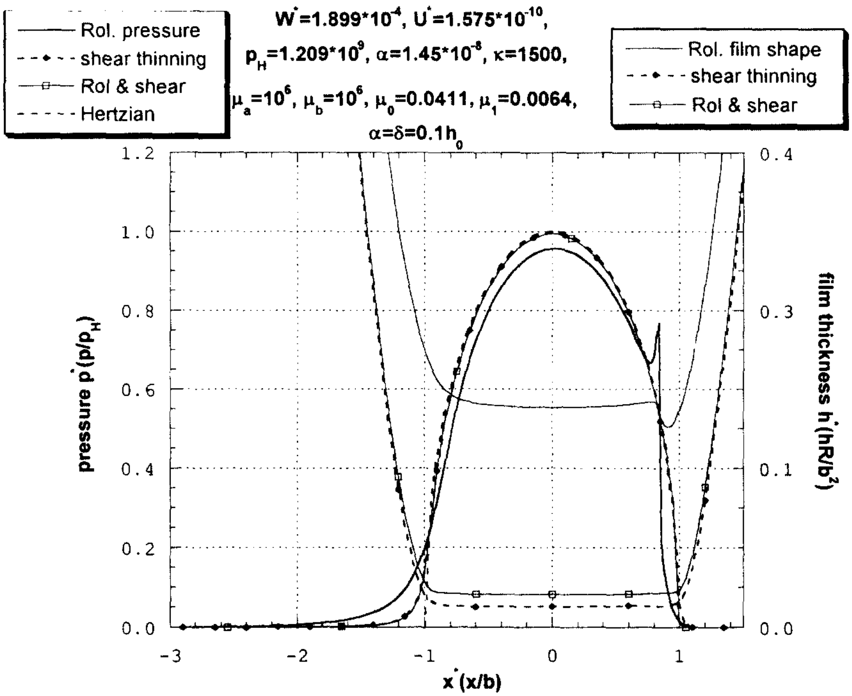

Figure 2 Film shape and pressure according to the viscosity variation by pressure, sliding speed and both effects due to viscosity index improvers

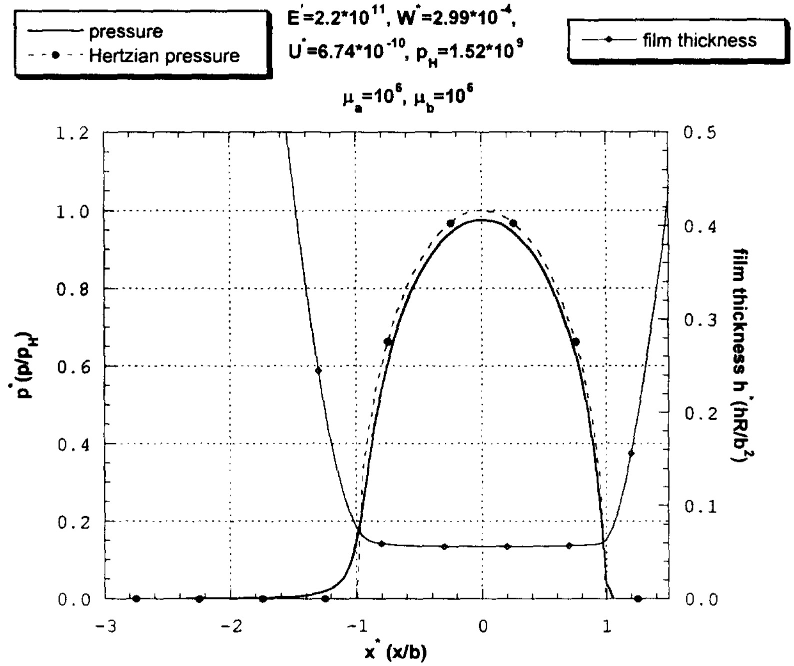

Figure 3 Film shape and pressure by shear thinning effect only

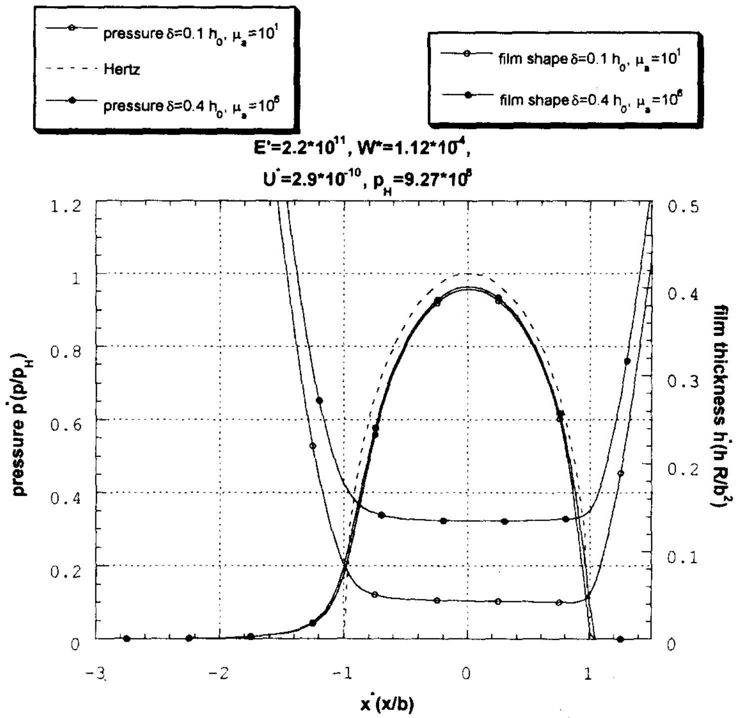

Figure 4 Film shape and pressure by shear thinning effect with different layer thickness