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A thermal mixed lubrication model to study the textured ring/liner conjunction

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ABSTRACT

In this paper, a semi-deterministic analytic thermal solution is presented for the rough textured ring/liner conjunction. The energy equation is employed to reveal more detailed information about the tribological performance of the textured surfaces in terms of the thermal effects and the viscosity change. The effects of surface texturing under the cold and warm engine conditions are studied over a wide range of engine speeds. It is shown that the thermal effects play a crucial role in hydrodynamic lubrication, particularly under the cold start condition. Including the thermal effects in the numerical simulation can ensure the accurate predictions.

1. Introduction

Since a large percentage of the mechanical friction loss in engines occurs in the ring-liner conjunction [1], the tribological performance of the piston ring pack has long been a concern of researchers during the past decades [2]. For designing the advanced internal combustion engines, some aspects, such as oil consumption, fuel consumption, blow by, power loss and wear, are important. In order to improve engine performance and reduce emission level, establishing a deeper understanding of the frictional behavior of the ring-liner conjunction serves as a prerequisite.

For the ring-liner conjunction, the lubrication is influenced by the oil viscosity, the oil film thickness, the piston ring configuration, and the operating conditions. Of all the parameters involved in the ring-liner lubrication problem, the lubricant viscosity is particularly important. According to the lubricant rheology, the oil film viscosity would be reduced with the increasing temperature, leading to the changing hydrodynamic loading carrying capacity. The effects of viscosity on the oil film thickness and on the total friction force of the conjunction are significant. When different viscosities of lubricants are supplied, the ring-liner conjunction may experience various lubrication regimes. In 1997, Taylor took into account the viscosity effects in the evaluation of the friction of one gasoline engine [3]. Both the fully warmed-up and cold-start conditions were considered. It was found that the total engine friction under the cold-start conditions was about five times higher than the results under the warmed-up conditions. Afterwards, the lubrication of one diesel engine considering the thermal effect was studied by Harigaya et al. [4,5]. The relationship between the lubricant viscosity and the oil film temperature was considered based on the solving of energy equation. Their results indicated that the oil film thickness increased with the engine speed and the viscosity was found to be important on the film thickness. The calculated film thickness would be changed, when the surface temperatures of the ring and liner were different. It was shown that the viscosity and density of the lubricant required an accurate assessment in the simulation of ring-liner conjunction. Otherwise, a calculation error would be generated. Recently, Morris et al. presented a new analytical thermal model in the study of the tribology of piston compression ring [6]. Through their model, the effective lubricant temperature in the contact was determined. It was found that the engine operating condition affected the lubricant viscosity by changing the temperature, which resulted in the change of power loss. Their thermal-mixed approach was also adopted in the work of Shahmohamadi et al. [7]. It seems a correct prediction about the tribological performance of piston-cylinder system is inseparable from the accurate assessment of lubricant rheology. The temperature dependence of

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Nomenclature

a_0	correlation parameter in the Vogel equation
A	the apparent contact area
b	ring face-width
c_L	specific heat capacity for liner
c_p	specific heat capacity for lubricant
c_R	specific heat capacity for ring
E_L	elastic modulus of the liner
E_R	elastic modulus of the ring
E'	composite elastic modulus
f_{boun}	friction induced by asperity contact
f_{total}	the total friction
f_{visco}	friction induced by hydrodynamic support
$F_{2.5}$	statistical functions
h	mean film thickness
h_0	minimum oil film thickness
h_p	depth of dimple
h_{ring}	profile of the ring
h_{text}	profile of the textures
h_{text_ring}	profile of the textured ring
k_L	thermal conductivity for liner
k_p	thermal conductivity for lubricant
k_R	thermal conductivity for ring
l	ring circumferential length
l_s	Stroke
p_c	cavitation pressure
p_{asp}	asperity contact pressure
P_{pow_los}	total power loss
r_p	radius of dimple
u	fluid velocity in x direction
U	sliding speed
U_L	sliding speed for liner
U_R	sliding speed for ring
v	fluid velocity in y direction
V_s	displaced volume of the cylinder
x	the ring axial direction in global coordinate system
x'	the ring axial direction in the local coordinate axis
y	the ring circumferential direction in global coordinate system
y'	the ring circumferential direction in the local coordinate axis
z, z_L, z_R	coordinates
t	time
tim	the period of the engine cycle
T	lubricant temperature
T_{in}	the inlet oil temperature
T_L	temperature for liner
T_R	temperature for ring
T_1, T_2	the correlation parameters in the Vogel equation
α	the correlation parameter in the Roelands equation
β	asperity radius of curvature
β_T	thermal expansion coefficient for lubricant
γ	surface pattern parameter
δ	ring crown height
η	number of asperities per unit contact area
κ_{asp}	boundary friction coefficient
λ	the Stribeck oil film ratio
μ	lubricant viscosity
μ_0	the corresponding viscosity under atmospheric pressure
υ_L	Poisson's ratio of the liner
υ_R	Poisson's ratio of the ring
ρ	lubricant density
ρ_0	the lubricant density under the atmospheric pressure
σ	composite roughness of the ring and liner
σ_L	Rq for the liner
σ_R	Rq for the ring
φ	the crank angle
ϕ_c	contact factor
$\phi_f, \phi_{fs}, \phi_{fp}$	friction-induced flow factors
ϕ_x, ϕ_y	pressure flow factors
ϕ_s	shear flow factor
Ω	area occupied by a dimple

viscosity, the ring configuration and the engine operational conditions are quite essential in analyzing friction encountered in the piston-cylinder system. In spite of the correct evaluation for the ring-liner conjunction can be obtained by the isothermal analysis [8,9], the consideration of thermal effects can provide an additional opportunity to find more detailed information about the frictional behavior of the piston-cylinder system.

On the other hand, in recent years, surface texturing has been proved as an exceedingly useful technique to reduce the friction of engines by expanding the behavior under hydrodynamic regimes instead of mixed or boundary lubrication regimes [10–12]. It is well known that the reduction of engine mechanical friction can increase the engine efficiency. In fact, over the last few decades, one of the earliest successful commercial applications of surface texturing was on the cylinder liners of engines [13]. According to the results of Etsion [14], a reduction of friction by 2–4% may be achieved by introducing the dimpled textures on the surface of piston compression ring. Rahnejat et al also observed a reduction of 2–4% in friction under engine operations by applying the surface texturing technology [15].

However, with the introduction of textures, some aspects of the tribological properties of the ring-liner system would be changed. One of the aspects is the thermal effect. On the one hand, application of surface texturing would bring the change of hydrodynamic load carrying capacity, resulting in the change of oil film thickness. It leads to different degrees of viscous shear. Different degrees of viscous shear would induce the change of the oil film temperature. On the other hand, with the textures on the surface, the metal to metal directly contact area is reduced. Thus, the conduction of heat is different.

In this paper, the textured ring-liner conjunction considering the thermal effect is studied. To the authors' knowledge, it is the first attempt to investigate the performance of the textured ring-liner conjunction with the consideration of thermal effects. The thermal effect is achieved by solving the energy equation. The paper provides a combined solution of the Reynolds equation, boundary interactions, and energy equation for the textured ring-liner conjunction. Benefit from the presented model, a comparative summary of different modeling techniques is conducted to provide the detailed temperature and viscosity distributions. By applying this model, the general effects of the textured surface during the cold starting and normal working conditions are studied over a wide range of engine speeds.

2. Theory

In the simulation of surface texturing, there is a considerable difference in scale between the global contact dimensions and local surface properties, such as textures or roughness. In the current paper, the texture scale is treated deterministically and the