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Improvement of Lubrication Characteristics in Fuel Injection Pump for Medium-Speed Diesel Engines: Part I - Application of Profile Shape

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Abstract – In this research, effects of profile changes of stem section of the plunger on the lubrication characteristics of a fuel injection pump (FIP) were evaluated by hydrodynamic lubrication analysis. The clearance between plunger and barrel was divided into two regions, head and stem. The head was not involved in preventing a decrease of fuel oil pressure. So, research efforts were focused on both edges of the plunger's stem. The two -dimensional Reynolds equation was used to evaluate lubrication characteristics with variations in viscosity, clearance and profile for a laminar, incompressible, unsteady-state flow. Moreover, the equilibrium equation of moment and forces in the vertical and horizontal directions were used to determine the motion of the plunger. The equations were discretized using the finite difference method. Lubrication characteristics of the FIP were investigated by comparing the dimensionless minimum film thickness, or film parameter, which is the ratio of minimum film thickness to surface roughness. Through numerical analyses, we showed that the profile of the lower edge of the stem had no effect on lubrication characteristics, but the profile of the upper edge had a significant influence on lubrication characteristics. In addition, changes in the profile were more effective in improving lubrication characteristics under low viscosity conditions.

Keywords – medium-speed diesel engine, fuel injection pump, profile, minimum film thickness

Nomenclature

- A : Dimensionless clearance of stem part
- $A1$: Dimensionless taper length of upper part in the axial direction (a_1/r_o)
- B : Dimensionless clearance of head part
- $B1$: Dimensionless taper length of upper part in the radial direction (b_1/r_o)
- C : Dimensionless clearance (c/c_0)
- $C1$: Dimensionless taper length of lower part in the axial direction (c_1/r_o)
- $D1$: Dimensionless taper length of upper part in the radial direction (d_1/r_o)
- F : Force (N)
- F_c : Contact force (N)
- $\bar{F}$: Dimensionless force (F/F_o)
- H : Dimensionless film thickness (h/c_0)
- H_m : Dimensionless minimum film thickness (h_m/c_0)
- H_t : Dimensionless film thickness in the taper section (h_t/c_0)
- L : Dimensionless plunger length (l/l_o)
- M_O : Dimensionless moment at point O
- O : Fixed point of plunger
- P : Dimensionless fluid film pressure $\left(\frac{(p-p_o)c^2}{\eta ul}\right)$
- R : Dimensionless plunger radius (r_o/l_o)
- R_q : Root mean square deviation (m)
- R_{q1} : Root mean square deviation of plunger (m)
- R_{q2} : Root mean square deviation of barrel (m)
- T : Dimensionless time (lt/u)
- X : Dimensionless axial distance (x_i/l)

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Y : Dimensionless radial distance (y_i/l)
Z : Dimensionless axial direction (z/c_0)
a_1 : Taper length of upper part in the axial direction (m)
b_1 : Taper length of upper part in the radial direction (m)
c : Clearance (m)
c_1 : Taper length of lower part in the axial direction (m)
d_1 : Taper length of lower part in the radial direction (m)
e : Eccentricity (m)
h : Fluid film thickness (m)
h_m : Minimum film thickness (m)
l : Plunger length (m)
n_o :Normal direction of fluid film
p : Fluid film pressure (Pa)
p_o : Atmospheric pressure (Pa)
r : Radial direction
r_o : Plunger radius (m)
t : Time (s)
u : Velocity (m/s)
z : Axial direction (m)
ε : Eccentricity ratio (e/c)
$\dot{\varepsilon}$: Eccentricity ratio variation
η : Viscosity ($Pa.s$)
λ : Film parameter (h_m/R_q)
θ : Circumferential direction
Δt : Time interval (s)

1. Introduction

The fuel injection pump (FIP) is a key element in the fuel injection system in medium-speed diesel engines that are used as power generators in marine and terrestrial applications. The FIP is a fuel feed pump for injection of fuel oil into a cylinder, and operated plunger to create high oil pressure. The compressed high pressure fuel oil is injected into the combustion chamber via the nozzle connected to the cylinder. Recent changes to medium-speed diesel engines mean that they require higher pressure fuel oil for efficiency of combustion and for smoke reduction. Researches into high-pressure fuel injection have been carried out. Reliability has arisen as a problem with the use of low-quality fuel oil due to high oil prices [1-2].

An undesirable "stick" occurs when various factors such as uneven pressure distribution surrounding the plunger, cause the plunger to move sideways and out of its centered position. Contact between the plunger and barrel causes an increase in friction, and the plunger eventually becomes stuck inside the barrel. This problem has occurred because the manufacturing clearance was too small, or when clearance is reduced by expansion at the high temperatures in engines. Moreover, lacquer generated by a combination of distillated fuel oil and lubricant oil can cause stick [3].

There is thus a need for design modifications that prevent wear and stick in the FIP that can be applied to a variety of operating conditions, and are compatible with the increased fuel pressure in modern medium-speed diesel engines. An improvement in lubrication characteristics is needed to keep lubrication stable in the FIP.

In a previous study, a design process for optimal clearance in the FIP was suggested that considered the results of structural analysis, hydrodynamic analysis and tolerance of clearance [4]. In addition, it has been reported that contact between the plunger and the barrel could occur when the clearance was large. The lubrication characteristics of the system could be improved by machining partial grooves on the surface of the plunger [5-7].

In this study, their influence of profiles changes are made in the form of tapers in the FIP is investigated. The profile changes are applied to cylindrical or tapered roller bearing in order to release stress concentration on the edges of the roller [8]. The design of this profile was based on Hertz's contact theory or elasto-hydrodynamic lubrication (EHL) analysis [9-15]. In addition, the lubrication characteristics of the spool valve, piston-type compressor and mechanical seal were improved by application of the altered profile [16-18]. Hydrodynamic lubrication analysis of the FIP with this altered profile is performed with variations in oil viscosity, and clearance.

2. Numerical analysis

2-1. Lubrication characteristics of fuel injection pump

Hydrodynamic lubrication analysis is performed to evaluate the lubrication characteristics of the FIP with the profiles. Lubrication characteristics of the FIP are investigated by comparing the dimensionless minimum film thickness, or film parameter, which is the ratio of minimum film thickness to surface roughness.

2-1-1. Hydrodynamic lubrication analysis

An unsteady-state two-dimensional Reynolds equation and Reynolds boundary conditions are used to analyze the fluid film between the barrel and plunger. The elastic deformation of surfaces is not taken into account. Velocity of the plunger and supply pressure of fuel oil with variation of crank angle are considered. In addition, the pressure of spill port, and position and the pressure of barrel grooves are considered.

1) Numerical model

The plunger has a reciprocal motion inside the barrel of the FIP. The numerical model is simplified, as shown in Fig. 1. The dimensionless geometries and pressure boundary conditions of barrel grooves is shown in Table 1.

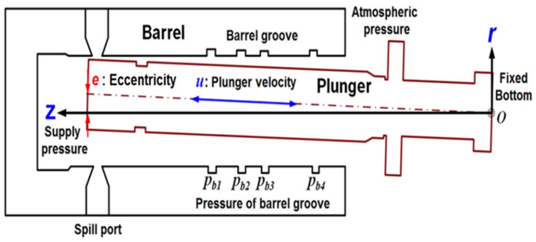

Fig. 1. Numerical model of hydrodynamic lubrication analysis.

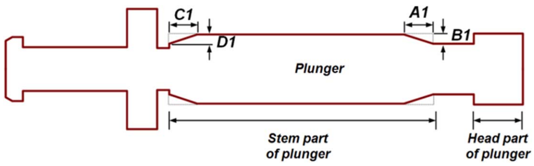

Fig. 2. Profile (taper) geometry of plunger.

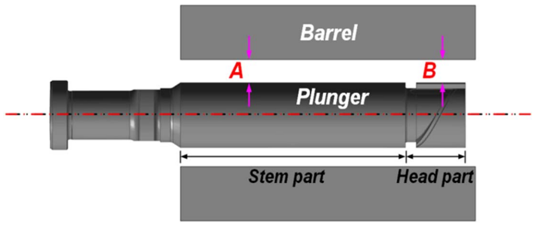

Fig. 3. Dimensionless clearance of stem part (A) and head part (B) [Reference 4].

Fig. 2 shows the tapered plunger. Tapers are added to the plunger stem. A1 and B1 are the dimensionless taper lengths of the upper part of the plunger stem in the axial and radial directions, respectively. C1 and D1 are the dimensionless taper lengths of lower part of the plunger stem in the axial and radial directions, respectively.

The clearance between the plunger and the barrel is

Table 1. Dimensionless plunger geometries and pressure boundary condition

Parameter	Value	
Dimensionless plunger radius	879	
Dimensionless plunger length	12582	
Dimensionless stroke length	1648	
Dimensionless pressure condition	Plunger top	Supply pressure
	Plunger bottom	0
	Spill port	Spill port pressure
	Barrel groove (p_{b1})	Spill port pressure
	Barrel groove (p_{b2})	0
	Barrel groove (p_{b3})	0.0025
	Barrel groove (p_{b4})	0.0025

divided into two sections, head and stem. In Fig. 3, A is the dimensionless clearance in the stem, and B is the dimensionless clearance in the head.

2) Governing equations and boundary conditions

The dimensionless form of the unsteady-state two-dimensional Reynolds equation is expressed as Eq. (1)

$$\frac{\partial}{\partial Z}\left(H^3\frac{\partial P}{\partial Z}\right)+R^2\frac{\partial}{\partial \theta}\left(H^3\frac{\partial P}{\partial \theta}\right)=6\frac{\partial H}{\partial Z}+12\frac{\partial H}{\partial T} \tag{1}$$

where the dimensionless parameters are as follows:

$$Z=\frac{z}{l}, H=\frac{h}{c}, R=\frac{l}{r_0}, P=\frac{(p-p_0)c^2}{\eta u l}, T=\frac{l}{u}t \tag{2}$$

where p_o and p are atmospheric pressure and fluid film pressure, respectively. h is film thickness, r_o is the radius of the plunger, l is the length of the plunger, u is plunger velocity, η is the viscosity of working fluid, t is time. The c is the clearance when the plunger and barrel are concentric [4].

When the spherical coordinates of center of the top plunger are the same as (e, θ) in Fig. 4, the film thickness equation is expressed as the z distance in the axial direction, and as the Φ in the circumferential direction (Eq. 3).

$$H(Z,\theta)=1+\varepsilon(Z)\sin(\phi-\theta)+H_t(Z) \tag{3}$$

where ε is the eccentricity ratio at the top of the plunger. The eccentricity ratio is the ratio of eccentricity and clearance in the head. H_t is dimensionless depth of the taper.

The Reynolds boundary condition is applied as expressed in Eq. (4).

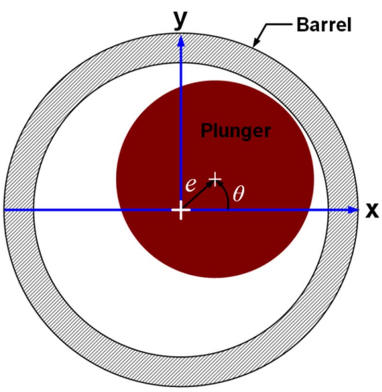

Fig. 4. Plunger position in the barrel.

$$P=0,\ \frac{\partial P}{\partial n_0}=0 \tag{4}$$

where n_0 represents the outward normal vector to the film rupture boundary [4].

The equilibrium equation of moment at the O point and the equilibrium of forces in the vertical and horizontal directions are used, as shown in Eq. (5) to determine the motion of the plunger. The moment at the O point is calculated with Eq. (6).

$$\sum M_{OX}=0, \sum M_{OY}=0, \sum \overline{F}_r=0, \sum \overline{F}_z=0 \tag{5}$$

$$\sum M_{OX}=\int_0^L\int_0^{2\pi}(P\cos\theta X)RdZd\theta=0$$
$$\sum M_{OY}=\int_0^L\int_0^{2\pi}(P\sin\theta Y)RdZd\theta=0 \tag{6}$$

If the moment equilibrium equation does not satisfy the equation, the change of eccentricity ratio with time is updated using the Newton Raphson method (Eq. 7).

$$\varepsilon_t=\varepsilon_{t-1}+\dot{\varepsilon}_{t-1}\Delta t \tag{7}$$

Fig. 5 is a flow chart of numerical analysis.

The dimensionless supply pressure is dependent on crank angle under a 100% load condition, as shown in Fig. 6(a). Fig. 6(b) shows the dimensionless pressure of spill port and barrel groove (p_{bl}). Fig. 7 shows the dimensionless plunger lift and dimensionless plunger velocity with variation in crank angle.

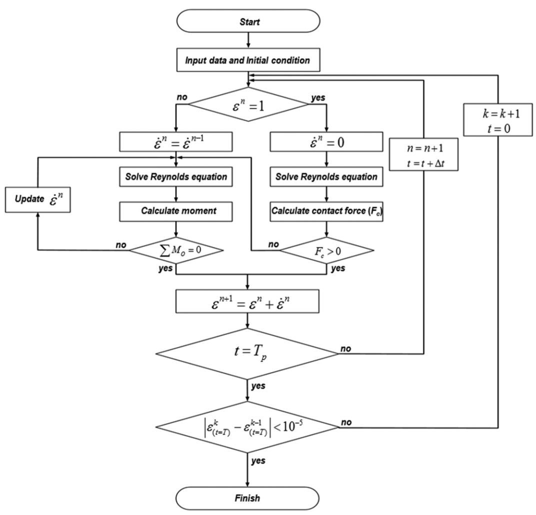

Fig. 5. Flow chart.

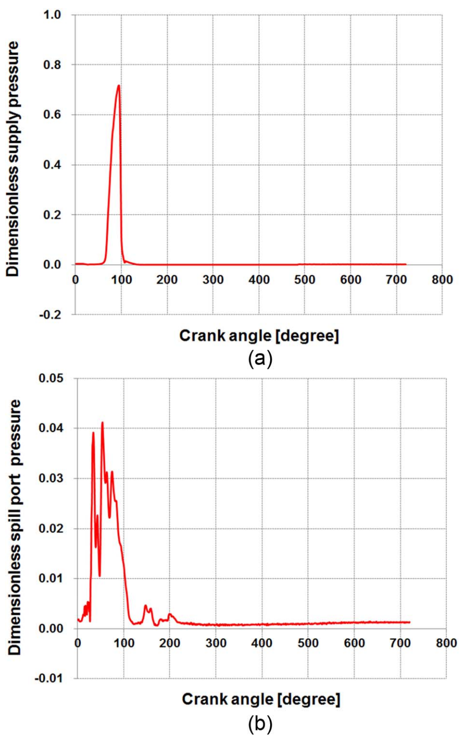

Fig. 6. Dimensionless pressure with crank angle. (a) Supply pressure, (b) Spill port pressure.

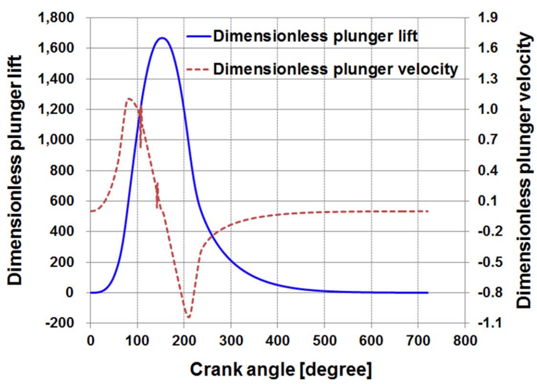

Fig. 7. Dimensionless plunger lift and plunger velocity with crank angle.

3) Numerical results

The lubrication characteristics of the FIP with the tapered plunger have been investigated. Fig. 8 shows the effect of tapering the upper part of the stem when the dimensionless taper length (A1) in the axial direction is varied, and the dimensionless taper length (B1) in the radial direction is constant (0.031). The dimensionless minimum film thickness in the tapered plunger is larger than that of an un-tapered plunger, as shown in Fig. 8. This is because the taper generates a wedge effect, and oil film pressure produced by the wedge effect can help to restore the plunger to the barrel center when the plunger moves from left to right. Therefore, the tapered plunger improves the lubrication characteristics of the FIP. When A1 is increased from 0.312 to 0.938, dimensionless minimum film thickness increases. However, there is no change in dimensionless minimum film thickness when A1 is increased beyond 0.938. The significant increment in the dimensionless minimum film thickness is caused by the taper when the dimensionless clearances of stem and head are 0.30 and, 0.36, respectively.

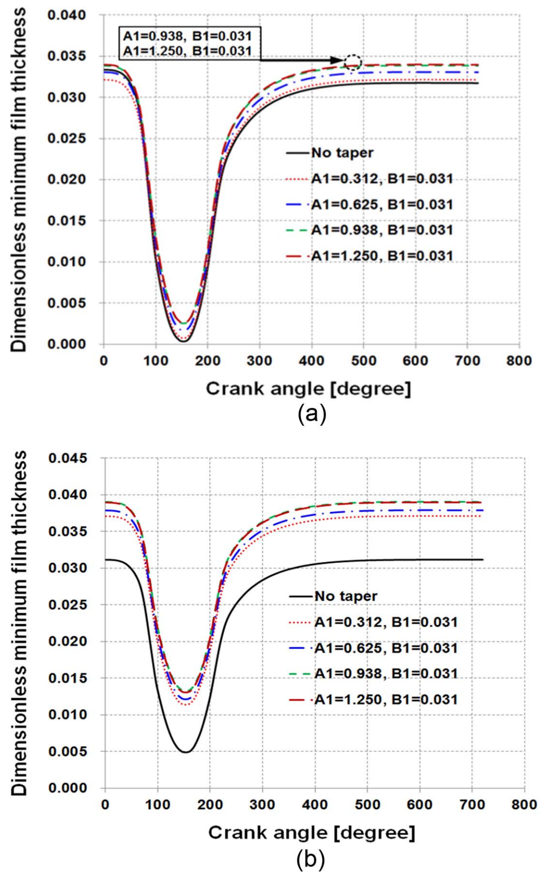

Fig. 8. Dimensionless minimum film thickness with taper geometries and crank angle. (Variable: A1), (a) A=0.36, B=0.58 (b) A=0.30, B=0.36.

Fig. 9 shows the dimensionless minimum film thickness when B1 is varied, and A1 is held at 0.938. The variation of the dimensionless minimum film thickness is less than 5% with variation in B1. Thus, taper length in the axial direction has a greater effect on lubrication characteristics than that in the radial direction.

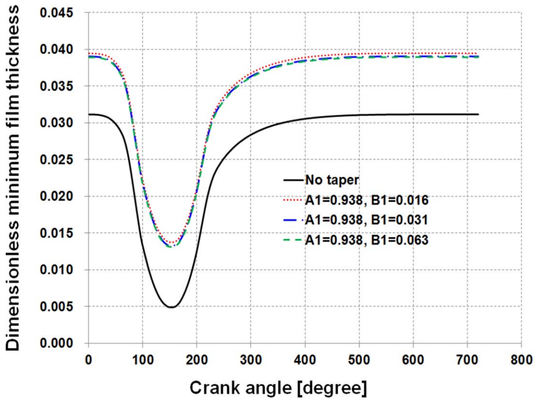

Fig. 9. Dimensionless minimum film thickness with B1 (A=0.30, B=0.36)

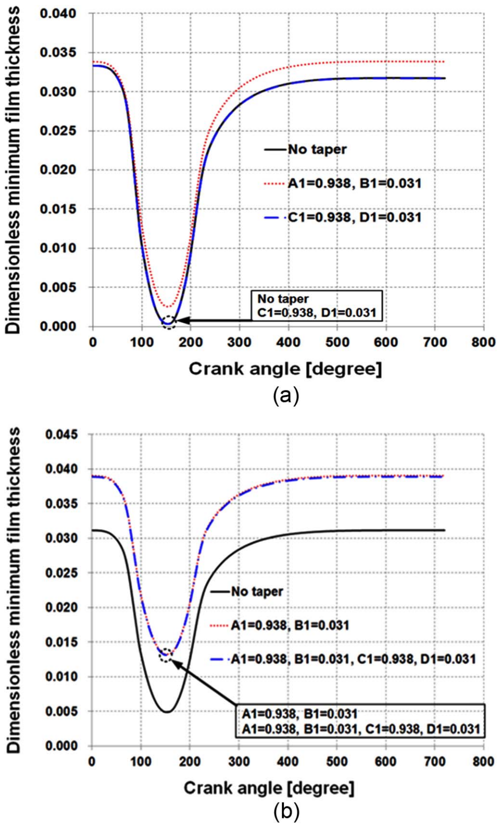

Fig. 10. Dimensionless minimum film thickness with taper geometries and crank angle. (effect of lower taper) (a) A=0.36, B=0.58 (b) A=0.30, B=0.36.

Tapering the lower part of the stem has no influence on the lubrication characteristics of the FIP, as shown in Fig. 10. This is because the lower part of the stem comes out of the barrel for a certain time during reciprocal motion. Moreover, the fluid film pressure in the lower part of the stem is less than that in the upper part of the stem.

Fig. 11 shows effect of the taper with variation in dimensionless clearance. The lubrication characteristics of the FIP are estimated such that the film parameter is the ratio of minimum film thickness to surface roughness, as shown in Eq. (8). Surface roughness is determined from the surface roughness of the plunger and the barrel, as shown in Eq. (9) [4].

$$Film\ parameter(\lambda) = \frac{Minimum\ film\ thickness(h_m)}{Surface\ \ roughness(R_q)} \quad (8)$$

$$R_q = \sqrt{R_{q1}^2 + R_{q2}^2} \quad (9)$$

Four variations are shown in Table 2. The film parameters of four cases are evaluated using the dimensionless minimum film thickness in Fig. 11(a). In cases of the un-tapered plungers, the film parameter of Case-1is higher than that of Case-3. The dimensionless clearance of Case-1 is determined by optimal clearance design process that was introduced in previous research [4]. The optimal clearance of the FIP is determined through structure analysis, hydrodynamic lubrication analysis and considering of machining limits and clearance tolerances. When the dimensionless clearances of stem and head are 0.30 and, 0.36, respec-

Table 2. Specification of cases

Case	Specification	
	Taper	Dimensionless clearance
Case-1	No taper	A=0.30, B=0.36
Case-2	A1=0.938, B1=0.031	A=0.30, B=0.36
Case-3	No taper	A=0.36, B=0.58
Case-4	A1=0.938, B1=0.031	A=0.36, B=0.58

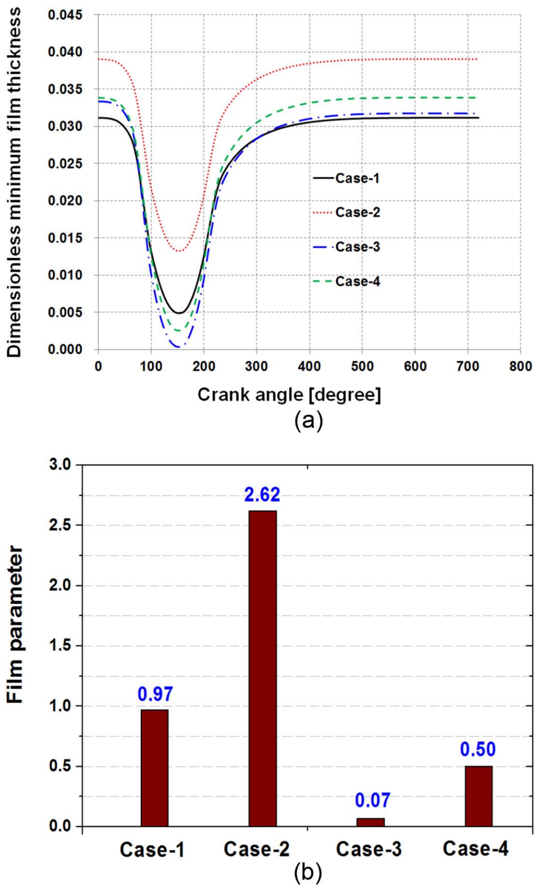

Fig. 11. Dimensionless minimum film thickness and film parameter with clearance. (a) Dimensionless minimum film thickness, (b) Film parameter.

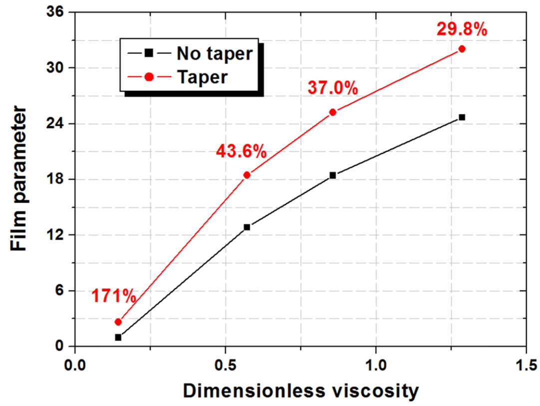

Fig. 12. Film parameter with dimensionless viscosity and taper (A=0.30, B=0.36).

tively, the film parameter of Case-2 is increased by about 170% compared with Case-1. Improvement of lubrication characteristics caused by the taper is effective when the dimensionless clearances of stem and head part are 0.30, 0.36 that is determined by optimal clearance process. The clearances have a significant influence on the function of the taper. Therefore, the identification of optimal clearance is paramount in producing an effective taper.

Fig. 12 presents film parameters with variation in dimensionless viscosity when the dimensionless clearances of stem and head are 0.30 and, 0.36, respectively. A1 and B1 are 0.938 and, 0.031, respectively. Medium-speed diesel engines use, LDO (light diesel oil), which has low viscosity, and HFO (heavy fuel oil), which has high viscosity. The dimensionless viscosity of LDO and HFO are 0.143 and, 1.286 respectively. The film parameter increases about 30% when LDO is used, and about 170% when HFO is used, compared with cases of plungers without taper. Improvement of lubrication characteristics resulting from a tapered plunger is more effective under low viscosity conditions. The risk of stick is high when the FIP is operated in low viscosity condition. Therefore, tapered plungers improve the lubrication characteristics.

3. Conclusions

In this study, the plunger of a fuel injection pump was tapered to improve lubrication characteristics. The lubrication characteristics of the tapered plunger were investigated with variations in viscosity and, clearance. Conclusions were drawn from this study are as follows;

1. Tapering the lower part of the stem has no influence on the lubrication characteristics of the FIP; on the other hand, tapering the upper part of the stem has a significant effect.

2. The use of a tapered plunger is more effective in low viscosity conditions than in high viscosity conditions with respect to the improvement in lubrication characteristics.

3. The clearances of both the stem and head signif-

icantly influence the function of the tapered plunger. Therefore, optimal clearance should be identified in order for the tapered plunger to be most effective.

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