Research of the Frictional Characteristics of Piston Ring - Cylinder Liner Based on GT-Suite

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Abstract. Establish the piston ring-cylinder liner frictional model using the software of GT-Suite combine both of the frictional condition and lubrication, analyze and compute the thickness of oil film between piston ring and cylinder liner, the distribution of oil stress, and the force and power of the friction in rated condition. Then, mainly analyze the thickness of oil film and power of friction at the first piston ring under different temperatures of lubrication oil and different speeds. The results indicate that: The lubrication effect at first piston ring is poor, and the consumption of frictional power is high. The frictional power is significantly reduced with the oil temperature increases. However, the thickness of the oil film will decrease with the oil temperature increases, which is bad to the lubricational condition. Considering both of the lubrication condition and the frictional power, the frictional characteristics are better when the oil temperature is maintained at 80-90°C. With the increase of rotational speed, the oil film thickness and frictional power increase, but comparing with the influence on the frictional power, the change of rotational speed has less influence on the oil film.

1 Introduction

Piston ring is one of the most demanding parts of working condition in diesel engine, which not only withstanding high temperature and high pressure gas, but also sliding with a high speed along the cylinder liner, and being constraint for a heavy diesel engine becoming a high power density engine.

Therefore, studying the friction characteristics of piston ring-cylinder liner has the instructive meaning for improving the reliability and life span of diesel engine.

Scholars [1-5] conducted an in-depth study on the friction, wear and lubrication between the piston ring and cylinder liner. The analysis model covered kinetics, friction, structural parameters, surface morphology of friction pair, lubricant oil, Axis symmetry and other factors.

This paper comprehensively considers the factors of deformation between cylinder liner and piston ring, the surface roughness of contact surface, and the gas leakage caused by the piston ring, combing all of the friction, lubrication and dynamic behaviors and establishes the frictional model of piston ring-cylinder liner using the software of GT-Suite.

Then, the frictional characteristics of piston ring and cylinder liner under rated condition was studied by using this model. The influence of oil temperature and rotational speed on the friction characteristics was also analyzed.

2 Theoretical analysis

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2.1 Analysis of Hydrodynamic Lubrication between Piston Ring and Cylinder liner

For the interaction between piston ring and cylinder liner surface, adopt the theory of raised by Patir and Cheng. Using the finite difference method in the length of axial direction in the piston ring, we can get the which represents the fluid frictional force.

Fluid dynamic pressure force between piston and cylinder surface is:

$$\frac{\partial}{\partial x} \left(\phi_x h^3 \frac{\partial p_h}{\partial x} \right) + \frac{\partial}{\partial y} \left(\phi_y h^3 \frac{\partial p_h}{\partial y} \right) = 6\mu U \left(\frac{\partial h_T}{\partial y} + \sigma \frac{\partial \phi_s}{\partial y} \right) + 12\mu \frac{\partial h_T}{\partial t} \quad (1)$$

In the equation, p_h is average fluid pressure, σ is the surface roughness between two surfaces, U is axial direction movement velocity of piston, h is nominal thickness of oil film, h_T is the actual thickness of oil film, ϕ_x and ϕ_y are pressure flow factor, μ is dynamic viscosity, t is time, ϕ_s is shear flow factor.

The dynamic viscosity of lubrication oil can be defined by equation

$$\mu = \frac{5.6625 \times 10^4}{(t+40)^{4.5076}} \rho \quad (2)$$

In the equation, μ is the temperature of ubrication oil, ρ is the density of lubrication oil.

Shear force and hydrodynamic friction F caused by hydrodynamic pressure are listed below

$$\tau = -\frac{\mu U}{h_T} (\phi_f + \phi_{fs}) + \phi_{fp} \frac{h_T}{2} \frac{\partial p_h}{\partial x} \quad (3)$$

$$F_h = R \iint_A \tau(\theta, y) \cos \theta d\theta dy \quad (4)$$

In the equation, ϕ_f , ϕ_{fs} and ϕ_{fp} are shear pressure factor, τ is the function of cut stress in the Axial and circumferential direction of piston.

2.2 Asperity elastic contact analysis

Due to the fact that there is always a thin shear film on the rough contact surface, the rough surface contact theory proposed by Greenwood and Trip is used to obtain the peak friction.

Assuming that the surface height obey the Gaussian, the peak load on the perimeter of the piston ring-cylinder liner under elastic deformation is:

$$W_A = \frac{16\sqrt{2}}{15} \pi (\eta \beta \sigma)^2 E' \left(\frac{\sigma}{\beta} \right)^{1/2} A_a F_{5/2} \left(\frac{d}{\sigma} \right) \quad (5)$$

$$A_r = \pi^2 (\eta \beta \sigma)^2 A_a F_2 \left(\frac{d}{\sigma} \right) \quad (6)$$

In the equation, η is the peak density in the roughness surface, β is Radius of curvature at the top peak, A_a is the nominal contact area, d is the distance between two surfaces (nominal oil film height), E' is the integrated elastic modulus between two surfaces, $F_{5/2}$ and F_2 is the equation model of F_n .

When the piston ring and cylinder liner surface contact occurs, the peak shear force and peak friction F_A are

$$\tau_\alpha = \tau_0 + \alpha p_\alpha \quad (7)$$

$$F_A = \int_A (\tau_0 + \alpha p_\alpha) dA = \tau_0 A + \alpha W_A \quad (8)$$

3 ESTABLISH THE MODEL

This paper analyzed and studied the friction characteristics of piston ring-cylinder liner in diesel engine. Established models mainly include the working process model of diesel engine and the single cylinder piston-cylinder friction model, and the working process model of diesel engine provides the boundary conditions for the friction model.

Piston rings in the diesel have three different rings, in which the first two rings are gas rings, and the third ring is the oil ring. The specific parameters of these rings are showed in Table 1. The GT-Suite software was used to establish a single cylinder piston-cylinder liner friction diesel engine model, which was shown in Fig.1.

Figure1. Piston ring - cylinder liner friction model

3.1structural parameters

The single cylinder diesel engines piston ring - cylinder liner structural parameters and some performance indicators was shown in Table 1.

Table1 Piston ring - cylinder liner structural parameters and performance indicators

Constructural factor and power indicator of piston ring and cylinder			
Mass of piston	2.63kg	Poissons ratio	0.32
Length of crank	91mm	Diameter of cylinder	150mm
Height of piston	120mm	Mass of connecting rod	7.986kg
Roughness of piston surface	0.4um	Length of connecting rod	320mm
Diameter of first ring	140mm	Height of first ring	3mm
Distance from first ring to top of piston	30mm	Elasticity of piston ring	16.1N
rpm	2000	The elasticity of first ring	24N

3.2 Boundary condition

The boundary conditions of the piston-cylinder liner friction model are the cylinder gas pressure and the cylinder liner inner wall temperature distribution. The GT-power software calculates the cylinder gas pressure and cylinder liner wall temperature distribution under the calibration conditions.

Reference [5] Piston ring group leak analysis method, the first ring gas pressure is the cylinder gas pressure; in the piston ring opening gap throttling effect, the gas pressure between the first ring and the second ring are one fifth of the cylinder gas pressure or so, and the location of the maximum pressure value postponed; after two gas rings seal function, the amount of gas leakage between the second ring and the oil ring are small, so the gas pressure is not considered.

The boundary conditions of piston ring - cylinder liner friction model are shown in Figure 2.

Figure2(a). Gas pressure at piston ring

Figure2(b). Temperature distribution in the inner cylinder

4 Calculation results and analysis

The maximum film pressure, film thickness at the first piston rings shown in Figure 3.

Figure3(a). Change rule of the maximum oil film pressure of the piston ring **Figure3(b).**Change rule of oil film pressure of the piston ring

It can be seen from Fig.3 (a)that the maximum oil film pressure of the piston ring is generally larger than the gas pressure between the piston rings which because of the convergence of the oil film, resulting in an increase of the pressure of the oil film in the convergent zone.

The maximum oil film pressure of the first ring and the change gradient is large, the maximum value appears at the place where piston is near the compression top dead point, and the maximum oil film pressure of the oil ring is small and appears the average periodic changes, this is because the gas pressure between the first ring and the second ring on the oil film plays a major role. After the first two piston rings seal, the gas pressure between the oil rings drastically decreases. The elastic force and motion of the oil ring play a major role on the oil film pressure.

It can be seen from Fig. 3 (b)that the minimum oil film thickness of the first piston rings appears at 0 °C A, during one stroke of the pistons, which correspond exactly to the upper and lower dead points of piston ring movement, which because that at this time the piston movement speed is very low, resulting in lower viscosity of lubricating oil;

In a piston stroke, the film thickness is at its largest when piston ring is located in the middle of the cylinder, due to dynamic pressure lubrication theory, the higher the velocity, the more viscosity of lubricating oil, then the thicker the thickness of the film, when the piston ring speed reaches its maximum , the film thickness also reaches its maximum;

The thickness of the top oil film is the smallest at the last stage of the working stroke (0 to 180) and the compression stroke (-80 to 0), indicating that the gas pressure greatly affects the oil film thickness.

4.1Friction and friction power consumption

The first piston rings friction and friction power are shown in Figure 5.

Figure4(a). The variation of friction force at piston ring **Figure4(b).** Change rule of the peak friction of the piston ring

It can be seen from Fig.4 that the peak friction of the first ring mainly occurs near the top dead center of combustion, and the value of the friction force is obviously higher than that of the other moments the peak element friction of the oil ring is almost zero during the whole cycle, which is due to the lubricating condition of the oil ring is good and the oil film is thicker.

Figure5. Change rule of piston ring friction power consumption

It can be seen from Fig.5 that ,for the first ring, the maximum frictional power dissipation of 1096.86W appears at 69.3° A with a slight lag from where the maximum friction occurs due to the fact that the frictional power loss is the result of a combination of friction and velocity Compression stroke and work stroke friction power consumption was significantly higher than other strokes, exhaust stroke and intake stroke friction power consumption quite.

Through the simulation results can also be seen: the first ring of the worst working environment Lubrication conditions are poor, high wear and tear, heat load, should be taken into account in the design. The following emphasis on the first ring for research and analysis.

4.2 piston ring torsional deformation and instantaneous elastic deformation

The first piston ring torsional deformation and instantaneous elastic deformation, as shown in Figures 6.

Figure6. Change rule of the distortion of the first ring

It can be seen from Fig. 6 that the distortion of the first ring is obviously large, especially the work stroke, the maximum twist and the maximum gas pressure in the cylinder. This is because the gas pressure inside the cylinder is large Resulting in a larger gas torque resulting in a larger amount of twisting. The amount of twisting of the first ring and the second ring is averaged over the other three strokes. The amount of twisting of the oil ring is periodically changed and averaged throughout the cycle. The amount of torsional deformation of the piston ring The direction opposite to the direction of the piston movement; the larger the amount of torsion of the piston ring, the smaller the corresponding friction and oil film thickness, the less the use of lubrication, which is due to the piston ring torsion lead to reduction of piston ring and cylinder liner contact surface, Large, film thickness decreases.

4.3 Effect of oil temperature on friction characteristics

The front of the diesel engine calibration conditions piston ring - cylinder friction characteristics were analyzed and found that the state of the lubricant has a great influence on the friction characteristics, and in the actual work process oil temperature is also affected by the cooling system. Therefore, the effect of oil temperature on the friction characteristics is further studied. The friction characteristics of the first ring when the oil temperature is 60°C, 70°C, 80°C, 90°C and 100°C are calculated respectively, as shown in Fig. 7.

Figure7(a). The effect of oil temperature on t the thickness of the first ring oil film **Figure7(b).** The trend of the thickness of he minimum oil film thickness

As can be seen from Fig.7, the trend of the thickness of the first ring oil film is similar at different oil temperatures. The higher the oil temperature, the thinner the oil film thickness is. This is due to the significantly lower viscosity of the lubricating oil with increasing temperature. The temperature rise of the minimum film thickness showed a significant decline, but the decline decreased. Oil temperature increased from 80°C to 100°C , the minimum oil film thickness decreased 28.7%, showing the oil temperature has a greater impact on the thickness of the oil film; at the same time as the oil temperature increases, the minimum oil film thickness decreases, piston ring - cylinder friction form in mixed lubrication The chances of lubrication with the boundary increase, not conducive to lubrication.

Figure8(a). The effect of oil temperature on first ring frictional power consumption **Figure8(b).** The effect of lubricating oil temperature on frictional power consumption

From Fig. 8(a) and Fig.8(b), it can be seen that the change tendency of the frictional power consumption of the first ring at different oil temperatures is similar. The higher the oil temperature, the lower the frictional power loss. This is attributed to the friction of the fluid caused by the decrease of the viscosity of the lubricating oil with the increase of the temperature As the oil temperature increases, the maximum frictional power consumption decreases significantly, but the decline decreases gradually. When the oil temperature rose from 80°C to 100°C , the maximum friction loss decreased by 41% and the average friction loss decreased by 37.3%. The effect of oil temperature on frictional power consumption was significant.

4.4 Effect of Speed on Frictional Characteristics

Through the above analysis, it is found that the moving speed of the piston ring has a great influence on the frictional characteristics. Therefore, the influence of the moving speed on the frictional characteristics is also studied in this paper. The friction characteristics of the first ring was studied when the engine speed is 2000 r / min, 1800 r / min, 1600 r / min and 1400 r / min.

Figure9(a). Effect of rotational speed on the thickness of the first oil film **Figure9(b).** Effect of Speed on the Frictional Power Consumption of the First Ring

From Fig. 9(a), it can be seen that the changing trend of the thickness of the first oil film at different speeds is similar. The higher the speed is, the thicker the oil film thickness is, but the influence is not big. This is because according to the dynamic pressure lubrication theory, Oil viscosity increased when the speed increased.

From Fig. 9(b), it can be seen that the trend of the frictional power loss of the first ring at different rotational speeds is similar, and the higher the speed is, the higher the frictional power is. This is because the higher the rotational speed per unit time, the longer the piston ring moves. At the same time, the change of speed has a significant effect on the frictional power consumption of compression stroke and work stroke.

5 Conclusion

This article establishes the model of friction between piston ring and cylinder liner using the software of GT-Suite, combining the friction, lubrication and dynamics, and researching the whole frictional characteristic of piston ring. The conclusions are listed below:

The max oil film pressure at the first ring vary greatly and the latitude of vary is big too, the max point occur around the comprocess top dead point. The frictional force and frictional power at the first ring are big and vary greatly at the stage of power and comprocesses. Therefore, the working condition at the first ring is the worst, lubrication condition, friction wear, and the temperature load are worse, we should pay more attention at the stage of design and use. Under different oil temperatures, the variation tendency of the friction characteristics of the piston rings is similar, but have a significant effect on the friction characteristics of the piston rings.

As the oil temperature increases, the oil film thickness is significantly reduced at the same time the frictional power consumption is significantly reduced too. Considering the effect of oil temperature on oil film thickness and frictional power consumption, we can conclude that the minimum oil film thickness and frictional power loss are ideal when the oil temperature is in the range of 80 ~ 90°C , which provides some references for the matching of lubricating oil cooling system.

The changing tendency of the friction characteristics of piston rings under different speed conditions is similar. With the increase of rotational speed, the thickness of the oil film increases while the frictional power consumption increases too. The rotational speed has little effect on the oil film thickness, but has a significant impact on the frictional power consumption.

References

1. Ye Xiaoming, Jiang Yankun, Hao Xiuli et al. Effect of Radial Deformation of Cylinder Liner on Elastohydrodynamic Lubrication Performance of Piston Ring[J]. Vehicle Engine, 2007, 168(2): 22-25
2. Zhou Long, Bai Minli, Lu Jihe et al. Study on heat transfer, lubrication and friction of piston ring-cylinder liner of internal combustion engine by coupling analysis method [J]. Journal of Internal Combustion Engines, 2008, 26(1): 69-75
3. Li Minghai, Li Xiaowei, Yan Shukuan. Effects of oil temperature on lubrication performance of main journal bearings [J]. Diesel Locomotives, 2009,
4. Liu Na. Study on the friction and lubrication performance of key friction pairs of diesel engine [D]. Shandong: Shandong University, 2012.
5. Yang Liping, et al. Analysis of Deformation Friction of Engine Cylinder Tubes and Approaches to Reduce Measures [J]. Automotive Practical Technology, 2017, 03: 54-56.