Study on Film Characteristics of Piston-Cylinder Interface of High-Pressure Common Rail Radial Piston Pump with Micro Motion

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Abstract. When the high-pressure common rail radial piston pump works, the piston is subjected to film pressure and cam driving force, resulting in some micro-motion such as offset and inclination. A large number of theoretical studies have shown that the micro-motion of piston has an important effect on the film characteristics of piston-cylinder interface. In this paper, according to the theory of hydrodynamic lubrication, Reynolds equation and film thickness equation of piston micro-motion are established, and solve the problem of the lubricant film of the piston-cylinder interface under different working conditions. The results show that the working pressure and cam speed have great influence on the film characteristics of piston-cylinder interface with micro-motion. The research results provide theoretical support for the optimization of the film parameters of the piston-cylinder interface.

1. Introduction
In recent years, with the increasingly stringent emission regulations and the continuous progress of electronic control technology of diesel engine, high-pressure common rail fuel injection system with its remarkable advantages has become the main trend of modern diesel engine technology development [1]. Piston-cylinder interface is the key friction pair of radial piston pump in common rail system, the film characteristics of which determine the working state of the piston-cylinder interface.

In addition to macro reciprocating motion, the piston also has micro motion while it is working on the micro scale. The micro-motion of the piston determines the film thickness of the piston-cylinder interface, the pressure distribution, and the force applied to the piston. Compared with the piston-cylinder interface of axial piston pump, the working pressure and movement of the piston-cylinder interface of radial piston pump are more complicated. Based on the theory of hydrodynamic lubrication, the film thickness equation and Reynolds equation of piston-cylinder interface with micro-motion are established in this paper. By solving the above equations, the film thickness and film pressure taking into account the micro-motion of piston are studied. The research results have certain theoretical and engineering value.

2. Mathematical model
The structural model of the piston-cylinder interface is shown as Fig. 1. The centre of the end face of the cylinder is taken as the origin, e as the eccentric distance of the piston-cylinder interface and θ as the eccentric angle of the piston. A is near the piston cavity and B is near the slipper. The film of piston-cylinder interface is expanded along the circumference direction, as shown in Fig. 2. x is the direction of the cylinder circumference, y is the...
axial direction of the cylinder, and $z$ is the direction of the piston-cylinder interface film thickness. $u$, $v$ and $w$ are the speed components of lubricating film in $x$, $y$ and $z$ directions.

![Diagram of piston-cylinder interface](image)

Fig 1. Eccentric model of piston-cylinder interface

Fig 2. Lubricant film model for piston-cylinder interface

2.1. Reynolds equation of lubrication film

In the study of Reynolds equation of piston-cylinder interface, the following hypothesis is made: Film flow is laminar flow, without turbulence and eddy current. The film has no slip on the piston-cylinder interface, neglecting inertia force and volume force. The film of the piston-cylinder interface is very thin. The pressure variation along the thickness direction of the film is not considered in modeling, but the velocity gradient along the $X$ and $Y$ directions is considered. Based on the above assumptions, under the micro motion conditions, the Reynolds equation of lubrication film of piston-cylinder interface can be expressed as:

$$\frac{\partial}{\partial x} \left( \frac{\rho h^3}{\mu} \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\rho h^3}{\mu} \frac{\partial p}{\partial y} \right) = 6 \nu \frac{\partial (\rho h)}{\partial y} + 12 \frac{\partial (\rho h)}{\partial t}$$

(1)

Where, $h$ is the film thickness, $\rho$ is the lubricating film density, $p$ is the film pressure, and $\mu$ is the film viscosity.

2.2. Film thickness equation

The piston sub-film thickness expansion equation can be expressed [4] as:

$$h(\theta, y) = C + \left[ e + \theta(y - 0.5) \right] \cos(\phi)$$

(2)

Where $C$ is the average gap between the piston and the cylinder, $\phi$ is the angle between the center line of any two sections in the axial direction of the piston and the $x$ positive half axis.

2.3. Reynolds boundary condition of piston-cylinder interface

The Reynolds boundary of piston-cylinder interface has three kinds: Reynolds boundary, half Sommerfield boundary and all Sommerfield boundary [5,6,7]. When the full Sommerfield is used to solve the problem, the bearing capacity of the lubricating film is small, which is not consistent with the actual situation. The semi Sommerfield boundary is simple and direct, but it cannot meet the continuity requirement of film flow. The Reynolds boundary not only satisfies the continuity requirements of film flow, but also avoids negative points [8]. Therefore, the Reynolds boundary is used to solve the Reynolds equation of lubricating film of piston-cylinder interface.

- Pressure outlet boundary conditions:
  $$P(x, 0) = 0$$
  (3)

- Pressure inlet boundary conditions:
  $$P(x, L) = P_s$$
  (4)

- Periodic boundary conditions:
  $$P(0, y) = P(2\pi d, y)$$
  $$\frac{\partial P}{\partial x}(0, y) = \frac{\partial P}{\partial x}(2\pi d, y)$$

(5)

2.4. Performance parameters of piston-cylinder interface
In the lubricating film of piston-cylinder interface, a micro-surface with a length of $dx$ and a width of $dy$ is selected. The pressure on the micro-surface is $p$, and the force of micro-surface acting on the piston is $pdxdy$.

The force of the bearing capacity $F_x$ and $F_y$ of the lubricating film in the $x$ and $y$ directions can be expressed as:

$$
F_x = -\int_0^L \int_0^{2\pi R_p} p(x,y)\cos\left(x/R_p\right) dx dy
$$

$$
F_y = -\int_0^L \int_0^{2\pi R_p} p(x,y)\sin\left(x/R_p\right) dx dy
$$

(6)

The force of the bearing capacity of the lubricating film on $x$ and $y$ is:

$$
M_x = -\int_0^L \int_0^{2\pi R_p} yp(x,y)\sin\left(x/R_p\right) dx dy
$$

$$
M_y = -\int_0^L \int_0^{2\pi R_p} yp(x,y)\cos\left(x/R_p\right) dx dy
$$

(7)

The flow rate of the lubricant film along the coordinate axis $y$ is:

$$
Q = \int_0^{2\pi R} \int_0^L v dz dx
$$

(8)

3. Calculation results and analysis

The generalized Reynolds equation of the piston-cylinder interface is an elliptic equation. The Reynolds boundary and the explicit point iterative method can satisfy the solution requirements, and the numerical solution is solved in MATLAB [9]. The cam speed and the film inlet pressure are the main parameters that affect the characteristics of the piston-cylinder interface sub-film. When the working condition is fixed, the greater the cam pressure angle, the greater the external load the piston bears. And the film characteristics of the piston-cylinder interface becomes the worst. The influence of cam speed and film inlet pressure on the film characteristics of piston-cylinder interface with micro-motion is studied under the max cam pressure angle.

3.1. Variation characteristics of film thickness and pressure of piston-cylinder interface

3.1.1 Variation characteristics of film thickness

Taking the cam speed 500 r/min, the film inlet pressure 40 MPa and the cam pressure angle maximum as example, the film thickness distribution characteristics of piston-cylinder interface are studied, as shown in Fig.3.

Fig 3. Film thickness distribution

In the case of piston micro-motion, the thickness of the film changes continuously in the axial and circumferential directions. The minimum thickness of the film is at the intersection of the axis corresponding to the expansion angle $\pi$ and the end face of the film outlet. The thickness of film is closely related to the lubrication characteristics of the piston-cylinder interface. The lubrication characteristics of the thick film are better than those of the thin film. The thickness of film of piston-cylinder interface is different under different working conditions, but the distribution of film thickness is basically the same.

3.1.2 Variation characteristics of film pressure
When the cam speed is 500 r/min, the working pressure is 40 MPa and the cam pressure angle is maximum, the dimensionless value of the eccentricity angle of the piston is 0.55, and the film pressure distribution is compared with the reference [10], as shown in Fig. 4.

3.2. Effect of working pressure on film characteristics of piston-cylinder interface

The film thickness and pressure distribution of piston-cylinder interface under different inlet pressure conditions were studied with the cam speed of 500 r/min and the maximum pressure angle as an example. The effect of different inlet pressure on the minimum film thickness of piston-cylinder interface is shown in Fig. 5.

The minimum film thickness of the piston-cylinder interface increases with the increase of the working pressure, and the minimum film thickness increases obviously when the film inlet pressure is low. When the film inlet pressure increases to a certain value, the minimum film thickness growth rate slows down. Increasing the inlet pressure of the film will help to increase the minimum film thickness and improve the lubrication characteristics of the piston-cylinder interface.

Under different inlet pressure conditions, the film pressure of the piston-cylinder interface varies along the axis direction corresponding to the expansion angle \( \pi \), as shown in Fig. 6.
Fig 6. The effect of film inlet pressure on film pressure variation along the expansion angle $\pi$ corresponding to axial direction

The film pressure gradually decreases along the axis direction corresponding to the expansion angle $\pi$, and the inlet pressure is relatively linear when the inlet pressure is low. When the inlet pressure is high, the nonlinear change of the film pressure gradually appears. The greater the inlet pressure, the greater the rate of decline of the film pressure in the axial direction.

3.3. Effect of cam speed on film characteristics of piston-cylinder interface

The effect of the cam speed on the minimum film thickness is shown in Fig.7 when the film inlet pressure is 120 MPa and the cam pressure angle is at its maximum. The blue point in the figure is the minimum film thickness corresponding to different rotation speeds, and the red line is the fitting curve of each point.

Fig 7. Effect of cam speed on the minimum film thickness

The minimum lubricant film is 3.45 μm at a cam speed of 500 r/min and 1.5 μm at a cam speed of 3000 r/min. With the increase of the cam speed, the minimum film thickness decreases in a quadratic curve, and the decline rate decreases with the increase of the cam speed. With the increase of cam speed, the axial velocity of the piston increases, the movement of the piston becomes more and more complex and the extrusion effect becomes more obvious.

Under different cam speed conditions, the film pressure of the piston-cylinder interface changes along the axis direction corresponding to the expansion angle $\pi$, as shown in Fig.8.

Fig 8. Film pressure variation along the expansion angle $\pi$ corresponding to axial direction

When the sealing position is fixed, the minimum film thickness decreases gradually with the increase of eccentric angle of piston, resulting in the gradual increase of film pressure. When the cam speed is low, the eccentric angle and offset of the piston are small, and the film pressure changes linearly along the axis direction corresponding to the expansion angle $\pi$. As the cam speed increases
gradually, the eccentric angle and offset of the piston increase, the film pressure first increases and then decreases, and the larger the rotational speed, the greater the pressure increase. Piston velocity is one of the main factors affecting the lubrication characteristics of the piston-cylinder interface. The greater the cam speed, the greater the reciprocating velocity of the piston, and the larger the offset and the offset angle, the greater the influence of the piston motion on the film pressure.

4. Conclusion
Based on the fluid lubrication theory, this paper establishes a hydrodynamic lubrication model for the piston of the high-pressure common rail radial piston pump that is included in the micro movement of the piston. The film properties of the piston-cylinder interface under different working conditions were discussed by solving the Reynolds equation and the film thickness equation of the piston. The following important conclusions can be drawn from the research:

(1) Due to the different working conditions, the thickness of piston vice film is changing. When the inlet pressure of the film is fixed, the eccentric angle of piston increases with the increase of cam speed, and the minimum film thickness decreases in a quadratic curve. When the cam speed is fixed, the eccentric angle of the piston decreases with the increase of the film inlet pressure, and the minimum film thickness increases in a quadratic curve. The film pressure is closely related to the thickness of the film. The sealing position is fixed, the pressure at the position where the film thickness is large is small, and the pressure at the position where the film thickness is small is large.

(2) When the inlet pressure of the film is fixed, the greater the cam speed, the smaller the minimum film thickness, and the lower the film bearing capacity, the worse the lubrication performance of the film. When the cam speed is low, the film pressure changes linearly along the axis direction corresponding to the expansion angle $\pi$; when the cam speed is high, the film pressure first increases and then decreases, and the rotational speed increases as the film pressure increases. The speed of the cam is fixed, and the greater the pressure of the film inlet, the greater the minimum film thickness. The lubrication performance of the piston-cylinder interface has been improved to a certain extent due to the enhancement of the bearing capacity of the lubricant film.

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