Analysis of thermal lubrication characteristics of aero-gear pump journal bearing

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Abstract. In order to study the thermal lubrication characteristics of aero-gear pump journal bearing (APJB) under certain load and low medium viscosity, a APJB numerical model was established based on the combination of Reynolds and adiabatic flow energy equations. The hydrodynamic lubrication and temperature effects on the viscosity are considered and the finite difference method is adopted. The results show that with the increase of APJB width parameters, the eccentricity decreases monotonically, the minimum oil film thickness increases, the friction resistance increases and the end discharge decreases. In addition, the eccentricity of bearing, maximum oil film pressure, end discharge flow and oil film thickness increase with the APJB radial clearance, while the friction and temperature inside the APJB decrease. When the APJB width changes from 21 to 27mm, the maximum oil film temperature and pressure increases by 2.16% and −35.23%, respectively; when the radial clearance changes from 0.0315 to 0.0413mm, the maximum oil film temperature and thickness decrease by 3.03% and 8.99%, respectively.

1. Introduction
APJB is one of important supporting parts of aero-engine fuel gear pump. Its lubrication performance is of great significance to guarantee the life and reliability of the pump. In the actual working process, APJB temperature inevitably rises due to the viscous dissipation [1], which causes the smaller lubricating oil viscosity and thinner oil film thickness. That seriously affect lubrication characteristics and APJB possibly fails due to the glue and wear. Thermal lubrication characteristics of APJB is urgently clarified in order to ensure the service life and reliability of aviation gear pump shafting.

The oil film temperature distribution seriously affects the journal bearing lubrication characteristics. Many researches on thermal effect are conducted. Dai et al. [2] analyzed the influence of oil cavity depth on the temperature field of heavy-duty hydrostatic sliding bearing; Akbar Zadeh et al.[3] studied the influence of gasket number, axial position and speed on bearing performance; Li et al.[4] researched the temperature distribution of sliding bearing considering the thermal effect; Li et al.[5] analyzed the performance of eccentric Journal Bearing; Bagheri et al. [6] studied the influence of load and speed on bearing; Solghar et al.[7] obtained the influence of boundary conditions on the fluid flow and heat transfer process in the finite length journal bearing.

The APJB uses low medium viscosity RP-3 fuel as the lubricating medium. The relevant lubrication characteristics and data of the sliding bearing formed in the current open literatures cannot meet the design requirements of the aviation sliding bearing, which caused the service life of the
domestic fuel pump sliding bearing is short. In this paper, the Reynolds and adiabatic flow energy equations are solved by the finite difference method. Thermal lubrication characteristics of APJB are studied with different width and radius clearance under low medium viscosity and certain load conditions.

2. Thermal lubrication calculation model for aero-gear pump journal bearing

Figure 1 is the APJB structural diagram. It doesn’t have an independent lubrication system and generates dynamic pressure support by the wedge-shaped clearance oil film formed between the gear shaft and the bearing, which avoids the direct contact between the gear shaft and the bearing bush. The heat transfer through the shell is small because APJB is installed in the oil pump housing and it inside APJB is mainly depends on the end discharge of the lubricating medium. Therefore, it is assumed to be adiabatic flow in the thermal fluid calculation process.

![Figure 1. Assembly drawing of sliding bearing of gear pump.](image)

2.1. Governing equations and boundary conditions

This type of journal bearing is cylindrical structure and generates pressure to support gear shaft by hydrodynamic lubrication principle:

$$\frac{\partial}{R^2 \partial \theta} \left( \frac{h^3}{\eta} \frac{\partial p}{\partial \theta} \right) + \frac{h^3}{\eta} \frac{\partial}{\partial y} \left( \frac{h^3}{\eta} \frac{\partial p}{\partial y} \right) = 6U \frac{dh}{R \partial \theta}$$  \hspace{1cm} (1)

where \( h = c(1 + \varepsilon \cos \theta) \), \( h \) is the oil film thickness; \( \varepsilon \) is the radius gap; \( \varepsilon \) is the eccentricity; \( \theta \) is the angle in the cylindrical coordinate system; \( P \) is the oil film pressure; \( R \) is the radius of the gear shaft; \( U \) is the rotational speed of the gear shaft.

The APJB contains divergent and convergent clearances, which causes the position of oil film outlet boundary cannot be determined in advance. The natural fracture boundary condition are used in Reynolds equation. Therefore, the adopted equation and boundary are as following,

$$p = 0 \quad \text{and} \quad \frac{\partial p}{\partial \theta} = 0$$  \hspace{1cm} (2)

$$p \big|_{r=a,b/2} = p_0$$  \hspace{1cm} (3)

The changes of temperature, pressure and viscosity along the direction of oil film thickness can be ignored due to the small clearance. The energy equation of lubrication clearance oil film is as follows:

$$q_x \frac{\partial T}{\partial \theta} + q_y \frac{\partial T}{\partial y} = \frac{\eta U^2}{J \rho_c p} \left( h^3 \frac{\partial p}{\partial \theta} \right)^2 + \left( h^3 \frac{\partial p}{\partial y} \right)^2$$  \hspace{1cm} (4)

where \( q_x = \frac{U h}{2} \frac{h^3}{12 \eta \rho c} \frac{\partial p}{\partial \theta} \); \( q_y = -\frac{h^3}{12 \eta \rho c} \frac{\partial p}{\partial y} \). \( J \) is mechanical equivalent of heat; \( \rho \) is the density of lubricating oil; \( c_p \) is the specific heat of lubricating oil; \( T \) is the temperature.

Considering the effect of temperature on viscosity, Reynolds temperature viscosity equation which is more practical is adopted as following.
\[ \eta = \eta_0 \exp \left\{ \ln \eta_0 + 9.76 \left[ \frac{T - 138}{T_0 - 138} \right]^{1.1} - 1 \right\} \] (5)

2.2. Numerical calculation process
The finite difference and over relaxation iterative methods are used to solve Reynolds and energy equations. Figure 2 shows the specific calculation flow. Firstly, the initial eccentricity is set. The initial pressure, film thickness, viscosity and temperature are given to calculate the oil film thickness distribution \([H]\) and pressure distribution \([P]\); then the current temperature and corresponding viscosity are obtained by solving the oil film energy and viscosity equations, and the convergence is judged by the pressure relative error. The oil film bearing capacity, which is obtained by the pressure integral, is judged whether it is in balance with the external load so as to adjust the eccentricity. Finally, the bearing lubrication characteristic parameters are obtained when the gear shaft is in balance.

3. Results and analysis

3.1. Influence of bearing length on bearing temperature rise under certain load
The influence of bearing width on lubrication characteristics with the certain external load is studied. The variation range of bearing width is 21, 23, 24, 25, and 27mm. The radius clearance, rotating speed, and inlet temperature of lubricating oil are 0.0043mm, 8000r / min, and 303K, respectively. The ends of the bearing are air pressure. In order to make the results representative, the radial loads of gear pump under different outlet pressures at rated speed are selected. The results are listed in Table 1.

| Serial number | Speed (r/min) | Outlet pressure/MPa | Radial force (N) |
|---------------|---------------|---------------------|------------------|
| 1             | 8000          | 10                  | 7300             |
| 2             | 8000          | 9                   | 6000             |
| 3             | 8000          | 7.6                 | 5000             |
Figures 3 and 4 show that the eccentricity decreases and the minimum oil film thickness increases with the bearing width increase. The eccentricity decreases under the unchanged bearing radius gap. The minimum oil film thickness between the journal and the bearing pad increases.

Figure 5 shows that the oil film frictional resistance increases with the bearing width. The eccentricity of the journal working position decreases and the oil film rupture position is pushed back, so the shear resistance increases. The deflection angle and pressure flow resistance increase with the bearing width.

Figure 6 shows that the end leakage flow rate decreases with the bearing width increase. The oil film pressure gradient in the axial direction determines the end leakage flow rate. The eccentricity and pressure gradient decrease with the bearing width increase. The increase of axial flow resistance causes the pressure gradient drop. These make the end leakage flow decrease. The increase of frictional heat cannot be effectively taken away due to the end discharge flow reduction and APJB temperature rise.

Figure 7 shows that the trend of temperature distribution is basically same. The temperature peak is mainly distributed in the center and front end of the bearing area and both ends of the minimum oil film thickness. The temperature distribution of oil film is related to its thickness and pressure gradient. When the bearing width changes from 21 to 27mm, the maximum oil film temperature increases by 2.16%.

Figure 8 shows that the oil film pressure is the highest in the center. The oil film pressure decreases with the lubricating oil viscosity and the increase on the film thickness. The minimum oil film thickness increases with the bearing width, which leads to the decrease of the oil film pressure, and the oil film pressure further decreases with the lubricating oil viscosity. When the bearing width changes from 21 to 27mm, the maximum oil film pressure decreases by 35.23%.

Figure 9 shows that the viscosity gradually decreases with the increase of bearing width, and the negative peak appears. The bearing width and temperature increases, and the viscosity and
temperature show an inverse relationship. Therefore, the viscosity of lubricating oil decreases with the temperature increase.

Figure 7. Temperature distribution under different bearing widths.

Figure 8. Pressure distribution under different bearing widths.
3.2. Influence of radial clearance on bearing temperature rise under a certain load

This section studies the influence of the eccentricity of the gear shaft on the bearing temperature. The variation range of bearing radius clearance is between 0.0315mm and 0.0413mm. The bearing width, rotating speed, and inlet temperature of lubricating oil are 21mm, 8000 r/min, and 303K, respectively.

Figures 10 and 11 show that the eccentricity and maximum oil film pressure increase with the radial clearance between the bearing bush and the journal. The eccentricity increases with the radius clearance, which makes the minimum oil film thickness decrease. The maximum oil film thickness continuously increases, which makes the wedge effect enhances. Then the maximum oil film pressure increases.

Figure 12 shows that the oil film friction resistance decreases with the increase on radius clearance. The eccentricity of journal working position increases and the position of oil film fracture is advanced, which causes the shear resistance decreases. The increase of radius makes the offset angle and pressure flow resistance decrease. The heat produced by the oil film decreases with the friction resistance. If the oil film thickness is too small, it will produce a large amount of hot film.

Figure 13 shows that the end discharge flow of bearing increases gradually with APJB radius clearance. Besides the increase of oil film pressure gradient in APJB axial direction, the flow capacity and area of lubricating oil between journal and bearing bush increase, which leads to the increase of end discharge flow. The heat generated by friction decreases with the force, and the increase of end discharge can effectively take away the friction heat, the temperature inside APJB will inevitably decrease.
Figure 14 shows the basic trend of temperature distribution under different radius clearance is basically same, and the temperature peak is mainly distributed in the bearing center, the front end of the bearing area and both ends of the minimum oil film thickness; with the increase of the radius clearance, the temperature rise gradually decreases and the radius increases. When the gap changes from 0.0315 to 0.0413mm, the maximum oil film temperature decreases by 3.03%.

Figure 15 shows that the oil film thickness distribution in axial direction is same with the change radius clearance. In circumferential direction, the oil film thickness with different radius clearances decreases from the maximum of 0°C to the minimum at 180°C, and then gradually increases to the maximum at 360°C. The difference is that with the increase of radius clearance, the minimum oil film thickness gradually decreases. The maximum oil film thickness increases, which enhances the wedge dynamic pressure effect of convergence gap. The minimum oil film thickness decreases by 8.99% when the radius clearance changes from 0.0315 to 0.0413mm. The oil film thickness increases with the bearing radius clearance, flow capacity and area of lubricating oil between journal and bearing bush increase.
4. Conclusion
With the increase on APJB width, the eccentricity decreases monotonically, the minimum oil film thickness, friction resistance and internal temperature increases, the end discharge decreases; APJB eccentricity increase with radial clearance, then the oil film pressure maximum value, end discharge flow and oil film thickness increases, the friction force and internal temperature decreases. When APJB width change from 21 to 27mm, the maximum oil film temperature and pressure increases by 2.16% and −35.23%, respectively. With the increase on APJB radius clearance, the minimum film oil film thickness and oil film temperature decreases, the viscosity increases. When the radius clearance changes from 0.0315 to 0.0413mm, the maximum oil film temperature and thickness decreases by 3.03% and 8.99%, respectively.
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