A Study on the Axial Flow of a Metal Progressing Cavity Pump

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Abstract. As a new type of oil production machinery, the metal progressing cavity pump has good adaptability for the working conditions of heavy oil thermal recovery. Because the stator and rotor of the metal progressing cavity pump are made of metal, the clearance fit is adopted. This paper analyzes the working principle of the metal progressing cavity pump, studies the clearance of the stator and rotor of the metal progressing cavity pump. Based on the Reynolds equation, the mathematical model of the clearance flow is established. The equivalent model of the axial clearance is established, the friction force and the flow are studied in depth, and the basis for analyzing the leakage and fatigue wear of the metal progressing cavity pump is provided.

1. Working Principle Of Metal Progressing Cavity Pump

Oil extraction progressing cavity pump is a commonly used hydraulic machinery in petroleum exploitation, and belongs to rotor type cative pump. The rotor of the oil extraction PCP performs planetary motion in the stator chamber, and the rotor itself makes its own rotation. The overall motion consists of these two movements. In the process of oil production, the rotor and stator are engaged each other to form the stator and rotor pairs. Due to the cycloidal multiple equivalent point effect formed by the stator and rotor pairs, a close chamber is formed, when the rotor moves relative to the stator, the chamber moves axially. [1].

Metal progressing cavity pump is a new kind of progressing cavity pump in recent years. It is made up of stator and rotor progressing cavity with double head spiral cavity. The stator is made by the hydroforming technology. The inner surface of the stator is treated by plating process to improve its hardness and wear resistance. The surface of the rotor is also polished and chrome plated to increase its hardness, thus prolonging its service life. [2] Because of the clearance coordination between the stator and rotor, the PCP of the metal stator will also have clearance between the chambers. When the progressing cavity pump begins to work, the rotor rotates in the inner cavity of the stator. The cavity volume formed by the fixed rotor wall is constantly changing, showing a single direction process. In the process of enlarging the cavity volume of the entrance, the fluid in the chamber is lifted by the pressure acting on the fluid medium into the slowly expanding chamber and filling the chamber to complete the closure, and the rotor continues to rotate the chamber to a higher position, and the chamber liquid is lifted. [3] The entrance forms a new enlarged chamber, the oil enters the new chamber, and the
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circulating chamber is generated and passed, which can transport the oil step by step to the high position to achieve the oil lifting.

The inner surface of the stator of the tradition single head PCP is covered with a layer of rubber, so the interference fit between the stator and the rotor can be used to ensure the closeness between the chambers. The stator and rotor of the metal stator PCP are made of special steel. Because of the material characteristics, the interference fit is not possible, but the clearance fit is adopted. [4] The seal between the chambers is realized by the viscous properties of the oil medium and the metal surface, and the existence of the clearances inevitably result in leakage, friction and corrosion. [5] Under the stable working condition of the metal stator PCP, the single stage differential pressure and the volume of the pump remain stable. Because of the principle of the volume pump, the flow is uniform and there is no larger impact flow.

2. The Clearance Of Metal Stator PCP

The clearance between the stator and rotor in the metal stator PCP will form two clearances, radial clearance and axial clearance. In the clearance along the section, the axial clearance between the inner surface of the stator and the axial surface of the outer surface of the progressing cavity is the axial clearance. The annular clearance belt formed by the cross section circle of the progressing cavity and the cross section circle of the stator inner cavity is radial clearance, and the positions and shapes of the two clearances are quite different. The clearance value of radial clearance is basically the difference of circular radius between stator and rotor section. The clearance is larger, and it is perpendicular to the direction of the pump fluid. The axial clearance is formed by the inner cavity surface of the stator and the rotor surface, so the clearance zone presents the state of axial distribution. [6].

Due to the existence of axial and radial clearance, the pressure difference between the inlet and the outlet of the metal stator PCP increases gradually. Under the action of pressure difference, the fluid medium will form leakage flow through the clearance, including the axial and radial clearance flow, which is the total leakage flow of the metal stator PCP. [7].

Under the action of pressure difference, the fluid medium flows from high pressure to low pressure through cracks in the flow field of metal stator progressing cavity pump, because the length of the two clearances is much larger than the clearance height, and the axial clearance height usually changes along the axis. After comparison with the common clearance flow model, the clearance flow in the axial clearance can be simplified into a slit flow model of a relatively inclined plate, and the clearance flow in the radial clearance is simplified into a clearance flow in the concentric annular clearance with a taper.

3. Axial clearance flow of single metal PCP

Because petroleum is a viscous incompressible fluid, its mathematical model can be derived from Reynolds equation by N-S equation and continuous equation:

\[ \frac{d}{dx} \left( \rho \frac{dp}{dx} \right) = 6\eta \frac{dh}{dx} \]

When the equation is integrated two times, its general solution can be written:

\[ p = \int \frac{6\eta}{\rho} \frac{dx}{h^3} + C_1 \frac{dx}{h^2} + C_2 \]

In the formula, C1 and C2 are integral constants, determined by the following boundary conditions. The two commonly used boundary conditions are as follows:

- \( p|_{x=0} = 0 \); \( p|_{x=B} = 0 \) (x is the export boundary, x=B, B is the width of slider)
- \( p|_{x=0} = 0 \); \( p|_{x=x^*} = 0 \) (x* is the undetermined export boundary, x*B)

When the thickness function is discontinuous or its derivative is discontinuous, the two sides pressure equation is written in discontinuities as the dividing line, so the number of undetermined integral constants will increase accordingly. Therefore, the corresponding connection conditions must be added to the discontinuities. If the coordinates at discontinuity are x*, then the connection condition is:

Pressure continuous condition:
Flow continuous condition:

\[
p|_{x=-x^*} = p|_{x=+x^*}
\]  \hspace{1cm} (1)

Figure 1. Axial clearance equivalent diagram

① As shown in Fig. 1, the oil film thickness equation for axial clearance is first determined. Set \( k = \frac{h_1 - h_0}{h_0} \)

So \( h = h_0(1 + k \frac{x}{b}) \)

② Pressure distribution

Since the oil film thickness \( h \) is linear to the coordinate \( x \), the derivative of the film thickness with respect to \( x \) can be obtained:

\[
dh = k \frac{h_0}{b} dx
\]

By substituting the above equation into the one-dimensional Reynolds equation and integrating the variable \( h \), the following equation can be obtained:

\[
p = -\frac{6U\eta B}{kh_0} (- \frac{1}{h} + \frac{\overline{h}}{2h^2} + C)
\]

\( \overline{h} \) is the maximum pressure film thickness at \( \frac{dp}{dx} = 0 \), \( U \) is speed, ETA is efficiency, and \( B \) is slot length.

Using boundary condition, \( P|_{h=h_0} = 0 \) \( P|_{h=h_1} = 0 \) can be obtained:

\[
\overline{h} = \frac{2h_0h_1}{h_0 + h_1}
\]

\[
p = -\frac{6U\eta B}{kh_0} (- \frac{1}{h} + \frac{h_0h_1}{h_0 + h_1} \frac{1}{h} + \frac{1}{h_0 + h_1})
\]  \hspace{1cm} (3)

③ Calculation load

Unit length bearing capacity:
\[
W = \frac{\int_0^L P \, dx}{L} = \frac{B}{h_0 k} \int_{h_0}^{h_1} P \, dh = \frac{6U \eta B^2}{k^2 h_0^3} [\ln \frac{h_1}{h_0} - \frac{2(h_1 - h_0)}{h_0 + h_1}] = \frac{6U \eta B^2}{k^2 h_0^3} [\ln(k + 1) - \frac{2k}{k + 2}]
\]  

(4)

In the form, \(L\) is the length of the Y direction.

The extreme value of \(K\) is obtained by \(W\), \(\frac{dW}{dk} = 0\), so that the \(K\) value corresponding to the maximum carrying capacity can be obtained. When \(K=1.2\) and \(h/h_0=2.2\) are obtained, \(W\) is the maximum value.

4. Determine the pressure center

The center of pressure is the point of load, and it can be obtained by taking the moment from the origin. As shown in Fig. 1, the distance between the center of pressure and the origin is \(x_0\), and the carrying capacity per unit length is \(W/L\), so

\[
\frac{x_0 W}{L} = \int_0^L P \, dx
\]

By substituting equations (1) and (2) into the equation, we can get:

\[
\frac{x_0}{B} = \frac{k(6 + k) - 2(2k + 3)\ln(1+k)}{2k[(2 + k)\ln(1+k) - 2k]}
\]

(5)

5. Friction force analysis

Shear stress on the surface of friction force

\[
\tau = \mu \frac{\partial u}{\partial z} = \frac{\hat{\partial p}}{2} (z - \frac{h}{2}) + \frac{\eta}{h} U
\]

The force of friction per unit length is:

\[
F_{h,0} / L = \int_0^L \int_0^B \tau \, dx \, dy = \int_0^L \int_0^B \left( \frac{\partial p}{\partial x} \hat{h} + \frac{\eta}{h} \right) \, dx \, dy
\]

In the formula, \(F_{h,0}\), \(\tau_{h,0}\), and \(F_0\) and \(\tau_0\) are respectively the friction force and shear stress on the surface of \(x=h\) and \(z=0\).

The first integral of the above equation can be obtained by integration by parts:

\[
\int_0^L \frac{\hat{p}}{2} \hat{h} \, dx = \frac{1}{2} \int_0^L \frac{\partial h}{\partial x} \, dx = \frac{1}{2} \int_0^L h_0 \frac{W}{2B} \, dx = \frac{1}{2} \int_0^L h_0 \frac{W}{2B} \, dx
\]

Therefore, the friction force can be obtained as:

\[
F_{h,0} / L = \frac{\eta UB \ln(K + 1)}{h_0} + \frac{h_0 K W}{2B} L
\]

(6)

6. Flow

Assuming the ideal state, the discharge flow at the end is considered, i.e., \(q_y = 0\), so the flow is

\[
Q_x = \int_0^L q \, dy = \int_0^L \left( - \frac{h^2 \, dp}{12 \eta x} + \frac{U h}{2} \right) dy
\]

It can be proved that when \(h = \frac{h_0}{k+1}\), so the flow per unit length is

\[
Q_x = \frac{L}{U \eta B} = \frac{U h_0}{h_0 k + 1}
\]
4. Conclusions and Future Work
The clearance flow of the metal PCP directly affects its leakage, lifting performance, fatigue wear and so on. Therefore, it is necessary to study the clearance flow. Through the research on the axial clearance flow of metal PCP, the flow is determined to be related to the same amount of pressure, velocity, viscosity of medium, axial clearance size of clearance and axial clearance length. Friction is related to oil film thickness, velocity, working efficiency and clearance length.

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