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Flow Characteristic and Trapping Characteristics of Cycloid Rotor Pump

Ren Zhenxing¹, Liu Chunyan², Li Yulong¹

¹Industrial Manufacturing School, Chengdu University, Chengdu, Sichuan 610106, China;
²Safety, Environment & Technology Supervision Research Institute, PetroChina Southwest Oil & Gasfield Company, Chengdu, Sichuan 610041, China;

Abstract: To accurately calculating the flow rate of cycloid rotary pump, as well as to correctly understand its trapped oil phenomenon. Firstly, the instantaneous flow rate formula of cycloid rotary pump was established based on the method of swept area, and compared with the two present approximate formulas by an example. Secondly, based on the just established flow rate formula and the created trapped oil model in present literature, the trapped oil pressure of a single cavity near in the minimum volume position was simulated. It is pointed that for cycloid rotary pump by an example, the flow non-uniform coefficient is 6.45%, in contrast, the flow nonuniformity coefficient of external gear pump is 21.2%; Relative to the accurate results, the two present approximate errors of flow rates are 1.93% and 2.90%; and the present approximate error of flow non-uniform coefficient is 7.13%; when the minimum position angle is added by 0.5° or 1° or 2°, relative to discharge pressure of the pump, the corresponding maximum peak of trapped oil pressure is increased by 1.6% or 6.0% or 21.7%. The results indicate that the flow characteristics of cycloid rotary pump is better than external gear pump; the two present approximate errors of flow rate are little, but the present approximate error of flow non-uniform coefficient is higher; also there is a trapped oil phenomenon in cycloid rotary pump, but not obvious.

Key words: cycloid rotary pump, flow characteristics, trapped oil characteristics, simulation, trapped oil model, swept area, trapped oil pressure

As an internal cycloid gear pump (“cycloid rotor pump” for short) having a mesh with tooth difference, its characteristics are to take the equidistant curve of complete curtate epicycloid as the inner rotor tooth profile, and the outer rotor tooth profile is circular arc profile conjugated with it. The pump is widely used in the various hydraulic systems, including the vehicles [1], because it has such advantages as compact size, simple structure, stable operation, small noise and good high-speed performance. In the recent decades, a lot of studies are carried out on it at home and abroad. In the Literature [2], the tooth profile envelope forming method of the cycloid pump is studied on the basis of the envelope theory in the differential geometry; in the Literature [3], the production method of cyclical toothing and spiral rotor and their geometry are studied with the gear pump and the cycloidal toothing on the Roots blower; in the Literature [4], the geometric correction method of the cycloidal profile is proposed; in the Literature [5-11], the study is carried out on the curve and the formation of its envelope line with the principle of gear meshing and differential geometry theory from different aspects, the foreign scholars mainly focus on studying the meshing theory of tooth profile, and there are relatively few studies on the actual application problem; and in the Literature [12-15], the study is carried out on the determination of the meshing clearance and its tooth profile design and influence of pressure distribution. The domestic literatures are mainly reflected in the study and design of tooth profile [1, 16-18] and parameter selection and optimization [19-21]. In the Literature [1], the detailed study and simulation calculation are carried out on the pump theory; and in the Literature [21], the volume of its working cavity is calculated and analyzed, but the computational process is too complicated, therefore, the practicability is not strong. Since the tooth form of the inner and outer rotors is relatively complicated, there are not many studies on the flow (displacement) characteristics of the pump currently, and in the actual application, the approximation formula is mostly used for calculating [22]. For the trapping phenomenon, it is thought that the trapping phenomenon is not presented by the internal meshing pump in the common sense, but the trapping phenomenon of the internal gear pump is studied and described in the literatures and part of network data [23]. In view of this, the paper plans to carry out the further study on the flow characteristics and trapping characteristics of the pump, so as to hope to get the accurate flow calculation formula, and correctly understand the trapping phenomenon of the pump.

1. Flow Characteristics

In Fig.1, it describes three positions of the cycloid rotor pump in a complete oil absorption process. In Fig.1a, it indicates the minimum volume position of a working cavity, called minimum position for short; in Fig.1c, it indicates the maximum volume position of a working
cavity, called maximum position for short; and in Fig. 1b, it indicates one unspecific volume position of a working cavity between the maximum and minimum, called one unspecific position for short. The formed meshing points of a working cavity are set as \( n_1 \) and \( n_2 \) respectively, the volume is set as \( V_1 \), the inner rotor is called the wheel \( o_1 \) for short, and the outer rotor is called the wheel \( o_2 \) for short, wherein the wheel \( o_1 \) and the wheel \( o_2 \) refer to the corresponding wheel center.

In Fig. 1b, the angle that the wheel \( o_1 \) and \( o_2 \) turn is set as \( d \varphi_1 \) and \( d \varphi_2 \) in the small time \( dt \). At this time, the small variation \( dV_1 \) of \( V_1 \) is

\[
dV_1 = 0.5(b(r_1^2 - r_2^2) - \Delta \varphi_1) + 0.5(b(r_1^2 - r_2^2) - \Delta \varphi_2)
\]

(1)

In the formula, \( r_1 \) and \( r_2 \) indicate the pitch radius of \( o_1 \) and \( o_2 \); \( f_1 \) and \( f_2 \) indicate the length from the node \( p \) to the point \( n_1 \) and point \( n_2 \); \( k_1 \) indicates the length from \( n_1 \) to \( k_1 \); and \( l_1 \) indicates the length from \( n_1 \) to \( k_2 \). Similarly,

\[
\begin{align*}
\Delta \varphi_1 &= f_2^2 - k_2^2 \\
\Delta \varphi_2 &= f_1^2 - k_1^2
\end{align*}
\]

(3)

In Fig. 1b, if the drop foot of \( n_1 \) and \( n_2 \) on the center line \( o_1o_2 \) is set as \( k_1 \) and \( k_2 \), it exists in the right triangle \( \Delta c_1o_2c_2 \) and \( \Delta pnc_1 \),

\[
r_1^2 - (r_1 - k_1)^2 = l_2^2 = f_2^2 - k_2^2
\]

(2)

In the formula, \( r_1 \) indicates the pitch radius of \( o_1 \); \( f_1 \) and \( k_1 \) indicate the length from the node \( p \) to the point \( n_1 \) and point \( k_1 \); and \( l_1 \) indicates the length from \( n_1 \) to \( k_1 \).

In the formula, \( r_2 \) indicates the pitch radius of \( o_2 \); \( f_2 \) and \( k_2 \) indicate the length from the point \( p \) to the point \( n_2 \) and point \( k_2 \); and \( l_2 \) indicates the length from \( n_2 \) to \( k_2 \).

The center distance, i.e. \( e = 2.5 \times 10^{-3} \) m, \( z_1 = 6 \), \( z_2 = 7 \), \( R = 8.8 \times 10^{-3} \) m, \( L = 24.5 \times 10^{-3} \) m, \( b = 20 \times 10^{-3} \) m, is used; the speed of the wheel \( o_1 \) is 2000 \( r/\min \), and its geometric calculation shall be shown in the Literature \([19]\). The corresponding \( DV_1 \) and \( Q_{ab} \) under the above parameters shall be shown in Fig. 2a-b. It can be seen from Fig. 2b that, \( DV_1 \) (shown in the small circle 1 in Figure) near the minimum position is gentle, relative to that (shown in the small circle 2 in Figure) near the maximum position. It can be seen from Fig. 2b that, the maximum flow is \( 3.293 \times 10^{-4} \) m\(^3\)/s, the minimum flow is \( 3.085 \times 10^{-4} \) m\(^3\)/s, and the average flow is \( 3.226 \times 10^{-4} \) m\(^3\)/s, so the

Fig.1 Minimum volume and maximum volume and one unspecific position of a working cavity

2. Instance Analysis of Flow Characteristics

The center distance, i.e. \( e = 2.5 \times 10^{-3} \) m, \( z_1 = 6 \), \( z_2 = 7 \), \( R = 8.8 \times 10^{-3} \) m, \( L = 24.5 \times 10^{-3} \) m, \( b = 20 \times 10^{-3} \) m, is used; the speed of the wheel \( o_1 \) is 2000 \( r/\min \), and its geometric calculation shall be shown in the Literature \([19]\). The
The nonuniform coefficient of the flow is \( \delta = (3.293 - 3.085)/3.226 = 6.45\% \), which is much more stable than the nonuniform coefficient of 21.2% flow for the external gear pump with the tooth number of 10 \(^2\), and the pulse frequency \( q = n_2 z_2 / 60 \) of the flow is consistent with that of the external gear pump which is provided with the side clearance \(^2\), wherein \( n_2 \) indicates the speed of the wheel \( \omega_2 \).

The approximate calculation formula of the two flows given in the Literature \(^2\) and their nonuniform coefficient is as follows:

\[
\begin{align*}
Q_{11} &= 0.5a b r_1^2 (0.5687 - 0.0333 (L - R)/e) \\
Q_{12} &= 0.5a b r_2^2 (16.5 - 2.36 (L - R)/e + 0.44 L/e) \\
\delta &= \left[ 16.5 - 2.36 (L - R)/e + 0.44 L/e \right] \%
\end{align*}
\]  
\( (8) \)

After the calculation, \( Q_{11} = 3.288 \times 10^{-4} \text{ m}^3/\text{s} \); \( Q_{12} = 3.227 \times 10^{-4} \text{ m}^3/\text{s} \); and \( \delta = 5.99\% \). Two approximation errors of the flow are 1.93% and 2.90% respectively; and the approximation error of the nonuniform coefficient of the flow is 7.13%, wherein the approximation error of the flow is relatively small, and the approximation error of the nonuniform coefficient of the flow is on the high side.

3. Trapping Characteristics

3.1 Trapping model

The working pressure of oil in \( V_1 \) is set as \( p_1 \), and if the volume increase of \( V_1 \) is positive, it is obtained as followed according to the definition of the elasticity modulus of the fluid \( ^{24-27} \):

\[
\frac{d \phi}{d t} = K [ -DV' - Q_1 (p_1) - Q_2 (p_1) - Q_r (p_1) ] / V'
\]  
\( (9) \)

Wherein, \( K \) indicates the bulk modulus of the oil; \( Q_1 \) indicates the exchange flow that the inside and outside of \( V_1 \) pass through the meshing clearance at the point \( n_1 \) and \( n_2 \); \( Q_2 \) indicates the exchange flow that the inside and outside of \( V_1 \) pass through the axial clearance of the end face; and \( Q_r \) indicates the exchange flow between \( V_1 \) and outside oil absorption cavity and oil drainage cavity. And \(-DV_1\) is marked as the trapped oil flow.

The theoretical crescent oil absorption cavity and oil drainage cavity of the pump can be opened into the form shown in Fig.1 and Fig.3, and the oil absorption cavity and oil drainage cavity are arranged symmetrically. The included angle of the oil cavity with \( x \) axis in the minimum position is set as \( \gamma_i \), and called the included angle of the oil cavity in the minimum position for short; and its included angle with \(-x\) axis in the maximum position is set as \( \gamma_o \), and called the included angle of the oil cavity in the maximum position for short. But in fact, the density of the sealing area between the oil absorption cavity and oil drainage cavity is often increased at the oil absorption site by improving \( \triangle \gamma_i \) value appropriately on the basis of \( \gamma_i \), so as to improve the volumetric efficiency \(^1\); and meanwhile, the sufficient oil absorption is often reached at the oil absorption side with the flow inertia of the oil by reducing \( \triangle \gamma_o \) value appropriately on the basis of \( \gamma_o \), so as to improve the volumetric efficiency \(^1\).
In Fig.3, when the wheel o2 rotates a circle, V1 goes through the following four areas. 1: [γ1 + Δγo, π−γ1 + Δγo], area 2: [−γ1 + Δγo, π+γ1−Δγo], area 3: [π+γo−Δγo, 2π−γ1−Δγ1], and area 4: [2π−γ1, −Δγ1, 2π+γ1 + Δγ1]. V1 in area 1 is always contacted with the oil absorption cavity fully, and V1 in area 2 is a little big relative to the trapped oil flow near the minimum position, but V1 is always contacted with the oil absorption cavity and oil drainage cavity fully, as shown in the connected area of the oil absorption and oil drainage sides in Fig.3a; and V1 in area 3 is always contacted with the oil drainage cavity fully. Therefore, Qr=0, and the probability of the obvious trapping phenomenon will not be presented, and the probability of the obvious trapping phenomenon is relatively big, therefore, we focus on the analysis of trapping characteristics in this area. So, the Formula (9) is simplified into

\[ \frac{dQ}{c} = K_1[-DV_1 - Q_o(p_1) - Q_o(p_3)](\omega_2 V_1) \]  

### 3.2 Leakage rate

In consideration of machining error and processing cost in the actual production, the meshing clearance of radial tooth top is often taken \( h_0 = 0.02*10^{-3} \text{ m} - 0.10*10^{-3} \text{ m} \) \(^1\), and the axial clearance of the end face is often taken \( h_o = 0.02*10^{-3} \text{ m} - 0.12*10^{-3} \text{ m} \) \(^1\). In Fig.1 and Fig.3, the wheel o1 is taken as the drive wheel, the power shall be transmitted by the meshing point located at one side of the oil absorption cavity, so as to push the driven wheel o2 to rotate, therefore, the clearance at these meshing points can be approximate to 0; but the power cannot be transmitted at the meshes of the oil drainage cavity, therefore, the clearance at these meshing points can be approximate to \( h_o \) \(^{11-14}\). Therefore, the meshing points at one side of the oil drainage cavity are not the meshing points in the true sense, and here, we define them as the side clearance points; the clearance here is defined as the one side of the oil drainage cavity, quantity \( Q_o3 \) of leakage flowing to the outer ring of the driven wheel o2; and the above-mentioned leakage rate is positive for outflow. The path length of the leakage 1 is far more than that of leakage 2–4, so the leakage 1 can be ignored, namely, \( Q_o = Q_o2 + Q_o3 + Q_o4 \).

In Fig.4a, the leakage angle of arc section \( g1g2 \) of the tooth space of the wheel o2 corresponding to the center of the circle of the axis o2 is

\[ \alpha_o = 2\pi / z_o - 2a \cos \left[ \left( L_1^1 + r_o3^2 - r_o3^2 / L_1^1 \right) / \left( 2Lr_o3^2 \right) \right] \]  

In the formula, \( r_{o2} \) indicates the root radius of o2; and based on the flow formula of long and thin hole, \( Q_o4 \) is obtained as follows:

\[ Q_o4 = \frac{\alpha_o r_{o2}^2 h_o}{12\mu(r_o3^2 - r_{o2}^2)}(p_i - p_o) \]  

In the formula, \( p_i \) indicates the viscosity of the oil; and \( r_{o2} \) indicates the radius of the outer ring of the wheel o2.

In Fig.4a, the leakage path of 2 and 3 can be approximate to the trapezoid path shown in Fig.4b when the pump is rotated in area 4. So \(^{28}\)

\[ Q_o2(p_o) = \frac{h_o h_o^2 \ln(h_o / a_o)}{12\mu(b_o - a_o)}(p_i - p_o) \]  

\[ Q_o3(p_o) = \frac{h_o h_o^2 \ln(h_o / a_o)}{12\mu(b_o - a_o)}(p_i - p_o) \]  

In the formula, \( p_o \) indicates the oil absorption pressure of the pump.

In Fig.4a, the point n2 located on the actual contour line of the oil drainage cavity is taken as the initial position of trapping analysis and the included angle of n2 to the initial position is set as \( \theta_o \), so

\[ a_2 = r_{o2} \cos \alpha_o \]  

\[ b_2 = r_{o2} \sin \alpha_o \]  

\[ h_2 = r_{o2} \cos(\alpha_o + \gamma_o - 0.5\alpha_o) \]  

\[ a_3 = r_{o2} \sin(2\gamma_o - \alpha_o) \]  

\[ b_3 = r_{o2} \sin(\gamma_o + 2\gamma_o - 0.5\alpha_o - \alpha_o) \]  

\[ h_3 = r_{o2} \cos(\gamma_o + 2\gamma_o - 0.5\alpha_o - \alpha_o) - r_{o2} \cos(2\gamma_o + 2\gamma_o - \alpha_o) \]  

In \( \angle n_o2c_o2 \), set \( \angle n_o2c_o2 = \theta_o \), rad; and in \( \angle n_o2c_o1 \), set \( \angle n_o2c_o1 = \theta_o \), rad, so

\[ r_{o2}(\theta_o) = \sqrt{L_1^1 + R^2 - 2Lr_o3^2 \cos \theta_o} \]  

\[ r_{o2}(\theta_o) = \sqrt{L_1^1 + R^2 - 2Lr_o3^2 \cos \theta_o} \]  

\[ r_{o2}(\theta_o) = \sqrt{L_1^1 + R^2 - 2Lr_o3^2 \cos \theta_o} \]  

Wherein, in \( \angle n_o2p \) and \( \angle n_o2p \), it can obtain the following formula according to the geometrical relationship of triangle:

\[ r_{o2} \sin(\pi - \theta_o - \theta_o) = L \sin \theta_o \]  

\[ r_{o2} \sin(\pi - \theta_o - (\theta_o - 2\pi / z_o)) = L \sin \theta_o \]  

In \( \angle n_o2p \), set \( \angle n_o2p = \alpha_o \), so
\[ \alpha_3(\phi_2) = \gamma + V_\gamma - \alpha_4(\phi_2) \quad (18) \]

And, in \( \triangle n = \phi \cdot p \cdot \phi \)

\[ \alpha_4(\phi_2) = a \cos \left( \frac{r_2^2(\phi_2) + r_2^2 - f_2^2(\phi_2)}{2r_2(\phi_2)r_2} \right) \quad (19) \]

In Fig.3b, if the corner deviation of theoretical and actual contour at two sides of the oil absorption cavity and oil drainage cavity relative to the wheel \( \phi_2 \) is set as \( \Delta \phi_2 \), namely, the value range of \( \phi_2 \) is \( \left[ \pi/2z_2 - \Delta \phi_2, \pi/2z_2 + \Delta \phi_2 \right] \). So, \( \phi_2 = \pi/2z_2 \) is substituted into the Formula (19), and at this time, \( \alpha_2 \) is equal to \( \gamma \); and \( \phi_2 = \pi/2z_2 - \Delta \phi_2 \) is substituted into the Formula (19), and at this time, \( \alpha_2 \) is equal to \( \gamma + \Delta \gamma \), namely

\[ \gamma' = \alpha_3(\pi/z_2) \quad ; \quad \Delta \gamma' = \alpha_4(\pi/z_2 - \Delta \phi_2) - \gamma \quad (20) \]

Fig.4 Axial leakage paths near in the minimum volume position

4. Instance Analysis of Trapping Characteristics

Based on the relevant parameters in Part 2, the calculation by taking \( r_{d2} = 1.5r_{C2} \), \( r_{e2} \) again shall be shown in the Literature [1, 19]; and the speed of the wheel \( \omega_0 \) is taken for 5000 r/min, \( p_1 = 1\times10^5 \) Pa; \( p_2 = 10^5 \) Pa, \( h_{in} = 0.03 \times 10^{-3} \) m; \( h_{out} = 0.03 \times 10^{-3} \) m, \( \mu = 0.09 \) Pa.s, \( C_n = 0.62 \), \( K_1 = 1.7 \times 10^{9} \) Pa, \( \rho = 870 \) Kg/m³. The trapping model shown in the Formula (10) is subjected to the simulation calculation with Runge-Kutta method [24], and the iterations \( N \) are taken for 50000. So the trapped oil pressure corresponding to \( \Delta \phi_2 = 0.5^\circ, 1^\circ \) and \( 2^\circ \) and various flows corresponding to \( \Delta \phi_2 = 1^\circ \) are shown in Fig.5.

Fig.5 Trapped oil pressure and all flows in the position of minimum volume

In Fig.5a, when \( \Delta \phi_2 \) is changed from \( 0.5^\circ \) to \( 1^\circ \), until to \( 2^\circ \), the maximum peak of the trapped oil pressure is changed from \( 1.016 \times 10^6 \) Pa to \( 1.06 \times 10^6 \) Pa, until to \( 1.217 \times 10^6 \) Pa, the trapping phenomenon is gradually obvious, and the pressure peak is \( 1.6\%, 6.0\% \) and \( 21.7\% \) respectively, relative to the increase percentage of the outlet pressure.

In Fig.5b, the trapped oil flow \( -DV_1 \) is mainly relieved by the side clearance flow \( Q_n \), namely, \( Q_n \approx -DV_1 \), therefore, the gear side clearance shall be reduced as far as possible. The axial flow is \( Q_o \ll Q_n \), namely, \( Q_o = 0 \). Thus, it can also get the simplest trapping model

\[ \frac{dP}{\phi} = \frac{K_1}{\alpha_2V_1} \left( -DV_1(\phi) - Q_o(p, \phi) \right) \quad (21) \]

5. Conclusion

1) Under the parameters of the case, the nonuniform coefficient of 6.45% flow of the cycloid rotor pump is much better than that of 21.2% flow of the external gear pump with the tooth number of 10, and the pulse frequency of the flow is consistent with that of the external gear pump which is provided with the side clearance. It can be seen that the flow characteristics of the cycloid rotor pump is far better than that of the external gear pump.

2) Under the parameters of the case, the calculation error of the two approximation formulas for the flow calculation is 1.93% and 2.90% respectively; the approximation error of the nonuniform coefficient of the flow is 7.13%, and the approximation error of the flow is relatively small and conforms to the actual requirement of the engineering, but the approximation error of the nonuniform coefficient of the flow is on the high side; and relative to the external gear pump, the trapping phenomenon is also presented by the cycloid rotor pump, but is not obvious.

3) In practice, it is theoretically practicable to improve the volumetric efficiency by increasing the included position of the oil cavity in the minimum position and decreasing the included angle of the oil cavity in the maximum position.

4) The relatively big side clearance leakage is presented by the rotor pump, therefore, the meshing clearance value of the radial tooth top shall be reduced as far as possible; and the axial leakage is far less than the side clearance leakage, therefore, the axial clearance value can be increased appropriately due to the process demand.

References:


CONFLICT OF INTEREST

We confirm that this article content has no conflict of interest.