Hydraulic axial plunger pump: gaseous and vaporous cavitation characteristics and optimization method

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ABSTRACT
Gaseous and vaporous cavitation have extremely harmful effects on hydraulic axial plunger pumps, reducing flowrate and increasing flow pulsation. The collapse of vapor bubbles strongly impacts the inner wall and produces many pits. Therefore, it is very important to reduce gaseous and vaporous cavitation to improve the performance of hydraulic axial plunger pumps. In this work, a full cavitation model and a compressible model are used to simulate the two kinds of cavitation, which are validated by a series of experiments. It is found that the vapor and gaseous bubbles in the plunger chamber collapse owing to pressurization caused by the water hammer effect. The results show that a better combination of plunger chamber radius and swash plate angle can reduce the two kinds of cavitation when the theoretical flowrate is unchanged; increasing the angle of the inlet of valve plate can effectively reduce its cavitation and increase the filling mass of plunger chambers; increasing the angle of the relief groove can significantly reduce its vapor and gaseous volume fraction. The results can provide a useful reference for reducing gaseous and vaporous cavitation in the optimization and design of hydraulic axial plunger pumps.

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1. Introduction
Fluid transmission devices feature compact mechanical structure, high energy density and stable transmission power. They have extensive applications in construction machinery, marine vessels, aerospace, robotics, etc. Hydraulic axial plunger pumps, as safe environmentally friendly hydraulic machinery, will inevitably become one of the most important core components for future developments in fluid transmission devices. However, the high saturated vapor pressure of water in hydraulic axial plunger pumps is more likely to cause cavitation and mechanical vibration than oil, thus reducing their flowrate efficiency and service life. Therefore, to design and manufacture hydraulic axial plunger pumps, more precise methods are needed. At the same time, it is of great significance to understand the cavitation characteristics and optimization mechanism of hydraulic axial plunger pumps.

Bubbles will be generated once the fluid pressure is lower than the saturated vapor pressure or air separation pressure. When the fluid flow is fast, a cavitation cloud can be found in hydraulic axial plunger pumps (Atsushi & Tetsuo, 1983). The concept of ‘cavitation’ was proposed by Parsons in 1897 when he found that, when the propeller rotation speed of torpedo boats and ships increased, there was a serious decrease in propulsion efficiency. There are two factors affecting cavitation: the lower the viscosity coefficient, the more easily cavitation will occur (Sinner, 1904). Moreover, it was found that cavitation could appear at the interface between a high-speed liquid and a solid wall (Cox & Clayden, 1958; Silberman, 1958). Since cavitation was proposed, it has also been reported in the field of pumps. Cavitation of axial plunger pumps mainly occurs in the plunger chamber (Chao, 2019; Chao et al., 2019a). Additionally, suction and rotation in the plunger chamber are two important factors causing pressure drop that lead to two kinds of cavitation. The first is caused when the hydraulic fluid enters the chamber and is subsequently accelerated (Kollek et al., 2007; Manring et al., 2014; Totten & Bishop, 1999). The second occurs when the pressure near the rotation axis of the plunger chamber decreases (Kunkis & Weber, 2016).

Cavitation has many adverse effects on axial plunger pumps. Bubbles collapse when their pressure is higher than the saturation value of the fluid domain, which produces an ‘impact force’. This impact force pits the inner wall of axial plunger pumps and makes the pump body vibrate (Dular et al., 2006; Dular & Coutier, 2008; Jones, 1959; Liu et al., 2015; Trummler, 2020). What’s more, cavitation in plunger chambers not only reduces the flowrate
efficiency, but also increases the pulsation of flowrate (Zhang et al., 2016). At the same time, the relief groove – the key structure of the axial plunger pump – is also the main place damaged by cavitation (Chao et al., 2019b,c; Liu et al., 2015).

It was validated by the experiments that cavitation can be reduced with three V-shaped grooves instead of the original V-shaped groove (Tsukiji, 2015). Another cavitation suppression method is two U-shapes in the relief groove, which were designed via numerical simulation (Zhang, 2019). In addition, an inward-inclined design of cylinder ports has a higher filling rate, reducing cavitation (Chao et al., 2019b). Furthermore, when the inlet pressure increases in an axial plunger pump, cavitation can also be reduced (Chao et al., 2019; Liu et al., 2015; Yin et al., 2016).

However, one of the most significant current discussions regarding axial plunger pumps is how to reduce cavitation. Although many previous studies of axial plunger pumps have mainly concerned the cavitation of relief grooves (Tsukiji, 2015; Zhang, 2019) and cylinder vibration (Wang et al., 2019), research on reducing cavitation in the plunger chamber of axial plunger pumps can hardly be found. In the present article, the cause and distribution of gaseous and vaporous cavitation in axial plunger pumps are analyzed. Numerical simulations are indirectly validated by a series of experiments. The present research proposes three optimization methods according to the formation mechanism of cavitation: by simultaneously amending the plunger chamber cylinder radius and swash plate angle, gaseous and vaporous cavitation in the plunger chamber will be reduced when the theoretical flowrate is unchanged according to the theoretical flowrate equation; backflow and jet flow can be effectively reduced by increasing the angle of the relief groove and the inlet of the valve plate, which can reduce the two kinds of cavitation. In order to verify the numerical simulations and optimal methods, experimental flowrates are compared with simulation results, since flowrate efficiency can represent cavitation. The results can provide an important reference for reducing gaseous and vaporous cavitation in the optimization and design of hydraulic axial plunger pumps.

2. Simulation model

Gaseous and vaporous cavitation are the two types of cavitation in hydraulic axial plunger pumps. Vaporous cavitation is the process of vapor bubble generation when the liquid pressure is lower than the saturated vapor pressure of the liquid. The collapse of vapor bubbles will certainly produce a strong impact force that will damage the inner wall of an axial plunger pump (Liu et al., 2015). Gaseous cavitation is when the gas dissolved in the liquid begins to be released as the pressure becomes lower than the air separation pressure. Gaseous cavitation does not have a destructive effect on axial plunger pumps, but both gaseous and vaporous cavitation reduce flowrate efficiency (Chao et al., 2019). Numerical simulation for solving these engineering problems has attracted a lot of attention owing to its effectiveness and applicability (Mosavi et al., 2019; Ramezanizadeh et al., 2019). The low-pressure regions of axial plunger pumps where cavitation occurs are also the regions of relatively high velocity. In such high-velocity regions, the velocity slips between the liquid and vapor phases are quite small. The homogeneous flow method known as the Equal Velocity Equal Temperature (EVET) method is a practical approach to simulating cavitation in fluid transmission devices. Therefore, both the homogeneous flow method and the full cavitation model proposed by Singhal et al. (2002) are adopted simultaneously. It is assumed that there is no relative velocity slip and that the temperature is constant in the axial plunger pump.

The full cavitation model and the standard $k$–$ε$ model are adopted to simulate cavitation phenomena in axial plunger pumps, and validated by the experimental results (Ding et al., 2011; Iannetti et al., 2015; Qian & Huang, 2006 Singhal et al., 2002). Therefore, this method is used for numerical simulations of axial plunger pumps by Pumplinx software (Ding et al., 2011; Meincke & Rahmfeld, 2008). The full cavitation model contains the vapor equation, the free gas equation and the dissolved gas equation. Two-phase flow is adopted with an interface between gas and liquid. It is easy to cause calculation divergence owing to numerical discontinuity with the differential equation. But the integral equation has better convergence, which can avoid this problem. The full cavitation model is the main method for simulating cavitation in axial plunger pumps. The vapor equation is

$$\frac{\partial}{\partial t} \int_{\Omega(t)} \rho f_v d\Omega + \int_{\partial \Omega} \rho (v - v_\sigma) \cdot n f_v d\sigma = \int_{\sigma} \left( D_n + \frac{\mu_n}{\sigma} \right) \cdot (\nabla f_v \cdot n) d\sigma + \int_{\Omega} (R_c - R_v) d\Omega$$

(1)

$$R_c = C_c \rho_1 \rho_v \left[ \frac{2}{3} \frac{(p - p_v)}{\rho_1} \right]^{1/2} (1 - f_v - f_g)$$

(2)

$$R_v = C_v \rho_1 \rho_v \left[ \frac{2}{3} \frac{(p - p_v)}{\rho_1} \right]^{1/2} f_v$$

(3)

where $C_c = 0.01$, $C_v = 0.02$; $\rho$ is the fluid density; $f_v$ and $f_g$ are the vapor mass fraction and the gas mass fraction; $\Omega$ is the control volume; $\sigma$ is the control body surface area; $v$ is the fluid velocity; $v_\sigma$ is the velocity of surface motion;
Figure 1. Axial plunger pump and fluid domains. 1. Spindle; 2. Swash plate; 3. Retainer plate; 4. Cylinder block; 5. Valve plate; 6. Bake cover; 7. Plunger; 8. Sliding boots; 9. Outer shell; 10. Flange cover.

\[ n \text{ is the surface normal of } \sigma; \quad D_f \text{ is the vapor diffusion coefficient; } \mu_t \text{ is the turbulent viscosity; } \sigma \text{ is the turbulent Schmidt number; } p_v \text{ is the saturated vapor pressure; } \]
\[ \text{Re} \text{ is the gas generation rate; } R_c \text{ is the gas dissipation rate; } C_c \text{ and } C_e \text{ are the cavitation condensation coefficient and the cavitation evaporation coefficient; } \rho_v \text{ is the vapor density; } \]
\[ \rho_l \text{ is the liquid density; and } p \text{ is the pressure.} \]

The equationsof free gas and dissolved gas are respectively as follows:

\[
\frac{\partial}{\partial t} \int_{\Omega(t)} \rho g_f d\Omega + \int_{\sigma} \rho ((v - v_{\sigma}) \cdot n) g_f d\sigma = \int_{\sigma} \left( D_f + \frac{\mu_t}{\sigma_f} \right) \cdot (\nabla g_f \cdot n) d\sigma + \int_{\Omega} \left( \frac{\rho (g_d - g_{dequil})}{\tau} \right) d\Omega \tag{4}
\]

\[
\frac{\partial}{\partial t} \int_{\Omega(t)} \rho g_d d\Omega + \int_{\sigma} \rho ((v - v_{\sigma}) \cdot n) g_d d\sigma = \int_{\sigma} \left( D_{gd} + \frac{\mu_t}{\sigma_f} \right) \cdot (\nabla g_d \cdot n) d\sigma - \int_{\Omega} \left( \frac{\rho (g_d - g_{dequil})}{\tau} \right) d\Omega \tag{5}
\]

\[ g_{dequil} = \frac{p}{p_{dequil ref}} \cdot g_{dequil ref} \tag{6} \]

where \( D_f \) is the diffusion coefficient of free gas; \( D_{gd} \) is the diffusion coefficient of dissolved gas; \( g_f \) is the free gas mass fraction; \( g_d \) is the mass fraction of dissolved gas; \( g_{dequil} \) is the equilibrium mass fraction of dissolved gas; \( g_{dequil ref} \) is the equilibrium mass fraction of dissolved gas under relative pressure; \( p_{dequil ref} \) is the relative pressure of the mass fraction of dissolved gas; \( t \) is time; and \( \tau \) is the dissolved gas dissipation time.

According to the typical axial plunger pump structure in Figure 1, the full-scale fluid domain is divided into six parts: inlet, outlet, inlet of valve plate, outlet of valve plate, plunger chamber and relief groove. In working conditions, the plunger chamber rotates about the axis. As the plunger chamber sucks in water, the length of the plunger chamber increases with rotation. As the plunger chamber drains, the length of the plunger chamber decreases with rotation.

The fluid domain is meshed according to the Cartesian grids of the binary tree rule, which has the advantages of high computational accuracy and high speed. The meshed parts are connected by a Mismatched Grid Interface (MGI), which is treated as the common face connecting cells on both sides of the interface. During the simulation process, the interface is the same as an internal interface between two neighboring cells in the same grid domain. Leakage is neglected owing to its tiny value.

In Figure 2, the bottom dead point is set to 0° and the top dead point is set to 180°. In actual working conditions, the plunger chamber is rotated from 0° to 180° to suck water, while the plunger chamber is rotated from 180° to 360° to drain water. During the suction stage, the length of the plunger chamber regularly rises, because the cylinder of the plunger chamber is stretched. During the drainage stage, the length of the plunger chamber regularly decreases, because the cylinder of the plunger chamber is compressed. A sliding mesh and a smoothing mesh are used for numerical simulations. The sliding mesh is used for rotation of the plunger chamber around the axis used, and the smoothing mesh is used
Figure 2. Grid domain and movement of plunger chamber.

Table 1. Key parameters of the axial plunger pump and conditions of simulation.

| Parameter                        | Value           | Parameter                        | Value           |
|----------------------------------|-----------------|----------------------------------|-----------------|
| Inlet pressure (MPa)             | 0.101,325       | Residual convergence             | $1 \times 10^{-5}$ |
| Outlet pressure (MPa)            | 15              | Viscosity (Pa·s)                 | $1.003 \times 10^{-3}$ |
| Swash plate angle                | 12.9°           | Bulk modulus of elasticity (MPa) | $2.15 \times 10^{3}$ |
| Rotational speed (rpm)           | 2500            | Revolutions                      | 13              |
| Dissolved mass fraction of air   | $2.3 \times 10^{-5}$ | Simulation method                | Transient       |
| Saturated vapor pressure (MPa)   | $3.567 \times 10^{-3}$ | Number of interactions          | 250             |
| Plunger chamber cylinder radius (mm) | 9              | Swash plate angle                | 12.9°           |
| Radius of distribution circle (mm) | 31.75          | Number of plungers               | 9               |

Figure 3. Grid independence analysis.

for compression and stretching of the plunger chamber. Therefore, the rotation speed and the expansion rate of the plunger (swash plate angle) need to be defined.

The key parameters of the investigated axial plunger pump and the conditions of the simulation are summarized in Table 1. The excellent stability of the simulation results is represented by the fact that the number of grids is more than one million, as shown in Figure 3. However, the number of grids in the simulations in this article is 1.02 million in order to improve and ensure the accuracy of the result.

3. Cavitation characteristics of plunger chamber and optimization method

3.1. Cavitation characteristics of plunger chamber

Because the state of the nine plunger chambers is repeatable, one of the plunger chambers can be used to display its cavitation clearly. Gaseous and vaporous cavitation do not affirmatively occur during the drainage stage (Gao et al., 2018), because the pressure in the plunger chamber is approximately equal to outlet pressure, which higher than the air separation pressure. Gaseous and vaporous cavitation will mainly take place in plunger chambers during the suction stage, as shown in Figure 4.

It is well known that the gaseous volume fraction and the vapor volume fraction represent the degree of gaseous and vaporous cavitation, respectively. Figure 4 shows the gaseous volume fraction and the vapor volume fraction during the suction stage. Owing to the centrifugal force, gaseous and vaporous cavitation take place mainly near the axis. As shown in Figures 4(a) and 4(b), gaseous and vaporous cavitation mainly occur at the top of the plunger chamber. Gaseous cavitation occurs mainly in Region ‘Top 1’ of the plunger chamber, and vaporous cavitation occurs mainly in Region ‘Top 2’ of the plunger chamber. It is shown that gas and vapor bubbles, at the top of the plunger chamber, begin to collapse at about 90°. Between 90° and 100°, gaseous cavitation occurs in the cylinder of the plunger chamber.
The mechanism of gaseous and vaporous cavitation at the top of the plunger chamber is introduced and shown in Figure 5. Curves of different color indicate the pressure at different distances from the center of the top of the plunger chamber. Due to the effect of viscous force, the farther the flow distance, the greater the pressure drop. So the plunger chamber has a lower pressure when the fluid is closer to the top of the plunger chamber, as shown in Region A of Figure 5. Vaporous cavitation only occurs at this condition, which is also displayed in Figure 4(b). It is known that the saturated vapor pressure is lower than the air separation pressure. Therefore, it is necessary to have a lower pressure to produce vaporous cavitation. As the distance from the top of the plunger chamber increases, the vapor volume fraction decreases.

The mechanism of collapse of gaseous and vapor bubbles at 90° is displayed here. The rate of increase in length of the plunger chamber is as follows:

\[ u_p = wR \tan(\beta) \sin(wt) \]  

where \( u_p \) is the rate of increase in length of the plunger chamber; \( \beta \) is the swash plate angle; \( R \) is the radius of the distribution circle; and \( w \) is the rotational speed. When the plunger chamber is at 90°, plunger axial velocity is the largest, so the suction velocity of the plunger chamber is also the highest. With the plunger chamber rotates from 90° to 180°, its axial velocity deceases. Owing to the inertia force and the very short time that the force acts, the water impacts the top of the plunger chamber and increases its pressure. To study the two cavitation characteristics of the plunger chamber more clearly, Figure 6 shows the gas-phase volume fraction and pressure during
Figure 6. Gas-phase volume fraction and pressure during the suction stage.

where $\alpha_{\text{gasphase}}$ is the gas-phase volume fraction; $\alpha_{\text{vapor}}$ is the vapor volume fraction; and $\alpha_{\text{gaseous}}$ is the gaseous volume fraction. As shown in Region B of Figure 5, the pressure increases sharply when the plunger chamber is about 90°. Figure 6 shows gas-phase volume fraction and pressure during the suction stage. Under the influence of the water hammer effect, the closer to the top of the plunger chamber, the higher the pressure, as shown in Region B of Figure 5 and Region D of Figure 6(b).

Gaseous and vaporous cavitation occur mainly at the top of the plunger chamber, so it can be found that the pressurization effect of water hammer makes vapor and gaseous bubbles collapse at the top of plunger chamber as shown in Region C of Figure 6(a). Kollek conducted experiments that a single plunger chamber moved in axial motion without any rotation (Kollek et al., 2007). Bubbles begin to be generated in the plunger chamber and increase with the upward movement of the plunger before the plunger is at 90°. Then some bubbles collapse due to the water hammer effect after the plunger is at 90°. Worst of all, the collapse of vapor bubbles will frequently pit the inner wall of the plunger chamber. The results of the simulation can be verified by measuring the roughness of the inner wall of the plunger (Liu et al., 2015).

Figure 7 shows the $Y$-velocity section of the plunger chamber at 90°, which is obtained along the tangent of the distribution circle of the plunger chamber. If the plunger chamber does not rotate and only the length increases, the $Y$-velocity would be represented by the dotted line in Figure 7. In actuality, the plunger chamber rotates around the axis and water is ‘thrown’ into Region F in Figure 7.

As a result, there is no water to replenish in Region E of Figure 7, which is sucked into the plunger chamber. Therefore, a pressure drop will occur at the front of the plunger chamber, as shown in Region $E_2$ of Figure 6. There is the biggest pressure drop at 90°owing to the biggest length increase rate of the plunger chamber. So gaseous cavitation occurs in Region $E_1$ of Figure 6.

It is known that the cylinder of the plunger chamber is stretched during the suction stage. Therefore, the capacity for suction is affected by the cylinder volume of the plunger chamber. The cross-sectional area of a
cylinder is greater than the cross-sectional area of the window of the plunger chamber, thus the plunger chamber cannot effectively suck water, as shown in Region G of Figure 7. Insufficient suction may be one of the reasons for gaseous and vaporous cavitation in the plunger chamber. If these two cross-sectional areas are equal, the plunger chamber may effectively suck water. So it is supposed that a reduction of the radius of the cylinder would decrease the gas-phase volume fraction during the suction stage. Figure 8 shows the effect of the radius of the cylinder plunger on the gas-phase volume fraction, which reduces with the radius reduction of the cylinder plunger as expected.

There is a directly proportional relation between gaseous and vaporous cavitation and the pressure drop of the plunger chamber. Therefore, choosing the parameters of the pressure drop is particularly important (Chao et al., 2019). The viscosity coefficient of water is lower than that of oil, so the pressure drop formula for the plunger chamber is suitable for a hydraulic axial plunger pump. The pressure drop of the plunger chamber at different times and positions can be expressed as

$$p_p = p_l - \frac{1}{2} \rho w^2 (R^2 \tan^2 \beta \sin^2 (\omega t) - r_p^2 - 2r_p R \cos(\theta_p))$$

(9)

where $p_p$ is the pressure in the plunger chamber; $p_l$ is the inlet pressure; $\theta_p$ is the angle of a certain element of water in the plunger chamber in a cylindrical coordinate system; $r_p$ is the distance between the water element and the center of the body-fixed cylindrical coordinate system. The value of $p_p$ is less than that of $p_l$. According to Equation (9), it can easily be seen that the plate angle, rotational speed and inlet pressure will affect the pressure drop in the plunger chamber. The influence of inlet pressure on the cavitation of the plunger chamber was introduced in detail by Chao et al. (2019), Liu et al. (2015) and Yin et al. (2016).

Based on Equation (9), there is also an effect of the swash plate angle on the gas-phase volume fraction. Figure 9 shows the effect of the swash plate angle on the gas-phase volume fraction of the plunger chamber. Additionally, the gas-phase volume fraction of the plunger chamber increases with increasing swash plate angle.

3.2. Optimization method of cavitation suppression in the plunger chamber

It can be seen from Figures 8 and 9 that the gas-phase volume fraction of the plunger chamber reduces with the reduction of swash plate angle and cylinder radius of the
plunger chamber. But reduction of these two parameters will reduce the flowrate of axial plunger pump. Since flowrate is the most important characteristic of an axial plunger pump, it cannot be changed. It is necessary to study how to suppress plunger chamber cavitation while keeping the theoretical flowrate unchanged. The axial plunger pump theoretical flowrate is given by

\[
Q_t = Q_1 + Q_2 + \cdots + Q_m = \sum_{i=1}^{m} Q_i = \pi r^2 w R \tan(\beta) \sum_{i=1}^{m} \sin(wt + i \times 2\pi/z) \tag{10}
\]

where \(Q_t\) is the theoretical flowrate; \(r\) is the radius of the cylinder plunger; \(m\) is the number of plunger chambers in the drainage; \(z\) is the total number of plunger chambers; and \(i\) is the serial number of the plunger chamber. To keep a constant theoretical flowrate, it should be noted that \(r^2 \times \tan(\beta)\) should be constant, as shown in Equation (10). If the swash plate angle is reduced, the radius of the cylinder plunger should be regularly increased. Therefore, the gaseous volume fractions of axial plunger pumps with four radii are shown in Figure 10.

By comparing with the four lines in Figure 10, it is found that there is a lower gaseous volume fraction in the plunger chamber with a small cylinder plunger radius \((r_1 = 7 \text{ mm})\) and a large swash plate angle \((\beta_1 = 20.737^\circ)\). This is because the radius of the cylinder plunger has a greater influence on the gaseous cavitation of the plunger chamber. This structure is the best for suppressing gaseous cavitation of the plunger chamber and improving flowrate efficiency, while also keeping the theoretical flowrate constant.

Figure 11 shows the coupling effect on the vapor volume fraction of the plunger chamber. At 193°, there is a sharp increase in the vapor volume fraction of the plunger chamber, as shown in Region H of Figure 11. When the plunger chamber is rotated from the suction stage to the drainage stage, the phenomenon of backflow will occur owing to the big pressure difference. The backflow phenomenon has a very high velocity, which leads to a suddenly increasing vapor volume fraction in the plunger chamber. Although the vapor volume fraction of the plunger chamber remains low during the suction stage, the structure \((r_1 = 7 \text{ mm}, \beta_1 = 20.737^\circ)\) is the best for vastly suppressing vaporous cavitation, whether at the suction stage or the backflow stage. Therefore, the optimized structure \((r_1 = 7 \text{ mm}, \beta_1 = 20.737^\circ)\) can suppress gaseous and vaporous cavitation simultaneously.

3.3. Effect of rotational speed on plunger chamber cavitation, and experimental verification

Figure 12 shows the gas-phase volume fraction with different rotational speeds in the plunger chamber. The gas-phase volume fraction drastically rises with increasing rotational speed. This is because, when the rotational speed increases, the centrifugal force and pressure drop of the suction increase.

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The gas-phase volume fraction will reduce the filling mass of the plunger chamber, which reduces flowrate efficiency. Therefore, the simulation results can be validated indirectly by comparisons of flowrate. The axial plunger pump flowrate experiment was conducted on the hydraulic experiment facilities shown in Figure 13.

The flowrate experiment process is as follows.

(a) Install the testing pump in the system and connect the motor through the flange. The inlet and outlet are connected with corresponding pipelines. Open the globe valve and exhaust the air in the testing pump.

(b) After the testing pump completely discharges the air, close the two-position two-way valve and reduce the opening of the flow control valve to stabilize the system pressure at the required working pressure. The flowrate of the testing pump is measured, and the experiment data is collected after the operation is stable.

(c) After the experiment is completed, completely loosen the flow control valve and the overflow valve in turn, open the two-position two-way valve after the pressure drops to the minimum, and finally turn off the motor and the system.

Because the compressible model is adopted, the mass flowrate replaces the volume flowrate, as shown in Figure 14. A purely mathematical method (Zhang et al., 2016) is used to calculate the discharge flowrate of the axial plunger pump without cavitation characteristics. The simulation flowrate is obtained by the compressible model and the full cavitation model. Flowrate loss can indirectly represent the degree of cavitation. On one hand, it is obvious that the simulated flowrate corresponds well with experiment in Figure 14, which indicates simulations of cavitation are indirectly verified. On the other hand, the flowrate loss increases with increasing...
rotational speed, which verifies that an increase in rotational speed raises the gas-phase volume fraction of the plunger chamber.

4. Cavitation characteristics of jet flow and backflow, and optimization method

4.1. Cavitation characteristics of jet flow and backflow

Figures 15 and 16 show the jet velocity and gaseous volume fraction section of the plunger chamber with rotation, which were obtained along the tangent of the distribution circle of the plunger chamber. When the plunger chamber rotates from the outlet of the valve plate to the inlet of the valve plate, the jet flow occurs at the junction of the plunger chamber and the inlet of the valve plate at 15°, as shown in Figure 15. There is no relief groove at the inlet of the valve plate. Owing to the especially large pressure difference, the jet velocity reaches 60 m/s. There is a reduction in jet velocity with rotation of the plunger chamber. Although the jet velocity is very high, the pressure here is still higher than the saturated vapor pressure and lower than the air separation pressure. Under this pressure, gaseous cavitation will appear on the wall of the inlet of valve plate (Region I) and the bottom side of the cylinder block (Region J), as shown in Figure 16. The direction of the jet flow shifts downwards with rotation owing to the inherent structure. The influence of the jet flow on Region J disappears and the gaseous volume fraction of region J decreases to zero. The gaseous volume fraction of Region I increases and then decreases with rotation, as shown in Figure 16. There is a maximum value of the gaseous volume fraction when the plunger chamber is rotated to 18°, and the maximum value reaches 69%. Because of the delay in bubble formation, the biggest gaseous volume fraction is not at the maximum of the jet velocity. Although the collapse of gaseous bubbles does not pit the inner wall of the valve plate, it reduces the filling rate of the plunger chamber. This is because the dissolved bubbles generated at the jet flow stage are sucked into the plunger chamber, which reduces the filling mass of the plunger chamber (Chao et al., 2019).

Figures 17(a) and 17(b), respectively, show the three-dimensional velocity of backflow and vapor volume fraction in the relief groove. When the plunger chamber rotates from the inlet of the valve plate to the relief groove, backflow occurs at the junction of the plunger chamber and the relief groove at 192°, as shown in Figure 17(a). Although the biggest pressure difference is at 192°, this is also the smallest open area to produce a damping effect, as shown in Figure 17(a). Therefore, it is known that the backflow velocity is very small, which will not cause a large pressure drop to produce gaseous or vaporous cavitation. As the plunger chamber rotates from 192° to 207°, the range of backflow expands along the bottom of the plunger chamber and the velocity of backflow
reaches 96 m/s. What is worse, as shown in Figure 17(b), vaporous cavitation occurs at the relief groove. Because the relief groove is in the high-pressure area, the vapor bubbles finally collapse under the influence of the high pressure. It is well known that the collapse of vapor bubbles will inevitably damage the wall of the relief groove. In order to improve the performance of an axial plunger pump, vaporous cavitation caused by backflow must be effectively suppressed. At the same time, the gaseous volume fraction of the plunger chamber should also be reduced at the moment of contact between the plunger chamber and the relief groove.
4.2. Cavitation suppression method: jet flow and backflow

Reduction of jet flow and backflow will significantly suppress gaseous and vaporous cavitation. When the plunger chamber is rotated to the inlet of the valve plate or relief groove, the plunger chamber is closed. Importantly, the volume of the plunger chamber will increase or decrease with rotation, which will result in reducing or increasing the pressure. When the plunger chamber is closed at a bigger rotation angle, the pressure change is also bigger.

Figure 18. Optimization scheme for valve plate.

Therefore, modification of the valve plate structure has an important impact on suppressing the cavitation effect of jet flow and backflow, as shown in Regions L and N of Figure 18.

The impacts of different angles (M1) of the inlet of the valve plate on the gaseous volume fraction are represented in Figure 19. The larger the angle (M1) of the inlet of the valve plate, the smaller is the gaseous volume fraction in the inlet of the valve plate. Although an increase in the angle (M1) will shorten the suction range, the filling mass of the plunger chamber increases from $3.4068 \times 10^{-3}$ to $3.5369 \times 10^{-3}$ kg. Therefore, in order to increase the filling mass of the plunger chamber and suppress gaseous cavitation, the angle ($M_1 = 29.4^\circ$) of the inlet of the valve plate is a better choice for axial plunger pumps.

Figure 19. Gaseous volume fraction at inlet of valve plate and filling mass in the plunger chamber.

Figure 20. Flowrate of backflow.
Figure 20 shows the flowrate of backflow. A positive mass flowrate represents backflow; a negative mass flowrate, on the contrary, represents drainage. An increase of the angle \(\alpha\) of the relief groove causes backflow later. But an increase in the angle \(\theta\) of the relief groove leads pressurization in the plunger chamber during the closed state. The backflow flowrate and velocity are decreased at the relief groove owing to a reduction in the pressure difference.

The vapor volume fraction and gaseous volume fraction in the relief groove are shown, respectively, in Figures 21 left and right. The larger the angle \(\theta\) of the relief groove, the smaller is the vapor volume fraction in the relief groove. This is because the pressure drop goes down as the backflow velocity is decreased. It is a satisfactory optimization that the vapor volume fraction peak is drastically reduced from 0.3689 to 0.0009% in the relief groove, as shown in Figure 21. A reduction in the vapor volume fraction causes less damage to the relief groove. Similarly, the larger the angle \(\alpha\) of the relief groove, the smaller is the gaseous volume fraction in the relief groove. The gaseous volume fraction is reduced from 13.3883 to 0.3981% in the relief groove. This is because the pressure during the closure stage of the plunger chamber is increased with the increase of rotation, resulting in the collapse of more gaseous bubbles generated during the suction stage. A reduction of the gaseous volume fraction will reduce flowrate pulsation. In conclusion, the angle \(\alpha = 30^\circ\) of the relief groove is a better angle to suppress vaporous and gaseous cavitation at the relief groove.

5. Conclusion

Gaseous and vaporous cavitation of plunger chambers, jet-flow and backflow are discussed and analyzed. The simulation results are validated by comparison with experimental flowrate results. Gaseous and vapor bubbles in the plunger chamber collapse owing to the pressurization effect of water hammer. Three hydraulic axial plunger pump structures are proposed for reducing cavitation of the plunger chamber or valve plate: the first optimized structure is a combination of a smaller plunger chamber radius and a larger swash plate angle, which can produce lower gaseous and vapor volume fractions in the plunger chamber than in the original structure; the second is an inlet for the valve plate. When the angle of the inlet of the valve plate is increased, the suction range will be shortened, but the filling mass of the plunger chamber will be increased; the last is the angle of the relief groove. The vapor volume fraction and gaseous volume fraction will be decreased with an increased relief groove angle. These optimization methods can be used in the design, manufacture and applications of hydraulic axial plunger pumps. However, more attention should be focused on reducing cavitation without changing the theoretical flowrate, because most current research has designed a reduction of the theoretical flowrate to suppress cavitation. At the same time, all the three optimized structures may have a coupling effect on cavitation suppression, which will be discussed in the near future.

Nomenclature

| Symbol | Parameter definition |
|--------|----------------------|
| \(\mu_t\) | turbulent viscosity |
| \(C_c\) | cavitation condensation coefficient |
| \(C_e\) | cavitation evaporation coefficient |
| \(D_f\) | vapor diffusion coefficient |
| \(D_g\) | diffusion coefficient of free gas |
| \(D_{gd}\) | diffusion coefficient of dissolved gas |
| \(f_g\) | gas mass fraction |
| \(f_v\) | vapor mass fraction |
| \(g_d\) | mass fraction of dissolved gas |
equilibrium mass fraction of dissolved gas
under relative pressure
free gas mass fraction
serial number of plunger chamber
number of plunger chambers in the drainage
surface normal of \( \sigma \)
pressure drop coefficient
pressure
relative pressure of mass fraction of dissolved gas
inlet pressure
pressure in the plunger chamber
saturated vapor pressure
axial plunger pump theoretical flowrate
radius of distribution circle
radius of cylinder plunger
gas dissipation rate
gas generation rate
distance between water and the center of the body-fixed cylindrical coordinate system
time
length increase rate of the plunger chamber
fluid velocity
velocity of surface motion
rotational speed
total number of plunger chambers
gaseous volume fraction
gas-phase volume fraction
vapor volume fraction
swash plate angle
angle of a certain water element in the plunger chamber within a cylindrical coordinate system
fluid density
liquid density
vapor density
control body surface area
turbulent Schmidt number
dissolved gas dissipation time
control volume

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