ABSTRACT: The stator and rotor of an all-metal screw pump are made of metal; so the matching method of the all-metal screw pump cannot be like that of the traditional rubber screw pump, and a certain gap must be reserved. If the gap is too small, it will affect the normal operation of the pump. If the gap is too large, the pump leakage will also become larger, affecting the efficiency of the pump. In this paper, the method of numerical simulation is used to optimize the gap of the pump. At the same time, it is found that the optimal gap of the pump is closely related to the viscosity of the fluid transported by the pump, and different viscosity fluids have different optimal speeds. The speed and clearance of the pump are optimized through numerical simulation to ensure high pump efficiency while taking into account energy saving and avoid the waste caused by excessively high speed. Finally, the relevant research results of numerical simulation are verified through experiments, and it is found that the experimental results are in good agreement with the simulation results, which also proves the accuracy of the numerical simulation results.

1. INTRODUCTION

As a kind of mechanical oil production equipment, the screw pump has a long history. The screw pump has many advantages, such as low price, simple structure, and so on.1−4 The stator of the traditional screw pump is composed of rubber. The manufacturing process of such a rubber screw pump is simple, but in a high-temperature environment, the rubber is easy to age.5 In the field of oil mining, workers often adopt the mining method of heating the formation to reduce the viscosity of crude oil and artificially create a high-temperature environment to improve the recovery factor.6−10 Therefore, the application of traditional rubber screw pumps is limited, and all-metal screw pumps came into being.11−14 The stator and rotor of the all-metal screw pump are composed of metal. In order to ensure successful assembly, there must be a gap between the stator and the rotor, but this will cause leakage.15−17 If the gap is too large or too small, it will seriously affect the pump efficiency; so the optimization of the gap size affects the design and use of the entire pump.18−20

Because of the gap, there is leakage in the pump. Pessoa et al.21 analyzed the leakage in the pump by establishing a flow model. Nguyen et al.22 established a new fluid model to simulate the actual flow of the fluid. Zheng et al.23 in China also studied the analytical model for the flow in all-metal screw pumps, and it is considered that the turbulent leakage of the pump is more complicated than the laminar leakage. Our previous article24 also carried out related research on the leakage of the all-metal screw pump but did not further optimize the gap between the stator and rotor. Jiang et al.14 in China used numerical simulation to optimize the gap of the all-metal screw pump but did not further study the speed optimization of the screw pump.

In view of these, there is still a lack of work to comprehensively consider the factors such as the gap, rotation speed, and fluid viscosity of the all-metal screw pump for optimal design and research. This article will synthesize the interaction between these three factors, optimize the structure, improve performance, and provide performance optimization in field applications.

2. CLEARANCE OPTIMIZATIONS

In order to ensure the successful assembly of the all-metal screw pump, a certain clearance must be left between the stator and rotor. If the clearance value is too small, it will affect the speed of the pump; if the clearance value is too large, the leakage is serious, affecting efficiency. All-metal screw pumps often
work in a high-temperature working environment. High temperatures will cause objects to expand, which will inevitably affect the clearance value. Therefore, it is very important to optimize the clearance value between the stator and rotor.

2.1. Influence of Temperature. Numerical simulation was used to study the effect of temperature on the clearance, and SolidWorks software was used to establish the model. As shown in Figure 1, the model type is a single-head screw pump, and the specific dimensions are shown in Table 1.

![Figure 1. Model diagram.](image)

| Table 1. Model Parameter Table |
|--------------------------------|
| parameter          | value/mm |
| rotor diameter     | 50       |
| eccentricity       | 5        |
| stator lead        | 160      |
| pitch              | 80       |
| model length       | 160      |

The clearance value can be calculated from the stator and rotor diameters, as shown in formula 1.

\[ \delta = \frac{d_r - d_s}{2} \]  

(1)

where \( d_r \) is the rotor diameter, m and \( d_s \) is the stator diameter, m.

When \( \delta < 0 \), the matching method of the all-metal screw pump is interference fit; when \( \delta > 0 \), the matching method of the all-metal screw pump is clearance fit, as shown in Figure 2.

![Figure 2. All-metal screw pump matching method.](image)

The analysis model uses a single-head screw pump, the materials of the stator and rotor are selected as steel in the ANSYS software, the Poisson ratio is 0.31, the elastic modulus is \( 1.93 \times 10^{11} \) Pa, and the thermal expansion coefficient is \( 1.7 \times 10^{-5} \) C\(^{-1}\).

A thermal load of 500 °C was applied on the model, and deformation of the stator and rotor was observed, as shown in Figures 3 and 4.

![Figure 3. Stator deformation diagram.](image)

![Figure 4. Rotor deformation diagram.](image)

It can be seen from Figure 5 that when loading a high temperature of 500 °C, as the initial clearance value increases, the clearance value after heating increases linearly. When the initial clearance value is less than 0.15 mm, the clearance value after heating is less than 0, indicating that the cooperation between the stator and rotor in this state is interference fit; when the initial clearance value is greater than 0.15 mm, the clearance value after heating is greater than 0, indicating that
the cooperation between the stator and rotor in this state is

Therefore, the initial clearance between the stator and rotor of all-metal screw pumps should be greater than 0.15 mm.

2.2. Influence of Leakage. In order to further optimize the clearance value of the all-metal screw pump, the model is imported into the Fluent software for calculation. The fluid domain and mesh division of the model are shown in Figures 6

![Figure 6. Geometry model of fluid computational domain.](image)

and 7. Fluent discretizes the computational domain into a series of control volumes, and solves these control volumes for conservation equations such as mass, momentum, and energy. Assuming that the fluid is an incompressible viscous Newtonian fluid, the flow element changes with time, so the transient model is selected. As the rotor spiral surface is used as the dynamic boundary of the watershed for planetary motion, the dynamic mesh model is selected, and the update process of the grid is automatically completed by Fluent according to the change of the boundary in each time step, and the prepared CG macro function is loaded to define the motion of the moving boundary. The pressure–velocity coupling algorithm uses the simple algorithm with faster convergence. The discrete format uses the second-order upwind style, and the convergence accuracy is set to $10^{-5}$. The convergence of the calculation is determined by monitoring the residual value while ensuring the conservation of mass. The control equation is iteratively solved until convergence.

Different working conditions have a great influence on the pump. Take the clearance value of 0.2 mm and the fluid as water with a viscosity of 1 mPa·s as an example. The inlet boundary condition is velocity inlet and the outlet is out flow. Because there is only one outlet, the outflow boundary flow weight is set to 1. The wall boundary condition is set to a no-slip boundary condition. The pressure graph at different speeds is shown in Figure 8.

![Figure 7. Grid of fluid computational domain.](image)

Simulation research was continued by turning the fluid into oil with a viscosity of 300 mPa·s. The flow rate and different pressure was monitored, and the corresponding relationship diagram was made, as shown in Figure 9.

As can be seen from Figure 9, for low-viscosity water, the flow rate decreases linearly and rapidly with increasing pressure; for high-viscosity oil, the decrease in oil flow rate is much smaller than that of water. This shows that the clearance will cause leakage, and viscosity is an important factor affecting the amount of leakage.

Through the above research, it can be seen that the clearance between the stator and rotor of the all-metal screw pump will cause leakage, and viscosity is an important factor affecting the amount of leakage. In order to further determine the relationship between the amount of leakage, viscosity, and clearance, further research on leakage is required.

As shown in Figure 10, it can be known from the concentric ring clearance flow theory:

$$\Delta p = \frac{16 \mu L}{\pi (R_0 + r_0) h^2} q$$

(2)

$$d = r_0 + R_0$$

(3)

where $\Delta p$ is the pressure difference between the pumps, Pa; $\mu$ is the viscosity of the fluid, Pa·s; $L$ is the gap length, m; $q$ is the clearance leakage, m³/s; $r_0$ and $R_0$ are the inner and outer radius of the concentric ring, m, respectively; $h$ is the height of the clearance, m; and $d$ is the average diameter of the clearance, m.

When the screw pump works, there are both high-pressure and low-pressure cavities in the pump. Pump leakage occurs between high-pressure chambers in the radial direction and high–low pressure chambers in the axial direction. That is, the leakage of the pump includes two cases, one is transverse leakage, and the other is longitudinal leakage, as shown in Figures 11 and 12.

Equation 2 can be transformed into

$$q = \frac{\pi \bar{d} h^3}{16 \mu L} \Delta p$$

(4)

For lateral leakage, the determination of $\bar{d}$ is complicated. It can be determined by the spiral method on the surface of the rotor, as shown in eq 5.

$$\bar{d} = \sqrt{\frac{4e^2 + T^2}{4\pi^2}}$$

(5)

where $e$ is the eccentricity of the screw pump, m; $T$ is the stator lead, m; and $\bar{d}$ is the average diameter of transverse leakage, m.

Combining eqs 4 and 5, the transverse leakage can be obtained as

$$q_l = \frac{\pi h^3 \Delta p}{16 \mu L} \sqrt{4e^2 + \frac{T^2}{4\pi^2}}$$

(6)

where $q_l$ is the total transverse leakage, m³/s.

The longitudinal leakage occurs between the adjacent high- and low-pressure chambers in the axial direction of the pump, and the following relationship exists.

$$\bar{d}_l = \frac{d_l + d'}{2}$$

(7)

where $\bar{d}_l$ is the average diameter of longitudinal leakage, m.
Combining eqs 4 and 7, the longitudinal leakage can be obtained as

\[ q_2 = \frac{\pi(d_i + d_o)h^3 \Delta p}{32 \mu L} \]  

where \( q_2 \) is the total longitudinal leakage, m³/s.

Combining eqs 6 and 8, the total leakage can be obtained as

\[ q = q_1 + q_2 = \frac{\pi h^3 \Delta p}{32 \mu L} \left( 2 \sqrt{\frac{e^2 + \frac{T^2}{4\pi^2}}{d_i + d_o}} \right) \]

It can be seen from eq 9 that the leakage of the pump is directly proportional to the third power of \( h \) and inversely proportional to the viscosity of the fluid \( \mu \).

Therefore, the volumetric efficiency can be obtained as

\[ \eta_v = \frac{Q}{Q_t} \times 100\% = \left( 1 - \frac{q}{Q_t} \right) \times 100\% \]

where \( \eta_v \) is the volumetric efficiency, %; \( Q \) is the actual flow rate, m³/s; and \( Q_t \) is the theoretical flow rate, m³/s.

The model clearance values and fluid viscosity were changed, and the models were simulated at the rotational speed of 200 rpm. The simulation results are shown in Figure 13.
Figure 13. Effects of clearances on the pump efficiency.

It can be seen from Figure 13 that, whether it is a low-viscosity fluid or a high-viscosity fluid, as the clearance value increases, the pumping efficiency decreases accordingly, but the overall pumping efficiency of the high-viscosity fluid is higher than that of the low-viscosity fluid. For fluids with a viscosity of less than 100 mPa·s, the pump efficiency drops sharply when the clearance value exceeds 0.25 mm; for fluids with a viscosity of more than 100 mPa·s, when the clearance value exceeds 0.4 mm, the pump efficiency decreases significantly. Combined with the research content in Section 2.1, the optimization results of the clearance value are as follows: for fluids with a viscosity of less than 100 mPa·s, the clearance value between the stator and rotor is 0.15–0.25 mm; for fluids with a viscosity of greater than 100 mPa·s, the clearance value between the stator and rotor is 0.15–0.4 mm.

3. SPEED OPTIMIZATION

Increasing the pump speed can increase the volumetric efficiency of the pump, but increasing the speed will also consume more energy, so it is necessary to do research on the optimization of the pump speed. For the all-metal screw pump, the following relationships exist

\[ P = Q \cdot \Delta P \]  
\[ P = \frac{\pi M n}{30} \]  
\[ \eta = \frac{P}{P_1} \times 100\% \]

where \( P \) is the active power, \( w \); \( P_1 \) is the total power, \( w \); \( \eta \) is the mechanical efficiency, \( % \); \( M \) is the torque, N·m; and \( n \) is the rotating speed, rpm.

The mechanical efficiency of the pump under different viscosities and different clearance value conditions were calculated, and the clearance value was 0.2 mm. The results are shown in Figure 14.

It can be seen from Figure 14 that as the speed increases, the mechanical efficiency of fluids with different viscosities tends to increase first and then decrease. For high-viscosity fluids with a viscosity greater than 100 mPa·s, the mechanical efficiency of the pump is the highest between 200 and 300 rpm; for low-viscosity fluids with a viscosity less than 100 mPa·s, the mechanical efficiency of the pump is the highest between 300 and 500 rpm. In addition, the overall mechanical efficiency of high-viscosity fluids is higher than that of low-viscosity fluids, which also proves that all-metal screw pumps have advantages in conveying high-viscosity fluids. In summary, the speed optimization results of the all-metal screw pump are as follows: for fluids with viscosity higher than 100 mPa·s, the recommended speed range is 200–300 rpm; for fluids with viscosity less than 100 mPa·s, the recommended speed range is 300–500 rpm.

4. EXPERIMENTAL STUDY

In order to verify the accuracy of the simulation results, the experimental method was used for further analysis. The all-metal screw pump produced by Yancheng Shihong petroleum assembly Limited Company was used as the test pump. The pump model is JDGLB160, the rotor diameter is 50 mm, the eccentricity is 5 mm, the rotor pitch is 80 mm, the stator lead is 160 mm, and the ambient temperature is 20 °C.

As shown in Figure 15, the experimental system includes a control system, a fluid system, and a data collection system. The control system is composed of a computer and a console, which is responsible for sending instructions to the fluid system; the fluid system is composed of a screw pump and a motor, which is responsible for the fluid transmission; and the data collection system is composed of a flow meter and a pressure gauge, which is responsible for collecting data during the experiment.

Water and hydraulic oil of different viscosity were chosen as the experimental fluid. The rotor of the single head screw pump rotor for the test is shown in Figure 16, and the single head screw pump for the test is shown in Figure 17.

5. RESULTS AND DISCUSSIONS

Different viscosity fluids were selected for multiple experiments, the clearance value of the pump was 0.2 mm, and volumetric efficiency of the pump was calculated, as shown Figure 18.

As can be seen from Figure 18, as the rotational speed increases, the volumetric efficiency of fluids with different viscosities increases, but the volumetric efficiency curve of high-viscosity fluids is smoother than that of low-viscosity fluids. At the same time, it can be seen that when the all-metal screw pump delivers fluid with a viscosity of less than 100 mPa·s, the volumetric efficiency is very low when the speed is between 100 and 300 rpm. After the speed reaches 300 rpm, the volumetric efficiency begins to tend to be gentle. When the all-metal screw pump delivers fluid with a viscosity higher than 100 mPa·s and when the speed is between 100 and 200 rpm, the volumetric efficiency changes drastically. Only after the speed reaches 200 rpm, the curve begins to become flat. This is
consistent with the research results in Section 3, which proves the accuracy of the numerical simulation results.

In order to verify the optimization results of the clearance value of the pump, all-metal screw pumps with different clearance values were selected to continue the experiment and the mechanical efficiency of fluids with different viscosity were calculated, as shown in Figure 19.

6. CONCLUSIONS

In this paper, numerical simulation and experimental methods were used to study the clearance value and speed of the all-metal screw pump, and the following conclusions are drawn:

1. Through numerical simulation of the all-metal screw pump, preliminary optimization design of the clearance value and speed of the pump is done. The preliminary optimization results are as follows: for fluids with a viscosity of less than 100 mPa·s, the recommended clearance value is 0.15−0.25 mm, and the recommended speed range is 200−300 rpm; and for fluids with a viscosity greater than 100 mPa·s, the recommended clearance value is 0.15−0.4 mm, and the recommended speed range is 300−500 rpm.

2. The experimental results are in good agreement with the numerical simulation results, which proves the accuracy of the numerical simulation results. At the same time, the
experimental results further complement the numerical simulation results. The final optimization result is as follows: for fluids with viscosity less than 100 mPa-s, the recommended clearance value is 0.15–0.25 mm, and the recommended speed range is 200–300 rpm; and for fluids with viscosity greater than 100 mPa-s, the recommended clearance value is 0.25–0.4 mm, and the recommended speed range is 300–500 rpm.

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