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Leakage of a Multistage Self-compensating Soft Plunger Pump under Different Methods

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Abstract

As a new type of crude oil recovery and lifting equipment, a multistage self-compensating soft plunger pump, which is suitable for alkaline-surfactant-polymer (ASP) flooding oil wells, has advantages over conventional pumping equipment. Owing to the existence of a soft plunger-pump barrel pair clearance, the pump will inevitably leak under the influence of alternating load factors, and the leakage is the main parameter in its operation. To explore the coincident relationship between the leakage of a multistage self-compensating soft plunger pump and different calculation methods, a numerical simulation model of vertical annular slit flow between a self-compensating soft plunger and a pump barrel was proposed in the study. Through the use of the Euler-Lagrange equation to describe the displacement of interface between fluid and solid, unidirectional and bidirectional fluid-structure coupling methods were presented, and the leakage distribution of a multistage self-compensating soft piston pump was determined. At the same time, a theoretical calculation model of the leakage of a multistage self-compensating soft plunger pump was obtained on the basis of hydrodynamics and the mass conservation law. Theoretical analysis, numerical simulation, and experimental study were performed to explore the influence of parameters, including the structural parameter of soft plunger length and the differential pressure operation parameter, on leakage. Meanwhile, the data of unidirectional fluid-structure coupling, bidirectional fluid-structure coupling, and theoretical calculation were compared with test results, and the optimal calculation method was proposed. Results demonstrate that under different initial clearance conditions between the soft plunger and the cylinder pair, the leakage of the pump and the length of the soft plunger are negatively correlated, that is, the larger the length of the soft plunger is, the smaller the leakage is. The pump leakage increases with the increase in pressure difference, but the rate of change of the leakage decreases gradually, which is also reflected in the change in the volume efficiency of the soft piston pump. The leakage of the multistage soft piston pump calculated by numerical simulation of bidirectional fluid-structure coupling is in the highest agreement with the leakage calculated using the experimental test method, and the difference between the two methods is within the allowable range. Therefore, the bidirectional fluid-structure coupling method adopted in this study is effective in analyzing the pressure characteristics and leakage of the multistage soft plunger pump and the proposed method provides engineering application value.

Keywords: Soft plunger, Leakage amount, Bidirectional fluid-structure coupling

1. Introduction

As the earliest and most widely used lifting equipment in crude oil exploitation, pumps are used to generate crude oil from over 90% of oil wells. With increasing difficulty of oil exploitation, alkaline-surfactant-polymer (ASP) flooding technology has been adopted in oil fields with alkali, polymer solution, and surfactant as driving fluids and the oil recovery has been improved. However, due to the addition of polymer, sand jamming and scaling phenomena occur in serious cases. At the peak of scaling, the inspection cycle of a pumping unit is shortened to only more than 70 days. Nevertheless, as a new type of crude oil lifting equipment, soft plunger pumps have irreplaceable advantages over conventional pumps and recovery equipment, and some achievements have been made in solving the scaling phenomenon of conventional plunger pumps.

On this basis, a large number of studies on the soft plunger material, leakage, and lifting performance of the pumps have been carried out [1-3]. The soft plunger material was optimized, and the relationship between leakage and lifting performance was revealed. However, insufficient exploration in the numerical simulation of single/bidirectional fluid-structure coupling has been conducted and theoretical calculation and experimental data have been minimally compared. The leakage of a multistage self-compensating soft plunger pump deviates from the actual working state, and the existing studies could not correctly solve the problems of pump efficiency and life. The influence law of the structural parameter of length and the differential operation parameter on the leakage of a soft plunger should be explored under the condition of two-dimensional fluid-structure coupling. The soft plunger pump model should be accurately predicted, and the mutual coupling relationship of soft plunger pump-soft deputy clearance within the fluid pump barrel and plunger at actual running state should be determined. Therefore, study of the

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optimal calculation method for the leakage of multistage self-compensating soft plunger pumps is an urgent problem.

A certain effect on solving the problems of stuck pump and scaling has been achieved by a single-stage soft plunger pump, but its low pressure is the key factor limiting its development. To prolong the service life of a single-stage soft plunger pump, a multistage self-compensating soft plunger pump adapted to ASP flooding mining technology was designed, which made each stage of the soft plunger bear uniform pressure and prolonged the inspection period of the pump. Through theoretical analysis and the finite element method, a new type of three-level self-compensating soft plunger pump was established. The leakage of the soft plunger pump was analyzed under different conditions of length and differential pressure. To explore the relationship between the leakage and calculation method of the multistage self-compensating soft plunger pump, a prediction model of soft plunger pump should be established.

2. State of the art

Soft seal piston pumps have been developed and applied in oil exploitation worldwide. According to statistics, the service life of soft piston pumps is 1.5-1.6 times that of ordinary pumps [4]. Scholars have carried out a large number of studies on soft piston pumps. Considering the frequent phenomena of tube fouling and pump blockage in ASP flooding wells, Ren et al. developed a multistage soft seal plunger pump and conducted pressure and pump efficiency tests. The test results showed that the average pump efficiency of 21 wells at the scene was 62.84%, and the longest exempt period was up to 184 days. The multistage soft sealing plunger pump could effectively prolong the pump inspection cycle. However, the preferred soft plunger in the study was subject to hydraulic swelling and sealing, and it was easy to wear when the pump barrel interference fit [5]. Wang et al. designed a kind of soft plunger that could generate a fixed valve rod pump and performed wear, pressure, and leak tests of the plunger pump in the Daqing Oil Field. The main material of the plunger was fluorine plastic, and inspection operations of the fixed pump were realized. The production cost of the well was greatly reduced. Nonetheless, this pump was only suitable for the producing condition of no sand or less sand, and this limitation prevented it from being widely promoted [6]. Yang et al. analyzed a lifting technology of ASP flooding system. The experimental data showed that the inspection cycle of a multistage self-compensating soft plunger pump was up to 215 days on average in 91 wells. The pump had good adaptability for the lift system that used the ASP flooding technique, but he did not deeply explore the operation and structural parameters of the soft plunger [7]. Aiming to achieve equal life of soft plungers and reduce the wear of soft piston pumps, Cui et al. studied the law of pressure transfer of a self-compensating soft piston pump and optimized the shape of a pressure relief tank and the angle of a cutoff pressure transfer hole. However, the problem of leakage caused by erosion of fixed valves had not been effectively solved [8].

Traditional oil well pumps have deficiencies, such as stuck pumps, leakage quantity deficiency in sand wells, and ASP flooding easy-fouling oil wells. Richardson developed a new type of composite pump plunger and shortened effectively the pump inspection cycle during test, but how to improve the high-temperature-resistant performance and anti-aging properties of sealing cups and to prolong the service life of soft plungers was not studied [9]. Lee analyzed the structural characteristics of ASP flooding anti-stuck pumps, created a solid model of anti-stuck pump, and verified the model through the wear resistance and leakage experiments of the pump. Owing to the complex working conditions in ASP flooding wells, the problem of wear failure needs further exploration [10]. Newton carried out a study on an immersion thickening pump, which had a hydraulic feedback force and turned the pressure difference of a liquid column between the tubing and the casing into the downward force of a rod string, which could solve the problem of rod string downward difficulty encountered in heavy oil wells. Nevertheless, further work needs to be done on the safety check of the sealing section of thickening pumps [11]. By analyzing the status quo of ASP flooding pumping wells, Jafri considered a new type of pumping pump that combined subsection lifting process and soft plunger technology and conducted an indoor simulation test to verify that its performance met lifting requirements, which was of great significance to further prolong the pump inspection period of ASP flooding pumping wells. However, the field application of this new type of pump had not been studied with complex working conditions [12].

Zhao conducted indoor temperature change and wear resistance tests of four soft plunger materials in view of the low wear resistance of Polytetrafluoroethylene (PTFE) soft plungers subjected to alternating loads. Given its high wear resistance and strong stability, Polyether ether ketone (PEEK) was selected as the multistage soft plunger material for the pump. The experimental data showed that the PEEK soft plunger not only met the requirements for downhole work but could also effectively reduce the cost of oil production [13]. A comparison method was employed by Li to analyze the sensitivity to suspended sand of general pumps and multistage soft plunger pumps. The results showed that under the working condition of sand, the performance of a multistage soft plunger pump was more stable, and soft plunger materials could effectively prevent the problem of pump blockage caused by sand. Nonetheless, the pump efficiency would reduce under high loading in a deep well, which limited its application scope [14]. Using the orthogonal multi-parameter optimization method, Li designed a new pumping system for soft plunger pumps and determined the reasonable clearance value of soft plunger-pump cylinder pairs through an indoor test, which solved the existing problems, such as soft plunger swelling and excessive load. However, the wear resistance properties of sealing and expansion ring materials of self-compensating soft piston pumps are poor, resulting in short pump inspection period and service life [15]. Wu et al. meshed a three-dimensional model of swash plate piston pump. Based on the Fluent software, the user-defined function (UDF) method was used to determine the flow state of the piston pump and explore the movement law of the two-phase boundary. Nevertheless, detailed analysis of the flow changes of the inlet and outlet of the piston pump in the convective solid-state coupling state was lacking [16]. Reinhard considered the behavior of viscous fluids with free boundary of elastomers, and the motion of the upper boundary was described through a combination of frictional boundary conditions, which quantified the elasticity of the boundary and proved the local existence of weak solutions of the coupled system in three-dimensional space by using a fixed-point parameter [17]. Mo discussed the influence of the valve type of a piston pump on performance improvement, mainly for ball and cap valves, used fluid-structure coupling and UDF technology to conduct a transient laminar flow analysis, and performed a standard pump test to verify the simulation results of the piston pump [18]. Irina explored the numerical simulation method of fluid-structure coupling for a flexible thin-wall structure installed on the side of a rigid non-rotating cylinder in a channel, adopted the modeling mode of bidirectional fluid-structure coupling in the ANSYS software and compared it with experimental data, and testified the effectiveness of the numerical simulation method [19]. Nie et al. simulated the field changes of temperature and velocity in the oil production process of a piston pump by using the Fluent software and studied the oil film of a plunger-clearance pair by using the two-way fluid-solid coupling method. However, the leakage amount of the clearance oil film was not calculated by simulating the operation condition of the piston pump [20]. Ahmed studied the structural parameter characteristics of different plunger sleeves and their deformation characteristics under the action of gap flow based on the fluid-structure coupling method and proposed a self-compensating hydraulic pump plunger pair structure. The variation rule of annular groove width with the deformation of the plunger sleeve was explored through theoretical analysis and experimental verification, but the correlation between the deformation of the plunger sleeve and the structural parameters, such as material thickness and inclination angle at the same working pressure, was not studied [21]. Schmitt analyzed the movement of plungers and ball valves by combining theoretical and experimental methods. On the basis of the Fluent software, he built a movement model of plunger pump and obtained the velocity field and pressure field of the plunger in the upper stroke to provide a reference for the analysis of internal flow field characteristics in other plunger movements. Nonetheless, a flow field analysis in different operating states is lacking [22].

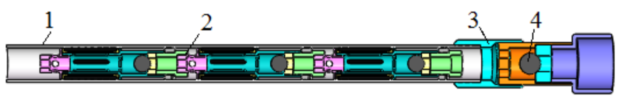
In view of the preceding discussion, research was mainly based on the structural design of soft plunger pumps, soft plunger materials, temperature field, and velocity field. However, studies on the correlation between leakage and the structural parameter of length and the parameter of differential operation were limited. Especially, work on the leakage of multistage self-compensating soft plunger pumps under different calculation methods was minimal. A characteristic model of soft plunger pump job was established in this study by using a two-way fluid-structure coupling analysis method, and the vertical annular clearance flow between the soft plunger and the pump barrel was boundary. Nevertheless, detailed analysis of the flow explored. A mathematical model of leakage was built, and the relationship between leakage and parameters under different lengths of the soft plunger pump structure and differential operation conditions was discussed. At the same time, the leakage obtained by the analysis method of unidirectional fluid-structure coupling and the theoretical prediction by using a mathematical model method were compared with the leakage measured by test.

The remainder of this study is organized as follows. As an example, a physical model of three-stage soft plunger pump is built in Section 3. A theoretical calculation model of leakage is obtained by analyzing the annular clearance flow. The influencing factors of differential pressure operation parameters and their functional relationship are explored through the coupling between the soft plunger and the clearance flow in the pump barrel and the length structure of the leakage volume. In Section 4, the leakage characteristics of the model are analyzed by combining numerical simulation with curve fitting. Through a contrast method, the model is deeply analyzed, and the difference in leakage amount under different calculation methods is obtained. The study is summarized, and relevant conclusions are given in the last section.

3. Methodology

3.1 Physical Model

The structure of a three-stage self-compensating soft plunger pump is shown in Fig. 1. Each stage of the soft plunger pump is composed of series connection. The device adopts the principle of hydraulic self-sealing and the principle of graded pressure. When the plunger is in the upper stroke stage, the soft plunger swims and closes, and the oil flows into the first stage of the soft plunger, so that the liquid pressure inside the soft plunger increases. At this point, the soft plunger force expansion is not enough to expand the whole pump barrel. At the same time, the oil will also pass through the gap between the first stage of the soft plunger and the pump barrel into the next stage of the soft plunger. However, because of the action of resistance, the oil has a certain pressure drop through each stage of the soft plunger. The low-pressure oil flows through each stage of the soft plunger those results in the expansion of the soft plunger deformation. Therefore, as the pressure decreases gradually, the formation of multistage sealing and graded pressure does not make each stage of the soft plunger bear excessive pressure difference and greatly improves the life of the soft plunger. When the soft plunger is in the lower stroke stage, the differential pressure causes the swimming Val near the third-stage soft plunger to open, and the oil in the pump barrel flows through the upper joint into the upper plunger. At the same time, the swimming Val of the first stage of the soft plunger opens, so the pump barrel connects up and down. Then, the soft plunger internal and external pressure difference is equal, and the soft plunger shrinks to restore to the original state. Afterward, the soft plunger's downward resistance is reduced.



1 –Pump barrel; 2 –Plunger assembly; 3 –Fittings of pump barrel; 4 –Fixed valve assembly

Fig. 1. Structural diagram of a three-stage soft plunger pump

3.2 Analysis of the leakage of the soft plunger-pump barrel pair

The soft plunger-pump barrel pair of the pump moves up and down in a clearance fit way to complete the oil absorption and discharge processes. The multistage soft plunger and pump barrel not only have relative motion, but also the two ends of the soft plunger and pump barrel are subjected to pressure difference. Therefore, the flow rate of oil in the gap should be in linear superposition caused by shear flow rate and pressure difference [23]. To construct a clearance flow model between the multistage soft plungers and pump barrel of the pump, the concentric and eccentric annular clearance flows under the action of pressure difference should be analyzed.

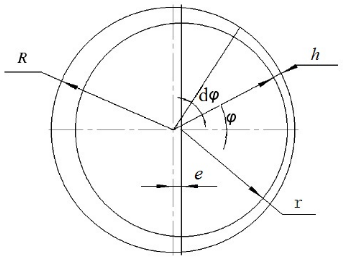


Fig. 2. Flow in an annular clearance

The flow of an eccentric annular clearance is shown in Fig. 2, where r and R are respectively the radius of inner and outer circles, e is the eccentricity, and h is the clearance height. The line between any point of the circle and the center of the circle is offset φ along the positive X axis, where $d\varphi$ is taken, because the gap formed by the internal and external cylinders corresponding to $d\varphi$ can be approximated as the gap between two parallel plates [24]. Thus, the flow here can be calculated in accordance with the gap flow formula of two parallel plates as follows:

$$dQ = \frac{bh^3 \Delta p}{12\mu l} \tag{1}$$

In Eq. (1), b is the width of the parallel plate, m; h is the clearance height, m; Δp is the pressure difference at both ends, Pa; μ is the hydrodynamic viscosity, Pa·s; l is the length of the parallel plate, m.

The width here is $b = Rd\varphi$, which is substituted into Eq. (1) to obtain the flow rate of annular clearance:

$$dQ = \frac{\Delta p}{12\mu l} h^3 R d\varphi \tag{2}$$

Let h_0 be the amount of clearance when the inner and outer circles are completely concentric, and the clearance height can be expressed as:

$$h \approx R - e\cos\varphi - r = h_0(1 - \varepsilon\cos\varphi) \tag{3}$$

In Eq. (3), h_0 is the clearance amount when the inner and outer circles are completely concentric; ε is the eccentricity, $\varepsilon = \frac{e}{h_0}$.

Eq. (3) is substituted into Eq. (2), and the following equations can be obtained:

$$dQ = \frac{\Delta p}{12\mu l} h_0^{\,3} (1 - \varepsilon\cos\varphi)^3 R d\varphi \tag{4}$$

The leakage of the flow throughout the annular clearance can be calculated as follows:

$$Q = \int_0^{2\pi} \frac{\Delta p R h^3}{12\mu l} (1 - \varepsilon\cos\varphi)^3 d\varphi = \frac{\pi d h_0^3}{12\mu l} \Delta p (1 + 1.5\varepsilon^2) \tag{5}$$

When $\varepsilon = 0$, the inner and outer cylinders are completely concentric, and it is substituted into Eq. (5) to obtain:

$$Q = \frac{\pi d h_0^3}{12\mu l} \Delta p \tag{6}$$

The initial installation between the multistage soft plunger and pump barrel is realized without eccentricity, and the influence of speed is considered. In the upper stroke, the pressure on the upper end of the soft plunger is higher than the pressure on the lower end, that is, $\Delta p > 0$, the direction of pressure difference is opposite to the direction of plunger movement, and the direction of leakage is opposite to the direction of oil discharge [25]. The velocity reduces the amount of leakage, as follows:

$$Q = \frac{\pi d h_0^3 \Delta p}{12\mu l} - \frac{v h_0}{2} \pi d \tag{7}$$

The following equations are obtained by conversion:

$$Q = 3600\pi d \left(\frac{\Delta p h_0^3}{12\mu l} - \frac{v h_0}{2} \right) (m^3 / h) \tag{8}$$

The dynamic leakage of the pump is shown in Eq. (8), that is, the leakage of the pump under pressure difference and relative movement. Without relative movement, the corresponding static leakage of the soft plunger pump is as follows:

$$Q = \frac{300\pi d h_0^3 \Delta p}{\mu l} \tag{9}$$

3.3 Influence of length on the leakage of the soft plunger pump

In this study, length was selected as the representative of structural parameters and pressure difference of operating parameters, and bidirectional fluid-structure coupling, which is difficult to calculate, was regarded as an example to explore their influence on the leakage amount. The Fluent software was used to establish a soft computing model of the plunger, and the leakage was calculated under different soft plunger lengths. The liquid medium oil well pump outlet pressure was 2 MPa, the inlet pressure was 0 MPa, the pump barrel diameter was 30 mm, the soft plunger thickness was 3 mm, and the soft plunger pump barrel-vice initial gap h_0 was 0.4, 0.45, 0.5, 0.55, and 0.6 mm, as shown in Table 1.

Table 1. Leakage of soft plungers with different lengths

lengths l (mm)	initial clearance h_0 (mm)				
	0.4	**0.45**	**0.5**	**0.55**	**0.6**
	leakage Q (kg/s)				
30	0.00603	0.00901	0.01275	0.01275	0.02261
35	0.00522	0.00771	0.01093	0.01093	0.01934
40	0.00456	0.00673	0.00956	0.00955	0.01693
45	0.00406	0.00627	0.00848	0.00848	0.01506
50	0.00365	0.00541	0.00751	0.00751	0.01359

3.4 Influence of differential pressure on the leakage of the soft plunger pump

A bidirectional fluid-structure coupling calculation method was adopted under the condition of water in the oil well pump. The calculation parameters of the soft plunger pump were as follows: the barrel diameter was 30 mm, the length was 50 mm, the thickness was 3 mm, and the initial gap of the soft plunger pump barrel-vice was 0.7 mm. Various pressure difference parameters, such as leakage of the soft plunger pump, deformation, stress, and strain, were also considered. The specific data are shown in Table 2.

Table 2. Deformation and leakage of the soft plunger with different differential pressures

differential pressures ΔP (MPa)	deformation χ (mm)	stress (MPa)	strain	leakage Q (kg/s)
0.8	0.023	2.590	0.0023	0.0064
1.0	0.046	5.178	0.0046	0.0122
1.5	0.068	7.761	0.0069	0.0175
2.0	0.091	10.375	0.0092	0.0222
2.5	0.114	12.893	0.0115	0.0264
3.0	0.136	15.437	0.0138	0.0302
3.5	0.159	17.959	0.0160	0.0335
4.0	0.181	20.467	0.0183	0.0365
4.5	0.202	22.946	0.0205	0.0393

3.5 Volumetric efficiency of the soft plunger pump under different calculation methods

Bidirectional fluid-structure coupling calculation had been carried out above, but the unidirectional fluid-structure coupling method was relatively simple and not described. In this study, the leakage amount of the soft piston pump was calculated by unidirectional fluid-structure coupling, bidirectional fluid-structure coupling, and Eq. (9) under the same conditions. The different results of the three methods and the test results were compared, and the data are shown in Table 3 and Table 4.

Table 3. Four methods used to obtain leakage of different lengths

Lengths l (Mm)	Different Calculation Methods			
	Unidirectional	Two-Way	Theoretical Formula	Test
	leakage Q (kg/s)			
30	0.03102	0.0278	0.02174	0.02016
35	0.02659	0.02383	0.01845	0.0173
40	0.02326	0.02085	0.01605	0.01516
45	0.02068	0.01854	0.01428	0.01348
50	0.01938	0.01738	0.01325	0.01262

Table 4. Four methods used to obtain leakage at different differential pressures

Differential Pressure ΔP (Mpa)	Different Calculation Methods			
	Unidirectional	Two-Way	Theoretical Formula	Test
	leakage Q (kg/s)			
0.5	0.00525	0.00491	0.00475	0.00466
1	0.0105	0.00981	0.00916	0.00889
1.5	0.01567	0.01472	0.01351	0.01276
2	0.02092	0.01962	0.01708	0.01618
2.5	0.02609	0.02453	0.02054	0.01924
3	0.03134	0.02945	0.02394	0.02201
3.5	0.03659	0.03435	0.02657	0.02442
4	0.04176	0.03925	0.02907	0.0266
4.5	0.04687	0.04415	0.03136	0.02864

4. Result Analysis and Discussion

On the basis of the calculation model and the value of leakage in the bidirectional fluid-structure coupling method in Subsections 3.3-3.5, the MATLAB software was used to fit the leakage of the multistage soft piston pump. The influence rule of the main structural parameters of soft piston on the pump leakage was explored, which provided theoretical support for structural optimization and parameter design.

4.1 Analysis of the influence of length on the leakage of the soft plunger pump

On the basis of the data in Table 1, the change curve of pump leakage with length was obtained using the method of curve fitting, as shown in Fig. 3. The deformation increased with the increase in the length of the soft plunger, and different initial clearances all met this rule. Under the influence of the deformation, the leakage amount changed accordingly. Under different initial clearance conditions, the leakage and the soft plunger length were negatively correlated; that is, the larger the soft plunger length was, the smaller the leakage was. Meanwhile, the larger the initial clearance was, the more obvious the decreasing trend of leakage was.

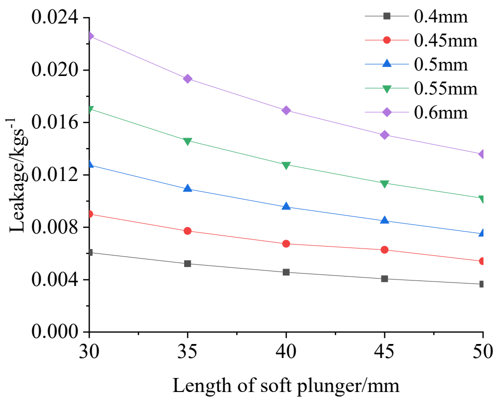


Fig. 3. Change curve of leakage with the length of the soft plunger

According to the data in Table 1, the fitting equation of change curve of oil pump leakage with the length of the soft plunger is as follows:

$$f(x) = kx^b \tag{10}$$

where k 、 b are coefficients.

The parameters of the fitting equation in Eq. (10) were also different when the initial clearance between the soft plunger and pump barrel pair was different. The specific parameters are shown in Table 5.

Table 5. Fitting parameters of the relationship between the leakage and the length of the soft plunger

Coefficient	Initial Clearance h_0 (10^{-1} Mm)				
	0.4	0.45	0.5	0.55	0.6
k	1.788	2.3446	4.1443	5.1319	6.7643
b	−9.9440	−9.5912	−10.2303	−10.0098	−9.9956

According to the fitting equation and parameters of the oil pump leakage curve changing with the length of the soft plunger, parameter b tended to constant -1, which was consistent with the theoretical calculation model of Eq. (9). The change law that leakage was decreased with the increase in the length of the multistage soft plunger oil pump was verified. Under the same parameters, if the length of the soft plunger was kept unchanged, the leakage amount of the pump would not be affected only by changing the series of the soft plunger.

4.2 Analysis of the influence of differential pressure on the leakage of the soft plunger pump

Curve fitting was carried out on the data in the above table, and the curves of soft plunger leakage and deformation with pressure difference were obtained, as shown in Fig. 4. Under the action of working pressure difference, the deformation of the soft plunger and the leakage of the pump both changed to some extent. The deformation of soft plunger increased with the increase in pressure difference and tended to change linearly. The leakage of the pump also increased with the increase in pressure difference, but the change rate of the leakage gradually decreased, which was also reflected in the change in the volumetric efficiency of the soft piston pump.

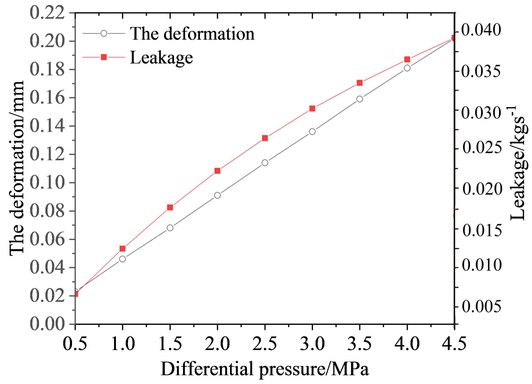


Fig. 4. Change curve of the leakage of the soft plunger and deformation with differential pressure

According to the above study, the leakage of the soft piston pump was positively correlated with the working pressure difference and negatively correlated with the length of the soft piston.

4.3 Comparison of different calculation methods

Fig.5 and Fig.6 depict the large difference between the leakage calculated by unidirectional fluid-structure coupling and the leakage measured by test. The leakage calculated by bidirectional fluid-structure coupling was quite consistent with the leakage measured by test, and the leakage calculated by the theoretical formula was between them. The calculation of two-way fluid-structure coupling was tedious, a heavy workload, and difficult to converge. The calculation of the theoretical formula was fast, simple, and easy, and the calculation of one-way fluid-structure coupling was moderate in difficulty. The soft plunger-barrel secondary fluid of the pump belonged to the slit flow, and the effect of the deformed solid on the flow field was a factor that could not be ignored. Therefore, to achieve a simulation effect close to actual working conditions, the relatively accurate optimization of soft plunger parameters must adopt the bidirectional fluid-structure coupling numerical calculation method. However, the theoretical calculation method could be used as the preliminary calculation to provide a reference for finite element analysis and numerical calculation.

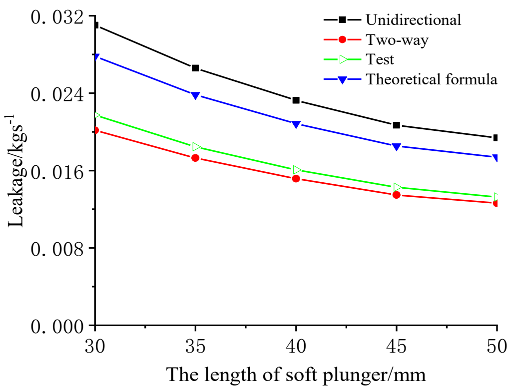


Fig. 5. Comparison of calculation methods under different length conditions

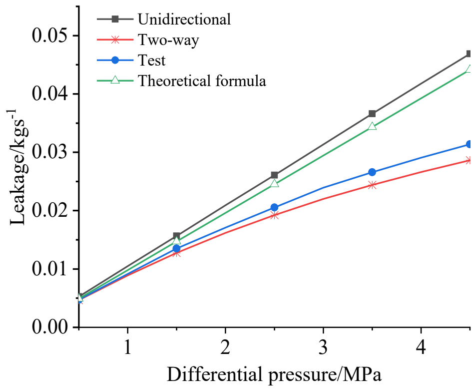


Fig. 6. Comparison of calculation methods under different pressure differences

5. Conclusions

To reveal the relationship between the leakage of a multistage self-compensating soft plunger pump and the structural parameter of soft plunger length and the differential operation parameter and to determine the optimal calculation method, a physical model of soft plunger pump was built, and numerical simulation technology and theoretical studies were combined. Then, the leakage of the multistage self-compensating soft plunger pump was analyzed. The following conclusions could be drawn:

(1) A theoretical calculation model of leakage was established. Then, the main influencing factors of leakage, including the length and thickness of the soft plunger, the gap between the soft plunger and the pump barrel pair, and the differential pressure, were identified.

(2) Both the models of theoretical calculation and numerical simulation of bidirectional fluid-structure coupling show that the leakage amount has a negative correlation with length. After the static pressures at the outlet and the inlet were determined, the reasonable length range for each stage of the soft plunger was determined by the leakage amount. On the premise of satisfying pump efficiency, the waste of manufacturing material can be reduced, and cost can be saved by selecting a reasonable length of the soft plunger.

(3) A positive correlation exists between leakage and differential pressure; that is, the leakage of the pump increases with the increase in pressure difference, but the change rate of leakage decreases gradually. The deformation of the soft plunger increases with the increase in pressure difference and tends to present a linear variation.

(4) Comparative analysis shows a large deviation between the leakage calculated by unidirectional fluid-structure coupling and the leakage measured by the test. However, the leakage calculated by bidirectional fluid-structure coupling is consistent with the leakage measured by the test, and the leakage calculated by the theoretical formula is between the two methods. To achieve a simulation effect close to actual working conditions, bidirectional fluid-structure coupling should be adopted for finite element numerical calculation.

The methods of numerical simulation and theoretical research were combined in this study, and a new understanding of the influence law between the leakage amount of a soft plunger pump and the main structural parameters of the soft plunger was proposed, which is a valuable reference for the subsequent development of multistage soft plunger pumps. Owing to the lack of actual data from field monitoring at the present time, if actual field data are combined with this model and the model is modified in future research, it would be more accurate to understand the operation law of soft plungers under complex working conditions.

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