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Pressure Characteristics of Multistage Soft Plunger in an Oil Well Pump

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Abstract

Soft plunger oil well pumps integrate the advantages of scale prevention, simple structure, and convenient maintenance, which can be effectively adapted to well conditions by using alkali-surfactant-polymer (ASP) flooding technology. However, the applic2ation of soft plunger oil well pumps has been greatly limited due to its short inspection cycle. In order to explore the variation law of pressure and velocity fields of multi-stage self-compensating soft plunger oil well pumps and thus prolong their service life, this study established a numerical fluid-solid calculation model via Fluent. This calculation was used to determine the optimal three-stage soft plunger oil well pump models with different lengths and outer diameters. Next, the fluid-solid interface displacement was described and operated by using the Lagrange-Euler model and the deformation condition and stress changes of multi-stage self-compensating soft plunger oil well pumps were analyzed. Meanwhile, the leakage of relatively large clearance flow was equalized based on the law of fluid mechanics and conservation of mass, and that of liquid flowing in the clearance between the soft plunger and the pump barrel was determined. The length of each stage of the soft plunger in the self-compensating oil well pump was then calculated. Theoretical analysis and numerical simulation were combined to explore the effects of structural parameters, including the length and outer diameter of the soft plunger, on the pressure and velocity fields. Moreover, the correctness of the theoretical calculation was verified through its comparison with the numerical results of the two-way fluid-solid coupling. The results show that the maximum stress of each stage of the soft plunger occurs in the lower part of its inner wall while that of the whole oil well pump structure declined gradually from the fluid inlet to the fluid outlet. The fluid pressure in the narrow clearance between the inner wall of the pump barrel and the soft plunger presents a continuous and progressive reduction law. The maximum and the minimum flow velocities appears at the fluid inlet and outlet of each plunger, respectively, where an eddy current forms in their connection areas. A continuous and uniform pressure distribution is realized from the inlet to the outlet in the clearance flow field between pump barrel pairs. With the third-stage soft plunger of the oil well pump as an example, the pressure field that is obtained under the optimized length and outer diameter of the soft plunger consistently conforms to the staged pressure-bearing characteristic law. Hence, the fluid-solid coupling method adopted in this study is feasible and practical in exploring the pressure characteristics of multi-stage soft plungers. This study provides certain engineering values for optimal pump structural design.

Keywords: Soft plunger, Pressure, Bidirectional fluid-structure coupling

1. Introduction

At present, most oilfields in China have entered the stage of tertiary oil recovery. With the annual decrease of underground oil reserves, environmental exploitation becomes increasingly complicated and the difficulty in crude oil exploitation increases day by day. This scenario leads to increasingly urgent requirements for the design of oilfield lifting equipment. Several oilfields have adopted alkali-surfactant-polymer (ASP) flooding technology, which contributes to a crude oil recovery rate of over 20%. However, several mineral components are dissolved and migrate due to the addition of polymers, thereby producing aluminosilicate mixture between the plunger and pump barrel of the oil well pump, or worse, scaling [1]. During peak scaling periods, the pump inspection period for pumping wells is considerably reduced to over 70 days.

Given this context, researchers have developed a hydraulic self-sealing soft plunger oil well pump. As an oil recovery device based on metal-nonmetal surface contact, this new-type oil well pump operates in the mixed medium of crude oil, water, and natural gas at medium and high temperatures and has helped solve the scaling of conventional plunger pumps [2-3]. However, restrictions by geometric, contact, and material nonlinearities of the soft plungers, the difference in material characteristics between its polymer material and the pump barrel metal, and the sensitivity to actual underground working conditions lead to difficulties in the analysis and calculations of the soft plungers of oil well pumps, which have been rarely explored in depth. No effective development and considerable progress have been achieved in relevant products and technologies. Moreover, single-stage soft plunger oil well pumps have not been extensively applied due to the short inspection cycle. As such, how to extend the service life and expand the scope of application of oil well pumps remain a problem that needs urgent solutions for oilfields.

With the aim to lengthen the service life of soft plunger oil well pumps, this study explores the staged pressure-bearing characteristics of multi-stage soft plungers for oil

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well pumps. By constructing a calculation model of multi-stage soft plungers for an oil well pump in line with actual working conditions, the stress and deformation of soft plungers under the action of clearance flow were examined by using the two-way fluid-solid coupling method. Meanwhile, the effects of deformation on the pressure and velocity fields were explored, and the pressure characteristics of multi-stage soft plungers were analyzed. Next, a structural optimization method is put forward for multi-stage soft plungers of oil well pumps based on the principle of uniform pressure bearing at all stages. This method presents considerable practical significance for prolonging the inspection cycle of soft plunger oil well pumps, improving their oil production efficiency, increasing economic benefits, and perfecting the oil recovery and pumping system.

2. State of the art

At present, soft plunger pumps are characterized by low leakage, high pump efficiency, small wear of pump barrel, and relatively low cost, gaining good graces from an increasing number of researchers who exerted considerable work in this field. Since the early 1980s, research has begun on the soft sealing plunger pumps in Liaohe Oilfield. For the pumps, Polytetrafluoroethylene (PTFE) and nylon rings were initially used in series. Although the wear resistance of such oil well pumps has been improved, the research work has basically stagnated due to the lack of in-depth analysis on supporting force, insufficient compressive strength, and limited heat and aging resistance [4]. Xu designed a hydraulic self-sealing plunger pump for lifting viscoelastic fluid containing polymers, and found that its leakage is lower than that of the conventional pump. When the clearance is 0.1-0.15 mm, the hydraulic self-sealing plunger pump with polymer-containing viscoelastic fluid shows low leakage, which can effectively solve the eccentric wear and leakage of rod and pipe in polymer flooding wells and thus considerably improve the pump efficiency [5].

Wang et al. developed a soft plunger-salvageable oil well pump with a standing valve. The wear of the outer surface of the pump, if any, can be automatically compensated by expansion without enlarging the fit clearance with the pump barrel. During pump inspection, the requirement is only to lift the plunger out together with the standing valve and replace any damaged components, rather than needing to lift the oil pipe [6]. Xu et al. designed a new type of combined plunger anti-sticking oil well pump, which effectively improved the pump inspection cycle during the test in Daqing No.3 Oil Production Plant. Subsequently, this plunger structure with combined sealing sections was successfully applied in ASP flooding oil wells. However, this plunger structure is restricted by its diameter, leading to difficulties in designing a combined plunger when the pump diameter is too small [7]. Cui et al. studied the application of hydraulic start-up soft plunger oil well pumps in sand production blocks. A pressure transmission and decompression groove on the central pipe and throttle orifices with different angles on the support ring were designed to disperse and balance the pressure and for each sealed leather cup. However, solutions are still needed on how to improve the high temperature and aging resistance of sealed leather cups and lengthen the service life of soft plungers [8]. Based on the theory of fluid mechanics, Stepanov analyzed the movement of fluid, determined three design forms of high-pressure plunger pumps, and calculated data of velocity and pressure. Specific to different pipeline design test schemes, a series of numerical tests were carried out to verify the influences of pressure and velocity on the changes in system characteristics. However, the indoor wear resistance and leakage of high-pressure plunger pumps were not tested [9].

To apply sucker rod and jet pumps to the drive of swing machines in oil wells, Oleg estimated the pressure distribution, obtained and applied the pressure equation under high- and low-pressure conditions in oil-gas jet pumps, and developed a calculation method for their relevant parameters [10]. Drozdov studied and discussed the impurity/gas separator of plunger pumps in oilfields, and explored its performance advantages and applications. The assembly of the plunger pump was established and the structure of the gas/impurity separator was designed. Moreover, the calculation model regarding the sedimentation influencing rate of particles with different diameters was constructed. However, the dependence of liquid viscosity on the sedimentation influencing rate requires further discussion [11]. Nomura discussed a core drilling metal wire tool for the pulsation of plunger pumps, and studied the swing characteristics and fine grinding technology. Analysis of the axial vibration of metal wire tools revealed that when rotated perpendicularly to the axis, the tool showed a wavy surface that can highly improve the surface roughness of its processing and provide a theoretical basis for application in fine grinding [12].

Zhao et al. carried out indoor temperature change and wear resistance tests for different plunger materials. Fluororubber, nitrile rubber, polytetrafluoroethylene, high molecular polyethylene, glass fiber nylon, and polyether-ether-ketone (PEEK) were optimally selected, and finally PEEK was determined as the main sealing ring material of the soft plunger oil well pump. Supplemented by nylon sealing material to replace the steel plunger pump, the results reflect that the PEEK soft plunger can not only meet the requirements of underground work but also effectively reduce the construction and operation costs because only the soft plunger is replaced. However, despite the preliminarily exploration of soft plungers, the optimization of their structural parameters was not investigated [13]. By analyzing the present situation of ASP flooding pumping wells, Li developed a new type of oil well pump combining segmented lifting and soft plunger technologies. The device replaces the traditional pump barrel with downhole tubing, and a fixed valve system is installed at its bottom. Moreover, multiple soft plungers are connected in series to improve the partial pressure capacity and the anti-sticking performance of the segmented lifting of the oil well pump. The performance is experimentally verified on a simulation well to meet the lifting requirements, but the applications are limited to certain well conditions [14]. According to the composition characteristics of the flexible pumping system, Li systematically analyzed the efficiency composition of the flexible pumping system, established the efficiency calculation model of each subsystem, put forward its efficiency calculation model and method, and developed the seamless hydraulic self-sealing plunger pump and the seamless hydraulic wellhead sealing device. However, the wear resistance of the sealing material of this mechanism failed to achieve the ideal effect [15].

Given the impurities-induced wear of the plunger pump under the influence of fluid in oil wells, Brazhenko designed a multivariate orthogonal test to optimize its structural parameters. Indoor wear resistance and leakage tests were carried out on the ASP flooding anti-sticking oil well pump. Given the complex working environment and conditions of ASP flooding oil wells, the developed ASP flooding anti-sticking oil well pump has been subjected to a series of wear and failure problems in its application, which needs further exploration due to the aggravated wear of friction parts and the reduction of relative volume flow. The pump parts were visually inspected, to identify the most vulnerable parts [16]. Aldo put forward a mechanical calculation model for the intermediate cavity of a reciprocating pump, numerically analyzed the pressure field relationship of the model, simulated the operation of the pump valve, and determined the diameter and length of the connecting rod. An experimental study was carried out, and the feasibility and reasonability of the theoretical study were verified. In the aspect of force balance analysis, however, the spring preload of reciprocating pumps needs comprehensive consideration [17]. Hys studied the influencing factors of plunger pump performance, including the operation status of its valve device. A regression analysis method was proposed to study the relationship between process quality and dimension value, exploring the important influencing factors of product quality and obtaining the exponential regression equation. However, the stochastic relationship between the product quality and the valuation of the plunger pump was not effectively considered [18].

The above studies mainly focus on the influencing factors, structural design, and materials of plunger oil well pumps, but the correlation between its pressure and deformation of has been less explored. In particular, the pressure performance of the multi-stage self-compensating soft plunger oil well pump has been very rarely studied through the two-way fluid-solid coupling method. In this study, the pressure characteristics of the multistage soft plunger of Oil Well Pump are further explored based on the fluid-structure coupling method [19]. In this study, analysis methods on one- and two-way fluid-solid coupling were combined to establish the physical soft plunger oil well pump model and study the clearance flow in the annular space between the soft plunger and the pump barrel. Then, a mathematical model of the flow rate was constructed and the pressure variation law of the oil well pumps under different soft plunger lengths and outer diameters were established to provide a theoretical basis for staged pressure bearing.

The remainder of this study is structured as follows. With two-stage soft plunger pump as an example, this study proposes the length calculation method according to the law of conservation of mass. Based on the bidirectional coupling between the soft plunger and the clearance flow in the pump barrel, the physical model of the three-stage soft plunger pump is presented in Section 3. In Section 4, the pressure field and the velocity field after length optimization are obtained by numerical simulation method, and the pressure characteristics of the model are analyzed. In addition, the pressure and velocity fields after the outer diameter optimization are obtained. The consistency of pressure field and velocity field under different calculation conditions is analyzed through comparison. Finally, Section 5 summarizes this study and presents relevant conclusions.

3. Methodology

3.1 Leakage of first-stage soft plunge

The parameters require timely adjustments during the calculation achieve the convergence of the bidirectional fluid-solid coupling algorithm. The leakage of small gap can also be calculated by using the curve fitting method, to solve the problem that the calculation of bidirectional fluid-solid coupling is suspended due to the small initial clearance between the soft plunger and the pump barrel pair. For the two-stage soft plunger oil well pump, the fitting method is used for grading calculation, and a quarter model of the first-stage polyether ether ketone soft plunger is established with a 50 mm length, 3 mm thickness, 4 MPa inlet pressure, and 2 MPa outlet pressure. The relationship between leakage and clearance is cubic power. When the leakage of oil well pump is constant, the dynamic viscosity is changed from 0.001 Pa.s to 1 Pa.s, and the clearance becomes 10 times of the original. At this point, the clearance refers to the static one that is not affected by the deformation of the soft plunger. Such deformation causes changes in the gap between the soft plunger and the pump barrel, thus influencing the proportional relationship. However, a numerical analogy relationship remains between the leakage of liquid medium with small gap and dynamic viscosity and that of liquid medium with large gap and dynamic viscosity. Under the initial clearance of 0.4-0.75 mm, the leakage and deformation of the first-stage soft plunger were calculated by using the one- and two-way fluid-solid coupling methods. respectively. The specific values are listed in Table 1.

Table 1. Leakage and deformation of the soft plunger (first stage)

Initial clearanc h_0 (mm)	**Unidirectional fluid-solid couplin**		**Bidirectional fluid-solid coupling**	
	Deformatio n x_1 (mm)	**Leakag e Q_1 (kg/s)**	**Deformation x_2 (mm)**	**Leakage Q_2 (kg/s)**
0.40	0.0902	0.00558	0.0883	0.00381
0.45	0.0895	0.00770	0.0882	0.00550
0.55	0.0883	0.01400	0.0876	0.01055
0.60	0.0877	0.01814	0.0871	0.01395
0.65	0.0870	0.02301	0.0867	0.01800
0.70	0.0865	0.02869	0.0861	0.02274
0.75	0.0858	0.03525	0.0857	0.02828

The unidirectional/bidirectional fluid-solid coupling leakage ratio is:

$$\gamma = Q_1 / Q_2 \tag{1}$$

where Q_1 and Q_2 are leakage values of unidirectional and bidirectional fluid-solid coupling, in kg/s, respectively.

Equation (1) is used to calculate the ratio of unidirectional and bidirectional fluid-solid coupling leakage values of the first-stage soft plunger. The results are shown in Table 2.

Table 2. Ratio of first class soft plunger unidirectional/bidirectional fluid-solid coupling leakage

Initial clearance h_0 (mm)	**0.40**	**0.45**	**0.50**	**0.55**	**0.60**	**0.65**	**0.70**	**0.75**
γ (%)	1.47	1.40	1.36	1.33	1.30	1.28	1.26	1.25

Fig. 1 shows the curve of the ratio of unidirectional/bidirectional fluid-solid coupling leakage of the first-stage polyether ether ketone soft plunger with respect to the initial clearance.

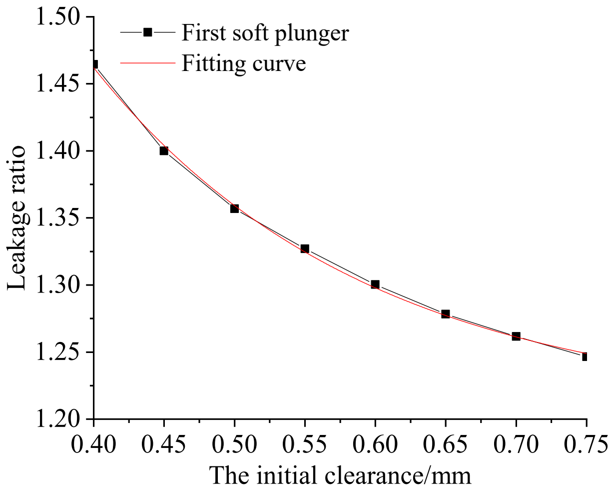


Fig. 1. Effect of initial clearance on the leakage ratio of the soft plunger (first stage)

Meanwhile, the corresponding equation of the fitting curve of the unidirectional/bidirectional fluid-solid coupling leakage ratio of the first-stage polyether ether ketone soft plunger with the change of initial clearance is obtained as follows:

$$f(x) = ae^{-x/t} + y_0 \tag{2}$$

where a, t and y_0 are coefficients. The specific parameter values in Equation (2) are given in Table 3.

Table 3. Fitting parameters for the influence of clearance on the leakage ratio of the soft plunger (first stage)

Coefficient	*a*	*t*	y_0	*R-s*	*RC-s*
Value	2.0100	0.1937	1.2070	0.9988	9.4520E-6

When the initial clearance is h_0 =0.14mm, the unidirectional fluid-solid coupling leakage is Q=0.000236 kg/s, which when substituted into Equation (2), leads to the bidirectional fluid-solid coupling leakage Q=0.000108 kg/s.

With the aim to solve the convergence problem of the numerical calculation of bidirectional fluid-solid coupling of micro-slit of soft plunger and pump barrel pair, the dynamic viscosity parameters are adjusted by exploring the relationship between dynamic viscosity and gap at the same leakage. The ratio of unidirectional/bidirectional fluid-solid coupling leakage of soft plunger with the initial clearance is then established by using the fitting method. The leakage of relatively large slit flow is equated to obtain the leakage of micro-slit of soft plunger and pump barrel pair. Similarly, the length of the second-stage soft plunger is calculated by using the fitting method.

3.2 Particle representation

The thickness and initial clearance between the soft plunger and pump barrel pair are set to 3 and 0.14 mm, respectively, which are the same values as those of the first-stage soft plunger to determine the length of the second-stage plunger made of polyether ether ketone. The oil well pump has a 2 MPa outlet pressure, 0 MPa inlet pressure, and 1 Pa.s dynamic viscosity. Unidirectional and bidirectional fluid-solid coupling calculation methods are then adopted. The leakage values and ratios of unidirectional/bidirectional fluid-solid coupling methods are obtained for different lengths of the second-stage soft plunger (30, 35, 40, 45, and 50 mm) and initial clearances (0.40, 0.45, 0.55, and 0.60 mm), as shown in Tables 4, 5, and 6.

Table 4. Leakage of unidirectional fluid-solid coupling

Coefficient	Length(mm)				
Value	30	35	40	45	50
0.40	0.00934	0.00801	0.00700	0.00623	0.00560
0.45	0.01324	0.01136	0.00994	0.00885	0.00797
0.50	0.01754	0.01503	0.01317	0.01170	0.01052
0.55	0.02329	0.01997	0.01747	0.01555	0.01398
0.60	0.02967	0.02545	0.02228	0.01980	0.01783

Table 5. Leakage of bidirectional fluid-solid coupling

Coefficient	Length(mm)				
Value	30	35	40	45	50
0.40	0.00607	0.00521	0.00456	0.00406	0.00365
0.45	0.00900	0.00771	0.00674	0.00600	0.00540
0.50	0.01275	0.01092	0.00955	0.00849	0.00765
0.55	0.01705	0.01461	0.01278	0.01137	0.01022
0.60	0.02260	0.01934	0.01692	0.01505	0.01358

Table 6. Ratio of unidirectional/bidirectional fluid-solid coupling leakage

Initial clearance(mm)	Length(mm)				
	30	35	40	45	50
0.40	1.539	1.537	1.535	1.534	1.534
0.45	1.471	1.473	1.475	1.475	1.476
0.50	1.376	1.376	1.379	1.378	1.375
0.55	1.366	1.367	1.367	1.368	1.368
0.60	1.313	1.316	1.317	1.316	1.313

Fitting the data in Table 5 is consistent with the fitting of Equation (2), and thus expresses the functional relationship between the unidirectional/bidirectional fluid-solid coupling leakage ratio and the initial clearance between the soft plunger and the pump barrel pair at different lengths, yielding varying fitting equations and parameters. Table 7 shows the parameters of the fitting equation between the ratio of unidirectional/bidirectional fluid-solid coupling leakage and the initial clearance when l is 30, 35, 40, 45, 50 mm.

Table 7. Ratio of unidirectional/bidirectional fluid-solid coupling leakage

Coefficient	Length(mm)				
	30	35	40	45	50
a	3.528	3.422	2.872	2.762	2.558
t	0.1671	0.1684	0.1855	0.1899	0.2016
y_0	1.22	1.222	1.206	1.202	1.186

The unidirectional fluid-solid coupling leakage of soft plunger with different lengths is also calculated when the initial clearance between the soft plunger and the pump barrel pair is h_0 =0.14mm, as shown in Table 8.

Table 8. Unidirectional fluid-solid coupling leakage of differentlengths when h_0 =0.14mm

Length (mm)	30	35	40	45	50
$Q(\times10^{-3})$	0.404	0.347	0.303	0.283	0.254

According to the fitting parameters in Table 7 and the data in Table 6, the bidirectional fluid-solid coupling leakage of different lengths with an initial clearance of 0.14 mm is calculated, as shown in Table 9.

Table 9. Unidirectional fluid-solid coupling leakage of differentlengths under the condition of h_0 =0.14mm

Length(mm)	30	35	40	45	50
$Q(\times10^{-3})$	0.1471	0.1279	0.1185	0.1122	0.0982

The above data are processed using MATLAB software to obtain the fitting equation, parameters, and curve for the length of the soft plunger with an initial clearance of h_0 =0.14 mm as follows:

$$f(x) = a_1 e^{-x/t_1} + a_2 e^{-x/t_2} \quad (3)$$

where a_1 , t_1 , a_2 , and t_2 are coefficients. The specific parameter values in Equation (3) are given in Table 10.

Table 10. Fitting parameter of the lengths that vary with leakage

Coefficient	a_1	t_1	a_2	t_2	*R-s*
Value	356.6	0.04356	15.2	-1.117	0.9901

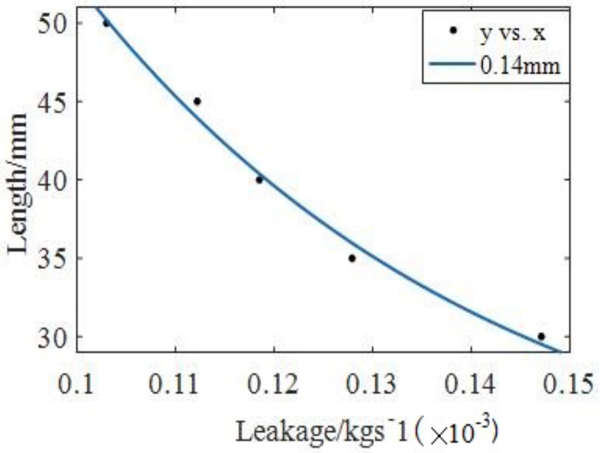


Fig. 2. Change curve of the second-stage soft plunger lengths with the leakage

After the equivalent treatment of slit flow leakage by the fitting method, the multi-stage soft plunger length Change curve is constructed, as shown in Fig. 2. When the initial clearance is h_0 =0.14 mm and the leakage of bidirectional fluid-solid coupling is Q =0.000108kg/s, the length of the second stage is l =47 mm.

3.3 Particle update rules

The non-convergence problem of bidirectional fluid-solid coupling of slit flow is solved by grid encryption. The solid grid of soft plunger adopts a 1 mm hexahedron while the fluid grid adopts a mix of tetrahedron and hexahedron with 0.05 mm fluid mesh size. The soft plunger unit grid has 198036 nodes and 39168 units while the fluid cell grid has 37424 nodes and 184749 grids.

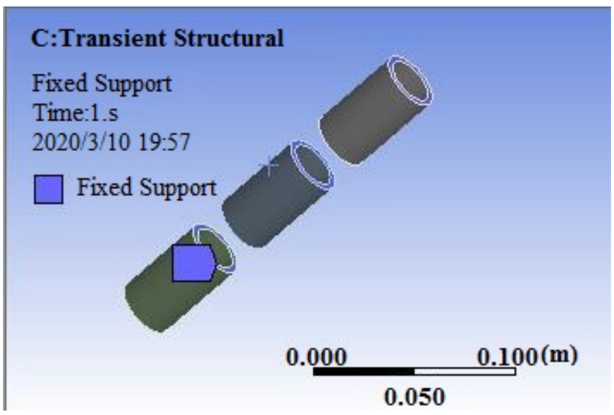


Fig. 3. Constraints setting

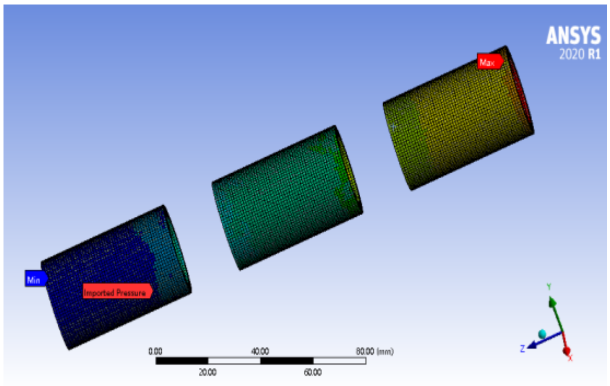


Fig. 4. Load setting

Displacement boundary setting: Given no pressure difference on the upper end face of each stage of the soft plunger, then no radial deformation occurs. Thus, the axial movement of the soft plunger can be limited by applying the Fix Support constraint on the inlet end face of each stage of the soft plunger, as shown in Figs. 3 and 4. Meanwhile, the structure belongs to the central symmetry model. Grid encryption is adopted to reduce the distortion caused by insufficient grid quality and avoid the eccentricity with the axis.

4. Result Analysis and Discussion

Based on the calculation model of three-stage soft plunger oil well pump obtained in Sections 3.1-3.3, the pressure and velocity fields under two-way fluid-solid coupling methods were fitted by MATLAB software, and the pressure characteristics under two different conditions of length and outer diameter optimizations were explored. The results provide theoretical basis for structural optimization and parameter design and technical support for experimental study.

4.1 Pressure field after length optimization

The initial calculation model of the three-stage soft plunger of oil well pump has 50 mm length, 3 mm thickness, 0.14 mm initial clearance with the pump barrel, and 30 mm inner pump barrel diameter. According to the principle of constant mass flow through each stage of soft plunger, the structural parameters are optimized. The mass flow is 0.3868 kg/s calculated by the bidirectional fluid-solid coupling method, and the optimized length parameters are determined as shown in Table 11. According to the data, the length of the soft plunger from top to bottom follows the changing law of decreasing in turn. If the length of the first-stage soft plunger is 50 mm, then the numerical simulation calculation result of the second-stage soft plunger is 47 mm, which is consistent with that of relatively large slit leakage by fitting method in Section 3.1. Thus, the correctness of the calculation method for length optimization is verified.

Table 11. Fitting parameter of the lengths that vary with leakage

Grade	1	2	3
Length(mm)	356.60	0.04356	15.20

The deformation nephogram of the three-stage soft plunger of oil well pump is obtained by bidirectional fluid-solid coupling method, as shown in Fig. 5. For a single soft plunger, the deformation of the outer wall surface gradually increases from top to bottom; that is, the maximum wall deformation of each stage of soft plunger occurs at its lower end. For the overall structure of the three-stage soft plunger, the maximum deformations at different stages slightly differ, decreasing in turn from the first to third stages; that is, the maximum deformation of the outer wall of the third-stage soft plunger occurs lat the lower part of the first-stage soft plunger.

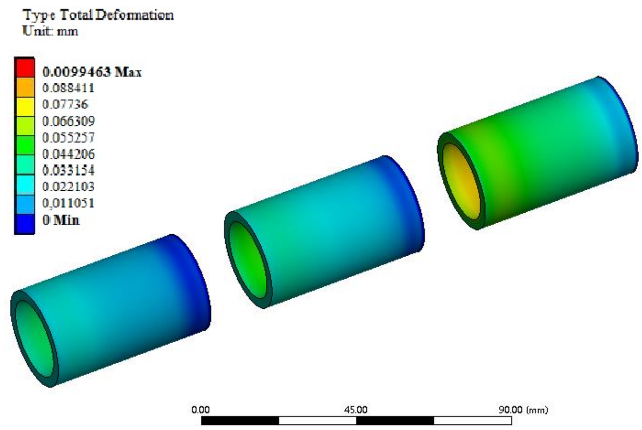


Fig.5. Deformation cloud diagram of three-stage soft plunger

The stress nephogram of the three-stage soft plunger of the oil well pump is shown in Fig. 6. The maximum stress of each stage of the soft plunger is located at the lower side of its inner wall. Several differences in the maximum stress of soft plungers occur at all levels. The maximum stress of the first-level soft plunger is slightly larger than that of the second and third levels; that is, from the fluid inlet to the outlet, the overall three-level soft plunger structure satisfies the changing law of the maximum stress decreasing in turn.

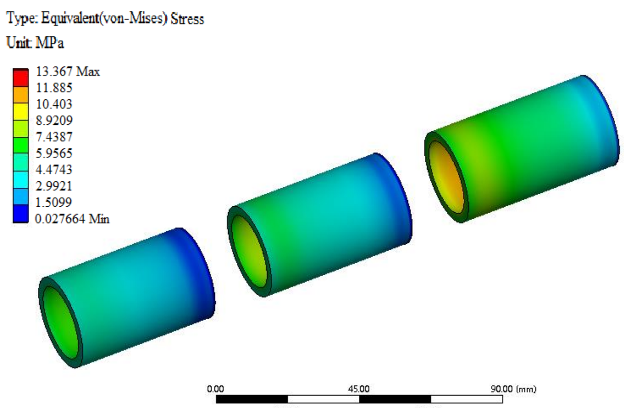
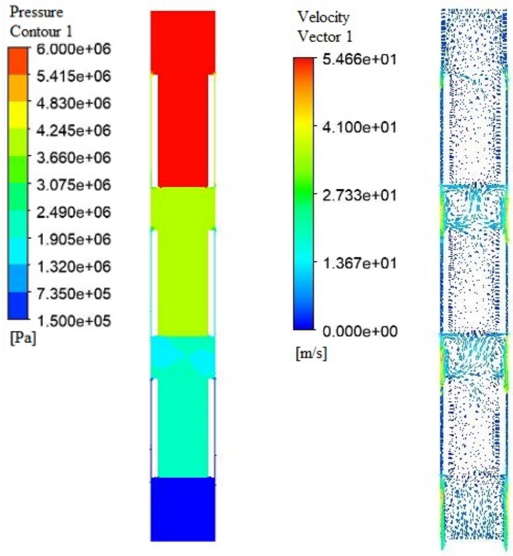


Fig.6. Stress nephogram of the three-stage soft plunger of oil well pump

The pressure and velocity fields of the multi-stage soft plunger of the oil well pump are shown in Fig. 7. In Fig. 7(a), the pressure levels on the inner wall surface and at the inlet of each stage of soft plunger are equal, at 6, 4, and 2 MPa for the first, second, and third stages, respectively. The fluid pressure in the vertical annular slit between the outer wall surface of the soft plunger and the pump barrel changes continuously and gradually; the upper pressure levels of the first, second, and third stages are approximately 6, 4, and 2 MPa, and the lower pressure levels are approximately 4, 2, and 0 MPa, respectively. No pressure decrease is observed in the connection area between each stage of soft plungers. In Fig. 7(b), the maximum and the minimum flow rates occur at the fluid inlet and outlet of each stage of soft plunger. Eddy current is formed in the connection area of the two-stage soft plunger.



(a) (b)

Fig.7. Pressure and velocity cloud diagrams of three-stage soft plunger of oil well pump. (a)Stress cloud diagram. (b)Speed cloud diagram

4.2 Pressure field after optimization of outer diameter

In the initial calculation model of the soft plunger oil well pump, the pump barrel has a 30 mm inner diameter while the soft plunger has 50 mm length and the 23.72 mm inner diameter, which are optimized by changing the outer diameter while maintaining the inner diameter. This method changes both thickness and initial clearance of the soft plunger, and the calculation is cumbersome and difficult. The optimized mass flow is determined to be 0.3038 kg/s by using the bidirectional fluid-solid coupling calculation, and the optimized parameters of the thickness and gap of the first-, second-, and third-stage soft plungers are shown in Table 12.

Table 12. Fitting parameter of the lengths that vary with leakage

Stage	1	2	3
Outer diameter(mm)	29.796	29.745	29.720
Thickness(mm)	3.0380	3.0125	3.0000
Clearance(mm)	0.1020	0.1275	0.1400

The deformation and stress nephograms of the three-stage soft plunger are calculated, as shown in Figs. 8 and 9, respectively. In Fig. 8, from the fluid inlet to the outlet, the maximum deformation of the outer wall surface of the soft plunger decreases in turn, occurring in the middle and lower parts of the first-stage soft plunger, which is mainly affected by the thickness and the initial clearance between the soft plunger and the pump barrel pair. The thickness of the soft plunger decreases from top to bottom, which in turn increases the deformation; however, the initial clearance of the soft plunger-pump barrel pair increases from top to bottom, which in turn decreases the deformation. For a certain level of the soft plunger, the deformation caused by thickness changes is smaller than the deformation caused by the initial clearance of the soft plunger-pump barrel pair. Therefore, this model can meet the required consistent flow through each stage.

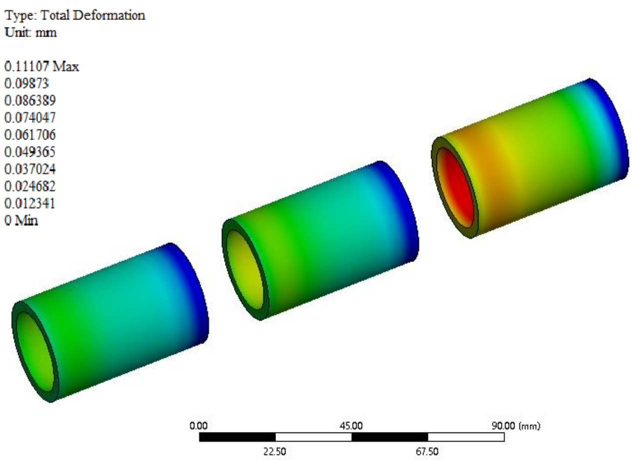


Fig.8. Deformation cloud diagram of three-stage soft plunger of pump

As can be seen in Fig.9, for a single soft plunger, the satisfying stress increases from top to bottom, that is, the maximum stress of each stage of soft plunger is located at the lower side of its inner wall. From the fluid inlet to the outlet, the stress of the three-stage soft plunger decreases in turn, that is, the maximum stress in the overall structure occurs at the lower side of the inner wall of the first-stage soft plunger.

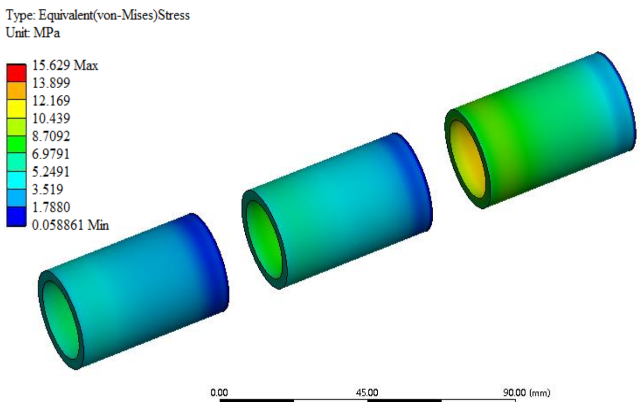


Fig.9. Stress cloud diagram of three-stage soft plunger of oil well pump

The pressure and velocity fields of multi-stage soft plunger of oil well pump based on bidirectional fluid-solid coupling are shown in Fig. 10. The flow velocity at the fluid inlet at the upper end of each stage is larger than that at the internal and clearance fluids between the soft plunger and the pump barrel. In the soft plunger, the pressure on the inner wall is equal to that at the inlet of each stage, which further verifies the correctness of the fluid equal load treatment in the simplified model of hierarchical calculation. The fluid pressure on the outer wall changes gradually between each stage with the pressure difference of approximately 2 MPa. From the fluid inlet to the outlet, the pressure of the flow field in the gap between the pump and the cylinder pair is continuously and evenly distributed at all levels. The pressure fields of the three-stage soft plunger of the oil well pump obtained by optimizing the length and outer diameter parameters can all meet the law of graded bearing characteristics, which presents excellent guiding significance for reducing the stress at each stage and prolonging the pump inspection period.

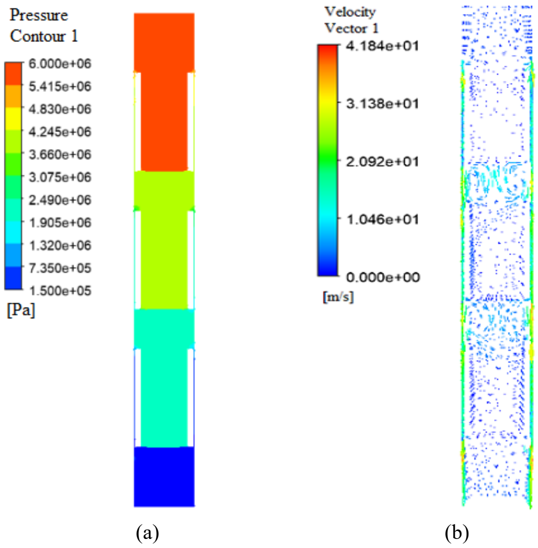


Fig.10. The pressure and velocity cloud diagram of three stage soft plunger of pump. (a)Stress cloud diagram. (b)Speed cloud diagram

5. Conclusions

This study established a model for the multi-stage soft plunger oil well pump and explored its pressure performance by combining fluid-solid coupling and theoretical calculations. Thus, the pressure distribution law was acquired. Finally, the following conclusions could be drawn:

(1)As a solution to the non-convergence problem of the numerical calculation of bidirectional fluid-solid coupling in the micro-slit of soft plunger-pump barrel pair, a fitting method was used to treat the leakage of relatively large slit flow with the change of the ratio of unidirectional to bidirectional fluid-solid coupling with the initial gap. Thus, the leakage of the micro-slit of soft plunger-pump barrel pair was obtained.

(2) The slit calculation model of the fluid-solid coupling fluid and solid domains of the soft plunger oil well pump was established, and its deformation under the action of gap flow pressure was calculated. The maximum deformation occurred at the lower position of each stage, decreasing from the first to the third stages. Moreover, the influence of soft plunger deformation on the flow field was analyzed.

(3) The bidirectional fluid-solid coupling analysis and calculation of the three-stage soft plunger of oil well pump were carried out via Fluent. Under the condition of mass conservation, the length of the soft plunger changed gradually from the fluid inlet to the outlet. The method of optimizing the structural parameters of multi-stage soft plunger of oil well pump by changing the length and outer diameter of soft plunger was then proposed.

(4) The vertical annular slit flow calculation model of multi-stage soft plunger-pump barrel pair was established. The flow field was simulated and calculated by using the bidirectional fluid-solid coupling method, and all levels of the continuous and uniform distribution law of flow field pressure in the gap between the soft plunger and pump barrel pair was obtained. The graded pressure-bearing characteristics of the multi-stage soft plunger of oil well pump were determined.

Combining numerical simulation and theoretical research, this study put forward the influence law of pressure and speed of soft plunger oil pump, which presents reference value for the subsequent development of multi-stage soft plunger oil well pump. Given the lack of actual data of field monitoring, the model could be further modified with field data in future research to obtain a more accurate operation law of soft plungers under complex working conditions.

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