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Research on the Reciprocating Sealing of Fracturing Pump

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Abstrak

Kegagalan penyegelan timbal-balik di dalam keretakan pompa OPI-1800AWS telah dianalisis kegagalannya dengan teknologi pemindaian mikroskop elektron (SEMT). Mekanisme pelumasan pasangan gesekan segel plunger telah dianalisis dengan teori pelumasan hidrodinamik. Selama peluahan dan stroke suction, pasangan gesekan penyegelan timbal balik telah memenuhi kondisi pelumasan hidrodinamik, suatu ketebalan tertentu film minyak dapat dibentuk dan dipelihara diantara plunger dan bentuk V segelan antarmuka, yang dapat melumasi pasangan penyegel, mengurangi gesekan dan meningkatkan usia pakai. Distribusi tekanan aksial dari penyegelan berbentuk V dilakukan dengan analisis teoritis dan pengujian eksperimental. Kegagalan bentuk-V penyegelan dan penentuan jumlah loop juga telah dibahas menurut yang dibahas menurut kurva distribusi tekanan sumbu.

Kata kunci: *kegagalan, keretakan pompa, pasangan gesekan segel plunger , tekanan aksial*

Abstract

The failure reasons of reciprocating sealing in OPI-1800AWS fracturing pump are analyzed by scanning electron microscope technology (SEMT). The lubrication mechanism of plunger seal friction pair is analyzed by hydrodynamic lubrication theory. During its discharge and suction stroke, the reciprocating sealing friction pair meets the conditions of hydrodynamic lubrication, a certain thickness of oil film can be formed and maintained between the plunger and V-shaped sealing interface, which can lubricate sealing pair, reduce friction and improve lifetime. The axial pressure distribution of the V-shaped sealing is carried out by theoretical analysis and experimental testing. According to the distribution curve of axial pressure, the V-shaped sealing failure and the determination of the number of loops are discussed.

Keywords*: axial pressure, failure, fracturing pump, plunger seal friction pair*

1. Introduction

At present, the proportion of increasing oil and gas production by fracturing or acidification technology is getting larger. A successful fracturing may increase the production of oil and gas wells several times, even more than a dozen or dozens, the benefit is extremely considerable. According to the working principle of fracturing and acidification, large displacement and high-pressure injection are necessary for this technology, and fracturing pump is the core equipment to complete the work. In the long-term practice and research, fracturing and acidification technology is getting better and better, in contrast, fracturing and acidizing equipment is not compatible. This seriously affects the normal implementation of the fracturing and acidizing technology [1], [2]. The working conditions of plunger, V-shaped seal, valve disk and valve seat are seriously bad. These wearing parts are the weakest link of the fracturing pump. From the current using of plunger and seals used in oil fields in China, their lifetime is very low, and for annual consumption is great. The investigation indicated, in Sichuan area, during acidizing operations, the lifetime of plunger is more than 100 hours, the lifetime of sealing ring is 30-40 hours, sometimes 10-20 hours. With the frequent fracturing and acidizing operation, the lifetime of plunger and seal will become increasingly prominent. So, the site urgently requires the systematic study of the plunger seal friction pair in fracturing pump, in order to improve their lifetime and ensure the smooth construction. This paper intends to carry out systematic research on the plunger seal friction pair of OPI-1800AWS fracturing pump. All these can provide a basis for design improvement and experimental research of reciprocating sealing in high-pressure fracturing pump.

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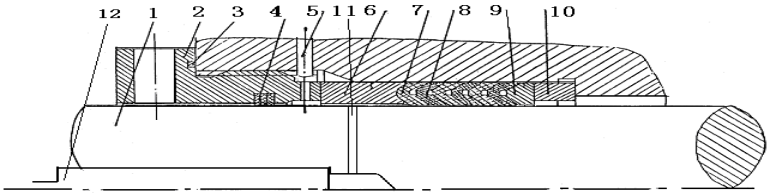
2. The Structure of Plunger Seal Friction Pair

The structure of hydraulic end of OPI-1800AWS fracturing pump is shown in Figure 1, the plunger 1 can only have reciprocating linear motion under constraint, the back pressure cap 2 is used to compress and adjust sealing, the seal body comprised of three V-shaped rubber sealing ring 7 and three V-shaped PTFE pad rings 8 alternately can ensure sealing ring working successively, which means after the failure of the first sealing ring, the differential pressure will transmitted to the second one which can also function as the same, thus the whole lifetime improved. Supporting ring 6 is the key component to support V-shaped sealing ring, pressure ring 9 is used to give V-shaped sealing ring initial compression and keep contacting adequately between the ring and the surface, the end face width of pressure ring is smaller than the width of the cavity. The gap between the pressure ring and the plunger is about 0.12-0.20 mm, so the pressure can act on sealing lip and make it fully open [3], [4]. The small hole 5 on the housing is the entrance of forced lubrication oil. It is evident that dirty pumping liquid will damage the seal. The solution to this problem at home and abroad is injecting lubrication oil through the small hole, and the injecting pressure of lubrication oil is slightly higher than the perfusion pressure of the fracturing pump. The purpose of this method is forming a high-pressure oil film between the plunger and seals to prevent dirty fracturing fluid (medium) from entering sealing interval and protect seals.



1 plunger, 2 back pressure cap, 3 O-sealing ring, 4 scraping ring, 5 lubrication oil entrance, 6 supporting ring, 7 rubber seal ring, 8 PTFE seal ring, 9 pressure ring, 10 front supporting ring, 11 testing pressure hole, 12 pressure sensor

Figure 1. The structure of plunger seal friction pair

3. Failure Reasons of Plunger Seal Friction Pair

3.1. Reciprocating Speed and Surface Quality of Plunger

When reciprocating speed of the plunger is high, more frictional heat will produce between the plunger and sealing rings. This will accelerate aging of the rubber pieces, losing their elasticity and reducing the radial acting force on the plunger. Along with well depth increasing, and fracturing acidizing radius expansion, it is urgent to strengthen fracturing acidification technology, which is means the injection of fracturing liquid with high pressure, high gravel ratio, high acidity is needed, so that the working condition of the plunger is harsher, and its lifetime reduces. The Chrome-plated technology is applied to the plunger surface of OPI-1800AWS fracturing pump. Theoretically, the surface has high wear resistance, high heat resistance and high corrosion resistance, but actually the lifetime of the plunger is short. The surface quality of the plunger is poor, so the plunger will be worn, pulling injury, erosion and corrosion frequently [5]. When the plunger is damaged, the fracturing and acidizing fluid will enter the crankcase, which will cause lubricating oil in the crankcase serious deterioration and losing lubrication. So the key components of the crankcase, such as, crosshead, gear, tension rod, bearing and so on, will have serious wear, erosion and corrosion, so that a major accident will occur. We use thermal spray technology to strengthen the plunger surface, the materials of spray welding are PHNi60A and WC, the thickness of spray welding is 0.5 mm, the surface hardness is more than HRC 60. After the spray welding technology, the plunger surface should be grinding processed. After these processing, the wear resistance and corrosion resistance of the plunger are improved evidently.

3.2. When Crosshead, Plunger, Tension Rod and Plunger Head Reciprocate their Concentricity with Cylinder

Crosshead and tension rod are connected by thread, plunger head and plunger are connected by thread, and plunger head and tension rod are connected by spherical hinge. All

these parts as a whole have a reciprocating motion. Their public axis should be coincidence with the public axis of crosshead and cylinder, otherwise, the sealing rings will be worn partially, and lose efficacy.

3.3. Materials of Sealing Ring

The material performance of sealing ring is the key condition of application scope and important factor of lifetime. The failure modes of sealing ring of OPI-1800AWS fracturing pump are permanent deformation, partial wear, burn, abrasive wear and fatigue wear, etc [5]. Burns caused by overheat are main failure reasons of the sealing rings, and burns will make the seal immediately lose working ability, while other failure modes resulting in loss of sealing capability is a gradual accumulation process. So we must choose the rubber with good heat resistance as the material of sealing ring. The original material of sealing ring is single cloth rubber, its wear resistance, pressure resistance, heat resistance and corrosion resistance are poor, so the lifetime of sealing rings was short. The new sealing rings are made of polyurethane rubber and filled PTFE (filled with bronze powder), which are used through interactive permutation and combination. Polyurethane rubber has good wear resistance, pressure resistance, corrosion resistance, heat resistance and ageing resistance, as well as has high breaking strength, good air permeability and elasticity. Filled PTFE has the characteristic of strong bearing capacity, good resistance of high and low temperature, strong resistance of oil and corrosion, anti-aging, small friction coefficient and good self-lubricating property. Combination use of these two sealing rings will have better performance and longer lifetime [6].

3.4. Abrasive Wear of Sealing Ring

The abrasive wear of sealing ring is also an important factor in failure. Under the action of working pressure, the V-shaped rubber sealing rings have deviation effect [7], [8]. That is, the lip of the V-shaped sealing rings will depart from the plunger surface, so abrasive will enter the plunger sealing friction pair, especially in the suction stroke of fracturing pump. Because, during the discharge process, the plunger pushes to cylinder, and the contacting stress between the plunger and seals is very large, abrasive is not easy to enter. But in the suction process, the contacting stress is small, abrasive is easy to enter. In order to reduce abrasive wear and improve the lifetime of plunger and seals, the abrasive media should be prevented from entering the gap of reciprocating sealing pairs as far as possible.

4. Lubrication Mechanism of Plunger Seal Friction Pair

Site investigation indicates that, when there is no lubricating oil, the V-shaped sealing rings will fail due to overheating in a few minutes, but under good forced lubrication condition, the lifetime of the sealing rings will reach 40-50 hours. Obviously, good forced lubrication is good for improving the lifetime of the rings. According to the working property, plunger seal friction pair is reciprocating sealing, its working medium has certain viscosity, for example, working medium is acid liquid, lubricating medium is lubricating oil. If convergent oil wedge can be formed, the conditions of hydrodynamic lubrication will be formed. Finite Element Analysis [7] has shown that, during the suction stroke of fracturing pump, under the action of working pressure, the V-shaped rubber sealing ring has deviation effect, as shown in Figure 2. That is, because of stretching, the lip of the V-shaped sealing ring will depart from the plunger surface, so convergent wedge is formed, working medium is brought into the sealing surface, and conditions of hydrodynamic lubrication are satisfied, so oil film is formed, which is called lubrication of medium. At the back of the sealing, because of the velocity direction of the plunger, convergent wedge can not be formed. During the discharge stroke of fracturing pump, as shown in Figure 3, depending on the pre-design of round corners or deformation at the seal back, convergent wedge is formed, lubrication oil is brought into the sealing surface, and conditions of hydrodynamic lubrication are satisfied, so oil film between the plunger and the seals is formed, which is called forced lubrication. So, during the discharge and suction strokes of fracturing pump, the reciprocating sealing friction pair can meet the conditions of hydrodynamic lubrication. A certain thickness of oil film can be formed and maintained between the plunger and V-shaped sealing interface, which can lubricate sealing pair, reduce friction and improve lifetime.

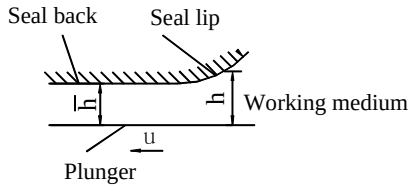


Figure 2. Suction stroke of fracturing pump

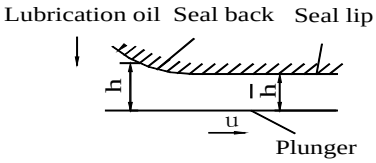


Figure 3. Discharge stroke of fracturing pump

5. Axial Pressure Distribution of Plunger Seal Pair

5.1. Theoretical Analysis on Axial Pressure Distribution of V-Shaped Seal

Assume that V-shaped seals have sufficient rigidity, the deformation of sealing ring caused by liquid pressure between the plunger and sealing rings is very small. Assume that the circumferential pressure distribution is uniform, so the gap between the plunger and the inner surface of sealing rings is concentric cylinder ring, according to literature [9], the axial pressure can be expressed with a formula below:

$$\frac{dp}{dx} = 12\eta u\left(\frac{1}{2h^2} - \frac{Q}{uh^3}\right) \quad (1)$$

where:

p : axial pressure
η : liquid viscosity
u : relative speed of reciprocating motion
h : thickness of liquid film
Q : flow of per unit circumference
x : distance along the seals

According to Equation 1, with designed equipment, certain pressure and medium, the axial pressure distribution is linear. Actually, the assumptions above are far way from the actual working conditions, on one hand from the view of material, V-shaped seals have low rigidity and the large deformation will emerged from liquid pressure, and high pressure generate large deformation, so the gap between the inner surface of sealing ring and plunger can not be parallel, and the thickness of hydrodynamic film between sealing ring and plunger is changing in axial direction. On the other hand, the plunger is produced by machining, turning or grinding will leave marks on the surface of the plunger. Simultaneously, the difference of rotational speed, feeding and granularity of grinding wheel will generate different roughness on the surface of plunger. From the view of microscopic point, different shape wave ridge and trough are generated on the surface of plunger, and the distribution of troughs is irregular, the channel of troughs will be formed on the place where troughs contact.

When installing sealing rings, initial contacting stress produced by extrusion and interference press the sealing ring on the surface of plunger, then, after having enough contacting stress, the material can be pressed into trough to stop leakage from the channel of troughs. When sealing ring works, to getting the purpose of sealing and guaranteeing lubrication and dropping temperature to extending lifetime of seals, the general leakage rate should be controlled in 5-8 drops per minute. So, in normal working condition, the contacting between seals and the plunger can not fill all troughs, the channels of troughs are always existed. When the plunger is stationary and the cylinder has pressure, the liquid will permeate from these channels. As for multiple sealing rings, first of all liquid will permeate into the gap on the high pressure side between the first and the second sealing ring, at the beginning, this gap has no pressure. But when the permeating liquid fills this place, the pressure will form, and the pressure will be increased because of the continuing permeating caused by pressure difference, so the pressure in the channel of troughs is high, then the filling from seals to troughs is decreased and the channel is increased. When contacting stress is decreased, the pressure in cylinder can be almost completely transferred to the gap between the first and the second sealing ring on the high pressure side, and this pressure is almost equal to sealing pressure. The permeating liquid from the last sealing ring (near the air side) can not be collected, because the out side of this seal is air, and the pressure in channel of troughs can not be increased, so the channel will not be increased, the pressure difference produced by resistance will not be eliminated. The biggest pressure difference exists in last sealing ring. When the plunger moves, during the discharge

stroke, the troughs sometimes communicate, and sometimes separate. Due to the dynamic pressure oil film, communicating becomes the majority. The axial pressure distribution of inward V-shaped sealing rings almost has no pressure reduction, the biggest pressure difference exists in last sealing ring. So, when the working pressure is high, multitude sealing rings can not withstand the pressure difference equally.

5.2. Axial Pressure Testing of V-Shaped Seal

In order to test the axial pressure distribution between the plunger and V-shaped sealing rings, a testing system was designed, as shown in Figure 1. Through the testing pressure hole 11 in the plunger, the pressure is elicited, and connected with BP4-600 semiconductor strain pressure sensor. In order to ensure testing accuracy, the diameter of the testing pressure hole is 0.2 mm. Performance indexes of the sensor are, nonlinearity error is less than 0.35%, hysteresis error is less than 0.04%, non-repeating error is less than 0.15%, output sensitivity is bigger than 39 mv/v. With no amplifying, the testing pressure is recorded by SC-16 light oscilloscope [10]. If there is air in testing pressure hole, dynamic pressure response will vary greatly and distortion will be serious. Therefore, before installing the pressure sensor, the air in the testing pressure hole should be drained. Because the V-shaped seal is stationary, when the testing pressure hole in the plunger moves a stroke, the pressure sensor will get the axial pressure distribution of the plunger seal friction pair. In the back and forth strokes, the pressure-rise spot in the cylinder and the point where plunger leaving the sealing surface to atmospheric side can be determined through analysis. The preload caused by back pressure cap can not be too large, otherwise, although the leakage is reduced, but the pre-radial deformation of seals will accelerate the wear of seals and reduce the lifetime of seals.

The materials of sealing rings are V-shaped cloth rubber and V-shaped PTFE. The internal diameter of these two kinds of sealing rings is ϕ101.6 mm, the outer diameter is ϕ127 mm, the working liquid is water, the reciprocating speed of plunger is 2.21 m/s. Adjust the throttle valve, so that the discharge pressure respectively is 30 MPa, 40 MPa, 60 MPa, 80 MPa, and we can get the axial pressure distribution of sealing rings, as shown in Figure 4 and Figure 5.

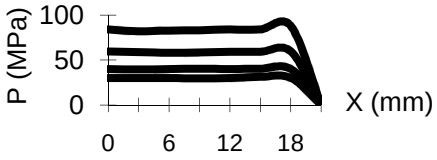


Figure 4. Axial pressure distribution of PTFE seal

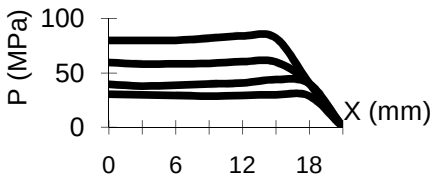


Figure 5. Axial pressure distribution of rubber

5.3. Influence of Axial Pressure on Failure and Number of Seal Ring

Wear and fatigue are the main reasons of sealing failure. Wear is related to the roughness of the plunger surface, lubrication and cooling. When the hydrodynamic oil film is existed and thick, wear can not easily happen. Fatigue damage is the result of high and low pressure periodic forcing, and the alternate contacting of wave ridge and trough between sealing ring and plunger surface. The plastic deformation is produced in the space where sealing ring contacts with wave ridge, and shifted to adjacent troughs. Because of the alternate existence of wave ridge and trough and the motion of plunger, the material deforms, transfers, and finally fall soff from the body due to the wear.

During its discharge stroke, the whole pressure difference occurs on the last ring, this indicates that trough channel is only squeezed by the outmost V-shaped sealing ring to prevent leakage, at the same time, the hydrodynamic oil film on V-shaped sealing lip is very thin, the plastic deformation produced by extrusion is large. During its suction stroke, the pressure in the cylinder is low, the hydrodynamic oil film between the sealing ring and plunger is near zero, so the portion of each lip is squeezed into trough channel. But the pressure caused by the back pressing cap can not be evenly transferred to each ring, the compressive stress of the outmost

ring is biggest. Therefore the outmost ring is the most one seriously squeezed into the trough channel than others, the outmost one has more fatigue and wear in working process and more easily fails than middle ones. Actually, the same situation is proved through the information collected from the users. When middle ones discharge liquid, because the oil film has large pressure and high thickness, their filling content in troughs are small as same as their wear. During suction stroke, due to the thickness of oil film is close to zero, the portion that squeezed into troughs is large, so the wear on the middle rings happen in the suction stroke.

From the distribution curve of sealing axial pressure, we can get that, the pressure difference in every V-shaped sealing ring is different, in the outmost sealing ring is largest. Increasing or decreasing the number of rings can not change the pressure distribution which the outmost ring bears, the pressure is higher, the lifetime of the most outside ring is shorter. Just from the effective sealing, fewer sealing rings can achieve, but in actual applications, when the sealing pressure is high, appropriately increasing the number of the sealing ring has a certain effect to extend the whole lifetime of seal. The author think that when the outmost fails, the second outmost one bears the highest pressure difference, so for the same working condition and same sealing rings, the whole lifetime will be improved when the number of rings increase.

6. Conclusion

Performance and service lifetime of reciprocating sealing of fracturing pump depends on surface quality of plunger, the material and structure size of sealing ring, and manufacturing precision of box and related parts. The design of reciprocating sealing should adapt to complex conditions and also have good performance and long lifetime.

During the discharge and suction strokes of fracturing pump, the reciprocating sealing friction pair meets the conditions of hydrodynamic lubrication, a certain thickness of oil film can be formed and maintained between the plunger and V-shaped sealing interface, which can lubricate sealing pair, reduce friction and improve lifetime. The axial pressure distribution of the V-shaped sealing has been gained by experimental testing.

Theoretical analysis and experimental studies have shown that, when the plunger of fracturing pump has reciprocating motion, in the working scope of sealing ring, the biggest pressure difference happens in the outmost seal ring, and has a sharp decline in the small section near the air side. This means that, this kind of sealing structure of fracturing pump is suitable for higher pressure sealing, and not suitable for low pressure seal.

Acknowledgments

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