American Journal of Engineering and Technology Management
2016; 1(3): 49-54
http://www.sciencepublishinggroup.com/j/ajetm
doi: 10.11648/j.ajetm.20160103.14

Structure Analysis and Design Improvement of Plunger Seal Pair in Fracturing Pump

Weibing Zhu*, Jingjiang Yan, Heshun Wang

School of Mechanical Engineering, Xihua University, Chengdu, China

Email address:

qazzwb@sohu.com (Weibing Zhu), jingjiang_yan@163.com (Jingjiang Yan), wangheshun@sohu.com (Heshun Wang)

*Corresponding author

To cite this article:

Weibing Zhu, Jingjiang Yan, Heshun Wang. Structure Analysis and Design Improvement of Plunger Seal Pair in Fracturing Pump. *American Journal of Engineering and Technology Management.* Vol. 1, No. 3, 2016, pp. 49-54. doi: 10.11648/j.ajetm.20160103.14

Received: September 9, 2016; **Accepted**: September 28, 2016; **Published**: October 25, 2016

Abstract: The performance and service life of the plunger and seal of fracturing pumps directly affect the implementation of fracturing technology. The structure characteristics of the plunger seal pair in OPI-1800AWS fracturing pump are analyzed. This paper focus on the contact stress between the plunger and the sealing ring, and the effect of the sealing ring structure parameters on the contact stress is analyzed, and the structure of the sealing ring is optimized. The failure and leakage reason of the plunger seal pair is analyzed. A new structural renovation plan for the plunger seal pair in fracturing pumps is put forward, that is, the sealing effect and service life of the plunger and seal can be increased by strengthening the plunger surface, selecting excellent sealing materials, improving the structure of the sealing ring, adding scraping ring, keeping the moving track of the plunger and the axis of the cylinder jacket in line.

Keywords: Fracturing Pump, Plunger Seal Pair, Contact Stress, Failure, Design Improvement

1. Introduction

At present, the fracturing and acidizing operations are effective increasing production measures which are used in oil gas well and water injection well, and fracturing pump is the important equipment to complete these operations. Key parts including the plunger and seal are the main worn parts of the fracturing pump. The performance and service life will directly affect the implementation of fracturing technology, and bad sealing will bring a great deal of maintenance labor.

The discharge pressure of fracturing pump is high, fracturing fluid contains a large number of high hardness of sand grains, fracturing fluid has performance of high acidity, low viscosity, poor self-lubrication. So the working conditions of the plunger and seal are extremely bad [1]. From the current using of plunger and seals used in oil fields in China, the lifetime is very low, and an annual consumption is great. The investigation indicated [2-3], 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, and the pump developing toward the direction of high pressure, the huge discharge and high power, 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 the lifetime and ensure the smooth construction. In this paper, the structure characteristics, the contact stress between the plunger and the sealing ring, failure reasons of the plunger seal pair in OPI-1800AWS fracturing pump are analyzed. All this will provide theoretical support for design improvement of the plunger seal pair.

2. The Structure of Plunger Seal Pair

The structure of hydraulic end of OPI-1800AWS fracturing pump is shown in Fig. 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 [4-5]. 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 [6-8], is that 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 that forming a high-pressure oil film between the plunger and seals to prevent dirty fracturing fluid (medium) from entering sealing interval and protect seals.

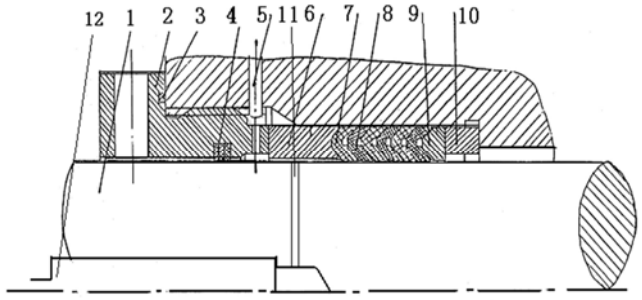

Fig. 1. *The structure of plunger seal pair.*

1 plunger, 2 back pressure cap, 3 O-shape seal 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

3. Force Analysis of V-shaped Seal Ring

3.1. Analysis of the Composition and Role of Contact Stress in V-shaped Seal Ring

As shown in Fig. 1, when installing the seal ring, there is interference between the V-shaped seal ring and the plunger, so there is preload between them. When rotate the back pressure cap, its axial displacement will produce compressive stress. The sum of the preload and compressive stress is pre-contact stress. When the plunger reciprocates, the fracturing pump will produce pressure. The pressure acting on the V-shaped seal ring will produce self-tightening force in the seal ring. The sum of the pre-contact stress and self-tightening force is called contact stress. Theoretically, in the discharge stroke, if the contact stress is greater than the pressure of the sealed liquid, the purpose of sealing is achieved. In the suction stroke, if air is not inhaled under the action of pre-contact stress, the purpose of sealing is achieved.

In discharge stroke, there are the pre-contact stress and the self-tightening force, and they are part of the contact stress, but in suction stroke, there is only the pre-contact stress. From the literature [9], we know that, in discharge stroke, except the seal ring near the air side, the liquid film pressure between the plunger and the other seal ring developments fully, the liquid film thickness is thick, so the wear of the seal ring is small. But in suction stroke, the plunger seal pair is almost in dry friction condition, the frictional heat produced by the plunger and the seal ring is not easy to send out rapidly, the wear is large, so the pre-contact stress is the main failure reasons. As for certain contact stress, if the proportion of self-tightening force increases, the proportion of pre-contact stress may decrease, so the wear may decrease, the service life may increase. But the proportion of pre-contact stress cannot be too small, otherwise, during the suction stroke air is inhaled, the volumetric efficiency of pump drops, seriously, the pump discharged no liquid. So just from the point of contact stress, the ideal sealing structure is that, during the suction stroke, the pre-contact stress is just to prevent inhaling air and seal the liquid working pressure. So in both suction and discharge strokes, the wear and generated heat are small, and the lifetime of seal ring is long. At the same time, when adjust the pressing force, it is difficult to cause excessive pre-contact stress and produce excessive wear.

3.2. Relationship Between the Pre-contact Stress and Cross Section Sizes of V-shaped Seal Ring

When install the seal ring, there is interference between the V-shaped seal ring and the plunger, so there is preload between them. But after working for some time, because of wear, the preload basically does not exist, at this time the actual preload is compressive stress which is the result of rotating the back pressure cap and its axial displacement. The compressive stress is related to the cross section sizes of V-shaped seal ring. If a suitable cross-sectional shape is designed, a smaller compressive stress can ensure that the suction stroke does not inhale air, therefore wear is reduced. 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 install sealing rings, initial contact stress produced by extrusion and interference press the sealing ring on the surface of plunger, then, after having enough contact stress, the material can be pressed into trough to stop leakage from the channel of troughs. Seal the same pressure, for different cross section sizes of V-shaped seal ring, the required axial compressive stress is different. As for the shape shown in Fig. 2, the contacting area between the working surface of the seal ring and the plunger is large. When rotate the back pressure cap to apply axial clamping force, if the sealing material is harder, the clamping force will mainly concentrate in the root of the V-shaped seal ring. The root not easily deforms to fill the trough channels, so larger axial clamping force is required. When the axial clamping force is too large, it is easy to cause damage to the body of the seal. If an angle α is designed in the sealing surface, as shown in Fig. 2, lip stiffness decreases, the position of radial compressive stress produced by the axial clamping force gradually moves forward with the increase of α, ability of the lip deformation

fill troughs channel greatly increases, and during the suction stroke wear significantly reduces. Tests show that an appropriate angle α is related to sealing material, as for rubber material, α=3°, as for PTFE, α=5°, as for rubber cloth, α=8°.

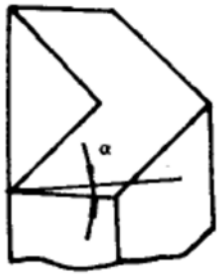

Fig. 2. *Cross-sectional view of V-shaped seal ring.*

4. Failure Reasons of Plunger Seal Friction Pair

4.1. 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 the 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, that 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 [10-12]. 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.

4.2. When Crosshead, Plunger, Tension Rod and Plunger Head Reciprocate, the Concentricity with Cylinder

Crosshead and tension rod are connected by thread, plunger head and plunger are connected by thread, plunger head and tension rod are connected by spherical hinge. All these parts as a whole have a reciprocating motion. the public axis should be coincidence with the public axis of crosshead and cylinder, otherwise, the sealing rings will be worn partially, and lose efficacy.

4.3. Materials of Sealing Ring

The material performance of sealing ring is 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 [10]. 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 [13].

4.4. Abrasive Wear of Sealing Ring

Fracturing fluid contains a lot of quartz sand or other hard phase, so abrasive wear of sealing ring is also important factor in failure. Under the action of working pressure, the V-shaped rubber sealing rings have deviation effect [14]. 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, which caused plunger abrasive wear, especially in the suction stroke of fracturing pump, as shown in Fig. 3. Because, during the discharge process, the plunger pushes to cylinder, the contact stress between the plunger and seals is very large, abrasive is not easy to enter. But in the suction process, the contact stress is small, abrasive is easy to enter. Fracturing fluids contain acids and other corrosive media, which caused corrosion damage, as shown in Fig. 4. At the same time, during the fracturing process, the working pressure is very high, the plunger long-term withstands reciprocation load function, which caused fatigue, so there are fatigue crack and spherical particles in plunger surface, as shown in Fig. 3 and Fig. 4. 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.

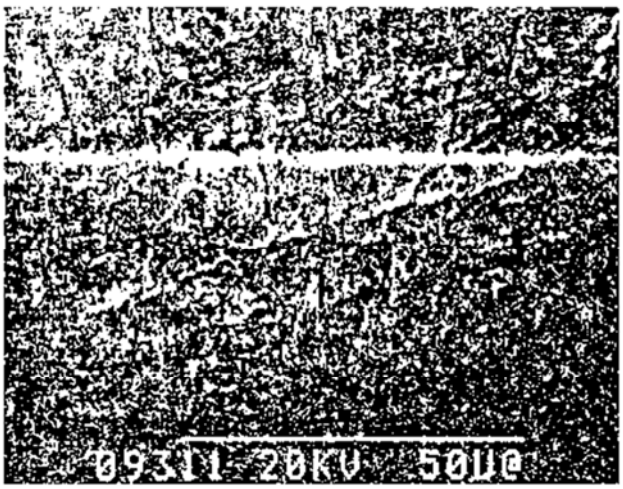

Fig. 3. *Scratches and fatigue crack.*

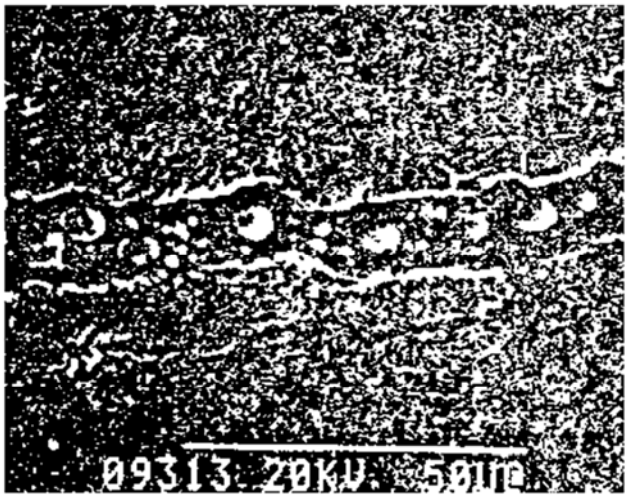

Fig. 4. *Corrosion pit and spherical particles.*

5. Structure Improvement of Seal and Design of Scraping Ring

5.1. Structure Improvement of Seal Ring

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 [15]. Finite element analysis [14] 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 Fig. 5. 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 medium lubrication. 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 Fig. 6, 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. When there is liquid between the plunger and seal surfaces, according to one-dimensional Reynolds equation [17], its pressure variation general equation is equation (1)

$$\frac{dp}{dx} = 12\eta u\left(\frac{1}{2h^2} - \frac{Q}{uh_3}\right) \tag{1}$$

Where p is liquid film pressure, η is liquid viscosity, u is reciprocating motion relative velocity, h is fluid film thickness, Q is per unit perimeter flow capacity, x is distance along the seal, h^* is The film thickness of the maximum pressure, $h^* = 2Q/u$.

Integral equation (1) and substituted boundary conditions, the expression of liquid film thickness is [18]

$$\bar{h}^{3/2} = \frac{\eta u r^{1/2}}{p_i + p_f} \tag{2}$$

Where, $\bar{h}$ is liquid film thickness of convergence oil wedge export, r is outline radius of sealing surface end, p_i is pre-contact stress because of initial interference, p_f is contact stress between plunger and seal because of Working medium role.

Obviously, the structure of seal ring plays an important role on the formation of liquid oil film. At present, the plunger seal of fracturing pump always adopts self-sealing V-shaped lip seal structure. In theory, the V-shaped seal ring may have many kinds of contours. Its main change is the proportion relationship between the bottom thickness and lip height, and the proportion relationship between the lip thickness and the total depth of the V-shaped grooves. As for V-shaped seal ring, its lip angle α controls the ratio of lip height and bottom thickness. By changing the value of α, we can get different structures of seals.

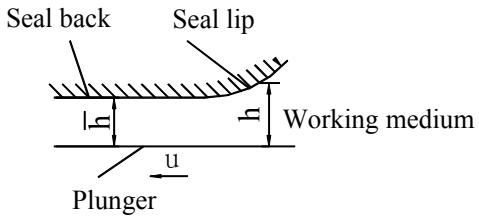

Fig. 5. *Suction stroke of fracturing pump.*

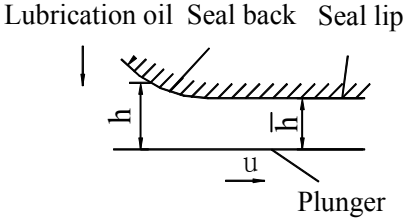

Fig. 6. *Discharge stroke of fracturing pump.*

As shown in Fig. 7, the V-shaped opening angle of the original seal ring lip, during the suction stroke of fracturing pump, under the action of working pressure, the V-shaped seal ring has deviation effect, and its back is acute angle shape, this type of structure does not favor the formation of hydrodynamic oil film. When many seal rings combine in together, before and after seal rings closely fit, the space between the seals is very small, this situation does not favor the heat radiation, and once an individual seal damages, the overall sealing property will reduce greatly [19].

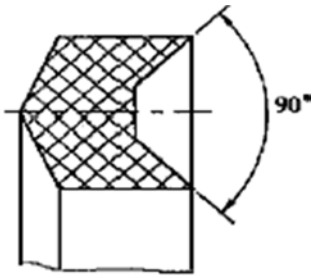

Fig. 7. *Original sealing structure.*

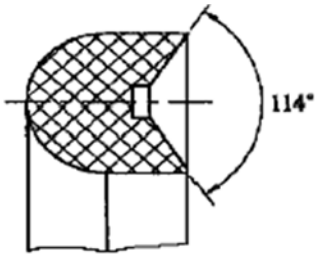

Fig. 8. *Improved sealing structure.*

Finite element analysis shows that [14], at first, the average contact stress of sealing surface of seal ring P_m decreases with the increase of lip opening angle α, when α=114°, it reaches its minimum value, then begins to increase. Practical experience has shown that sealing surface ideal stress distribution curve of stress peaks would be closer to the lip, and would be lower than the average stress. This is because, when the seal ring abrades with the plunger, the friction coefficient is big, the calorific capacity is high and rubber is a poor conductor of heat, so the temperature rises faster. It seriously affects the lifetime of the seal rings, therefore, the contact stress of the sealing surface is would not be too much. By comparative analysis of the relationship between the sealing surface contact stress and the lip opening angle α, the ideal sealing structure is, α=114°.

Improved sealing structure still uses V-shaped structure as shown in Fig. 8, but the lip opening angle α increases from 90° to 114°, the acute angle shape of seal back becomes semicircular, this type of structure favors the formation of hydrodynamic oil film. The seal rings do not fit closely, thereby enhances the diathermancy of sealing rings, ensure that the sealing rings work in turn. That is, when the first seal ring failures, the following seal rings continue to work, the phenomenon which because of some seal ring damages causes the overall sealing property to reduce is avoided. In addition, because the back of seal ring is semicircular, when many seal rings combine in together, the semicircular back of the front seal ring contacts with the lip of later seal ring, so the V-shaped lip of later seal ring can open greater, so the self-sealing performance of seal ring is enhanced.

5.2. Design of Scraping Ring

The abrasive wear of sealing ring is also an important failure factor. Under the action of working pressure, the V-shaped rubber sealing rings have deviation effect. 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. During the discharge process, the plunger pushes to cylinder, the contact stress between the plunger and seals is very large, abrasive is not easy to enter. But in the suction process, the contact 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 plunger seal pair as far as possible. So a scraping ring which has cross section of comb shape is designed, as shown in Fig. 9, it is installed between the front supporting ring and pump shell. The scraping ring would have good flexibility, it may select metal or other hard materials such as hard rubber. The structure of this type of scraping ring is simple, and easy to install. During the discharge or suction stroke, the scraping ring is close to the sealed side, so it can constantly wipe the plunger surface, abrasive media can not enter into the gap of plunger seal pair. Because the cross section of the scraping ring is comb shape, it allows the working medium to pass, so it does not bear too much pressure, it may have a relatively long working lifetime. Even if the scraping ring fails, it does not affect the normal work of fracturing pump, only increases the possibility of the abrasive entering into the sealing surface.

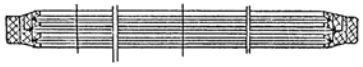

Fig. 9. *Structure drawing of scraping ring.*

6. Conclusions

(1) During the discharge stroke of plunger seal pair, its contact stress is composed of pre-contact stress and self-tightening force, but in suction stroke, there is only pre-contact stress which is the main wear failure reasons of seal ring. The ideal sealing structure is that, during the suction stroke, the pre-contact stress is just to prevent inhaling air and seal the liquid working pressure. So in both suction and discharge strokes, the wear and generated heat are small, and the lifetime of seal ring is long. At the same time, when adjust the pressing force, it is difficult to cause excessive pre-contact stress and produce excessive wear.

(2) Self-tightening force and pre-contact stress are closely related to the cross section sizes of V-shaped seal ring. Design an angle α in the sealing surface, lip stiffness will decrease. As for same clamping force, the ability of the lip deformation fill troughs channel greatly increases, and during the suction stroke wear significantly reduces.

(3) In order to favor the formation of hydrodynamic oil film, the sealing structure is improved. That is the acute angle shape of seal back changes to semicircular, the lip opening angle α increases from 90° to 114°.

(4) Performance and service lifetime of plunger seal pair in fracturing pump depend 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 have good performance and long lifetime. The improved plunger seal pair has been used in Sichuan and Changqing oilfields for several years, its effect is very satisfactory, it solves the problem of plunger seal leakage, the fracturing and acidizing fluid would not enter the crankcase. The service life of the improved plunger and the seal rings improves a lot. The lifetime of plunger enhances from the original 3-4 months to 15 months, the lifetime of seal rings enhances two times.

Acknowledgements

This work was supported by the Training Fund of Sichuan Academic and Technical Leader (Grant No. 13202625), the Parental Affection Plan Project, China's Ministry of Education (Grant No. Z2014072), and the Key Project of Sichuan Education Department (No. 15ZA0126).

References

[1] W. Zhu and X. Zhou, “Study on Performance and Mechanism of Reciprocating Seal of Fracturing Pump” , Natural Gas Industry, vol. 26, no. 1, pp. 60-62, 2006.

[2] H. Wang, Principles of hydraulic fracturing. Beijing: Petroleum Industry Press, 1987.

[3] H. Wang and D. Xu, Oil drilling equipment, tool and accessories. Beijing: Petroleum Industry Press, 1994.

[4] T. Guang and D. Wang, Seal user's manual. Beijing: Mechanical Industry Press, 1993.

[5] Z. Zhang and Y. Zhang, “Development of model RST200 plunger/rod sealing member test stand”, Field Equipment, no. 4, pp. 27-29, 2000.

[6] De Jong et al, “A Finite Element Calculation of the EHD behavior of A reciprocating Seal”, Proc. 9th IC on FS. BHRA Fluid Engng Paper, 1981, J3, pp. 403-411.

[7] L W. Winn and C C. Lee, “Lip Seals-Stress and Deformation Studies”, ASLE Paper 80-C2/Lub-11, 1981, pp. 1-8.

[8] Y. Yang and W F. Hughes, “An Elastohydrodynamic Analysis of Preloaded Sliding Seals”, ASLE Trans., vol. 27, no. 3, pp. 197-202, 1983.

[9] W. Zhu and Z. Zhang, “Analysis of Lubrication State of Plunger Seal Friction Pair in Plunger Pumps”, Journal of Sichuan University of Science and Technology, vol. 23, no. 2, pp. 28-30, 2004.

[10] Z. Zhang and W. Zhu, “Failure analysis of the plunger of plunger pump OPI-1800AWS”, Journal of XiHua University (Natural Science Edition), vol. 24, no. 5, pp. 26-28, 2005.

[11] G. Wang, G. Hu, X. He, et al, “Sealing performance analysis of Y-ring used on reciprocating seal shaft”, Machine Design and Research，30 (6), pp. 37-42, 2014.

[12] Y. Zhou, Z. Huang, Y. Bu, et al, “Simulation studies on drilling mud pump plunger seal failure under ultrahigh pressure and ultra deep conditions”, Engineering Failure Analysis, vol. 45, pp. 142-150, 2014.

[13] J. Li and S. Zhang, “A review of reciprocal packing material and its forecast”, Petroleum Machinery, no. 12, pp. 48-52, 1992.

[14] W. Zhu, “Finite element analysis of sealing ring in plunger pumps”, Sichuan University of Science and Technology, vol. 23, no. 1, pp. 17-19, 2004.

[15] W. Zhu, G. Zhou, and H. Wang, “Research on the Reciprocating Sealing of Fracturing Pump”, TELKOMNIKA, vol. 10, no. 3, pp. 499-504, 2012.

[16] X. He, M. Li, G. Wang, et al, “Effects of the packer rubber surface morphology on the sealing performance”, Chinese Journal of Applied Mechanics，33 (03), pp. 454-458, 2016.

[17] X. Dong, Lubrication theory. Shanghai: Shanghai Jiao Tong University Press, 1984.

[18] W. Zhu, X. Qin, G. Mao, “Lubrication Mechanism Analysis of Plunger-Seal Pair in Fracturing Pump”, Journal of Sichuan University of Science and Technology, vol. 21, no. 2, pp. 7-9, 2002.

[19] Zh. Huang, Q. Li and X. Zhou, “Study on plunger seal pair in fracturing pump”, Oil Field Equipment, vol. 29, no. 6, pp. 12-15, 2000.