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Calculation and Experimental Verification on Leakage Rate of SRM Sealing Structure

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Abstract

The leakage rate of the SRM sealing structure was numerically calculated and the numerical calculation was verified by the experimental research. Based on the Roth leakage theory and the rubber aging prediction model, the leakage rate model of SRM sealing structure under long-term storage was established. The influence of the storage time and the medium pressure on the leakage rate of the SRM sealing structures was analyzed. The leakage rate test and the test device for measuring leakage rate were designed to verify the numerical calculation. The results show that the influence of the initial compression ratio and the rubber aging on the sealing performance of the rubber O-ring is consistent with the conclusion of the numerical calculation. Also, the test results and the numerical calculation are in the same order of magnitude under the same condition. Thus, the credibility of the numerical calculation is verified.

Keywords

Sealing structure; Rubber O-ring; Sealing performance; Leakage test.

1. INTRODUCTION

Solid rocket motor (SRM) is widely used as the main power source of missile weapons for its simple structure, easy long-term storage and high reliability. Long-term storage is required in central storage after delivery and use of solid missiles. The rubber O-ring in the SRM sealing structure is prone to aging during storage, and its failure will directly affect the working performance of important components such as the overall structure, grain, and electronics [1]. Therefore, the study of the sealing performance of SRM rubber O-ring under long-term storage has important theoretical guiding significance and application value for accurately grasping the storage reliability of SRM.

Aiming at the study of sealing performance of rubber sealing structure, many scholars at home and abroad mainly carry out the study of sealing performance from many aspects such as sealing principle, leakage mechanism, sealing ring performance and life and its influencing factors, leakage rate, etc., but mainly focus on sealing structure design, reliability and life evaluation, while there are not many studies on sealing performance after O-ring meridian-thermal aging, and no one has carried out the evaluation of SRM sealing performance using leakage rate [3-5].

Aiming at the problem that the aging of rubber ring in SRM sealing structure affects the sealing performance during storage, combining with the current domestic and foreign research results, this paper focuses on the sealing performance of rubber ring after aging by combining theoretical numerical calculation with test method verification, and performs numerical calculation and test verification of the leakage rate of SRM sealing structure under long-term storage.

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2. LEAKAGE MECHANISM AND NUMERICAL MODEL

The SRM sealing structure is mainly sealed by the mutual extrusion of rubber O-ring and the contact surface of the upper and lower metal flanges, so it can be classified as a plane sealing problem [3]. Macroscopically, the surface of the flat seal can be considered as two smooth and flat "ideal planes". However, from a microscopic point of view, because the core shaft will beat during machining, the actual machined seal ring surface is not an ideal plane, and there will be many subtle convexities and trenchs [6]. As shown in Figure 1, these convex peaks and trenchs concave the surface of metal flanges, and the concave area is effectively filled with rubber material to form a channel, which makes it possible for gas leakage to occur [7].

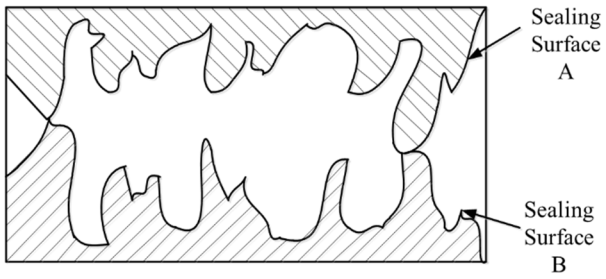

Figure 1. Microstructure of flat sealing surface

A. Roth measured and counted the metal surface after machine addition by effective test means and proposed the Roth model [8,9]. That is, the basic equation for the leakage phenomenon of monomer rubber O-ring is:

$$Q = C \cdot \Delta p = 4\sqrt{\frac{T}{M}} H^2 \frac{L}{b} \exp(\frac{-3\bar{\sigma}}{R_s}) \Delta p \tag{1}$$

Where: Q is the leakage rate; C is the total flow conductance of gas flowing through the sealing surface of sealing ring; Δp is the internal and external pressure difference of sealing device; T is the absolute temperature of external gas; M is the medium molecular weight of external gas; H is the surface roughness of metal processing surface; L is the section contact length of sealing surface. According to the geometric relationship, the section contact length of sealing surface is $L = \pi(D + d)$, D is the inner diameter of rubber ring, d is the section diameter of rubber ring; b is the contact surface width; $\bar{\sigma}$ is the contact stress on the sealing surface during extrusion filling; R_s is the sealing coefficient, reflecting the ability of soft sealing materials to fill the leakage channel under a certain compression force, which can be obtained by test or numerical simulation calculation [6].

Most SRMs for missile weapons undergo a long storage period during their service, and rubber O-ring in the sealing structure undergoes natural aging in long-term storage. The essence of rubber aging is that when rubber is squeezed by external force for a long time, some elastic strains transform into plastic strains, which in turn causes the decreased ability of rubber materials to fill uneven channels on the metal surface, resulting in poor sealing performance [6]. To add the factor of aging time into the leakage rate model, the following empirical formula is used [10]:

$$\bar{\sigma}(t) / \bar{\sigma} = B \exp(-K_c t^{\alpha}) \tag{2}$$

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Where: B and α is the aging model coefficient; K_c is the aging rate constant.

Combining Equation (2) and Equation (1), the rubber ring leakage rate model formula of SRM under long-term storage condition can be derived:

$$Q = C \cdot \Delta p = 4\sqrt{\frac{T}{M}} H^2 \frac{L}{b} \times \exp\left(\frac{-3\bar{\sigma} B \exp(-K_c t^{\alpha})}{R_s}\right)\Delta p \tag{3}$$

3. LEAKAGE RATE NUMERICAL CALCULATION OF SRM SEALING STRUCTURE

3.1. Effect of Storage Time on Rubber Ring Sealing Performance

The silicone rubber used in a certain type of SRM is selected as the study object, and the initial compression rate is taken as 0.25, with an elastic modulus E of 5.22 MPa. The sealing coefficient R_s is 0.99 MPa, the rubber O-ring geometric dimension: inner diameter D = 314 mm, section diameter d = 5.5 mm, the flange surface roughness = 0.8 μm. The SRM gas tightness check gas is nitrogen, and the medium pressure is 0.3 MPa. The selected aging model has coefficients of B = 1, α = 0.4, and aging rate constant K_c = 0.0123. Both contact stress and contact width are obtained by numerical simulation. Substituting the above parameters into the rubber ring leakage rate model Formula (3) of SRM under long-term storage conditions, the leakage rate as a function of time under the influence of rubber aging factors within 30 years of storage time can be derived. The curve of leakage rate with time is plotted, and the trend of the curve is shown as Figure 2.

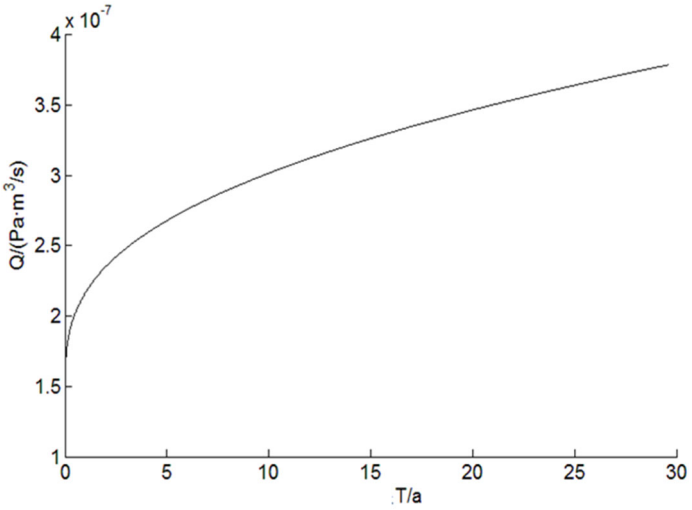

Figure 2. Leakage rate curve of time

It can be seen from Figure 2 that the leakage rate of SRM rubber ring showed an increasing trend with the increase of storage time. In addition, the rate of leakage increased rapidly with time in the initial stage of storage, but gradually decreased after a period of storage, with leakage values in the order of 10^{-7}. This change rule is consistent with the change rule of permanent deformation rate measured by aging test of rubber material with time, because the permanent deformation rate of rubber ring directly affects the leakage rate of sealing structure, which will gradually increase with the increase of storage time, so the contact stress on the sealing surface correspondingly decreases, resulting in the increase of leakage rate.

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3.2. Effect of Dielectric Pressure on Sealing Performance of Rubber Ring

When the initial compression rate of rubber ring is 0.25 amd the surface roughness of flange is 0.8 μm, the leakage rate of unaged rubber O-ring is plotted as a function of medium pressure in Figure 3.

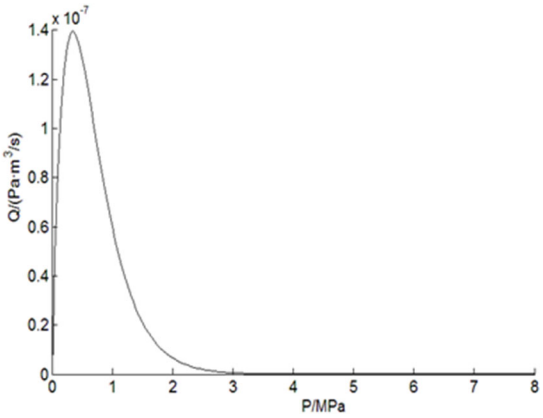

Figure 3. Leakage rate curve of medium pressure

It can be seen from Figure 3 that in the pressure range of 0.1 MPa~8 MPa, when the medium pressure increases, the leakage of rubber ring first increases and then decreases, and the peak value occurs around 0.4 MPa. The reason is that on the one hand, the increase of pressure can promote the diffusion of gas molecules from the leakage channel, which is called "driving force effect"; on the other hand, with the increase of pressure, the contact stress will be generated on the sealing surface to improve the sealing performance and inhibit the gas leakage, which is called "self-locking effect". When the medium pressure is small, the "driving force effect" dominates, the leakage rate of rubber ring increases with the increase of medium pressure, when the medium pressure exceeds a certain value and continues to increase, the "self-locking effect" becomes dominant, and the leakage rate of rubber ring gradually decreases.

4. LEAKAGE TEST

4.1. Effect of Dielectric Pressure on Sealing Performance of Rubber Ring

The To verify the credibility of the numerical calculation results, this paper uses the O-ring leakage rate measurement test for verification [2][4]. Firstly, aging test is conducted on rubber O-ring by installing the silicone ring in a special fixture with preset compression rate, and place the fixture in the accelerated aging box for accelerated storage test according to the equivalent storage time. On this basis, the rubber ring after accelerated aging is put into the sealing flange leakage detection device for leakage rate determination.

4.2. Accelerated Aging Test

The industrial department has conducted the accelerated aging test for G105 silicone rubber, and deduced the equivalent storage time at room temperature in combination with Arrhenius formula: The accelerated aging of G105 silicone rubber ring with initial compression amount of 25% in an accelerated aging oven at 130°C for 8 days, 16 days and 28 days is equivalent to 6 years, 12 years and 20 years of natural storage. The silicone rubber ring is installed in a special fixture with preset compression rate. The fixture is placed in the accelerated aging oven for the accelerated storage test according to the equivalent storage time. The test materials and equipment are as follows:

(1) Rubber O-ring. O-ring sealing with G105 silicone rubber manufactured by Academy of Aerospace Solid Propulsion Technology. The rubber ring of outer channel is 392 mm × 5.5 mm,

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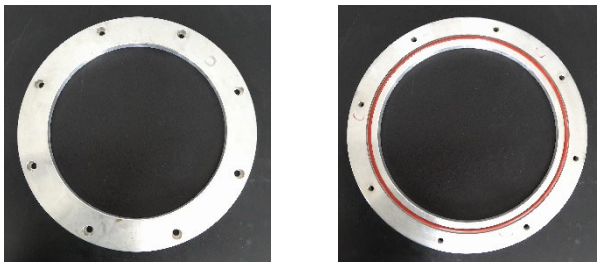
and the rubber ring of inner channel (to be tested) is 314 mm × 5.5 mm. The number of units tested per condition was 3 for different initial compression rates and accelerated aging times.

(2) Accelerated test equipment. The blast system in the LR016 thermal oxygen aging accelerated test chamber produced by Chongqing Galaxy Test Instrument Co., Ltd. can blow the hot and cold air into the working chamber, with the temperature range of room temperature + 20°C ~ 300°C and the temperature control accuracy of 1°C.

(3) Special fixture for acceleration test. In order to simulate the actual compression working state of rubber O-ring in SRM sealing structure, a special fixture for accelerated storage is designed, which is composed of upper and lower hollow metal discs and 8 fixed bolts, and the material is aluminum alloy, as shown in Figure 4.



(a) Upper disc (b) Lower disc

Figure 4. Fixture of accelerated storage

4.3. Leakage Rate Detection Test

(1) Leak rate detection device

The leak rate detection device consists of a sealed flange combination, a helium cylinder, a temperature and pressure sensor, and a helium mass spectrometric leak detector as shown in Figure 5.

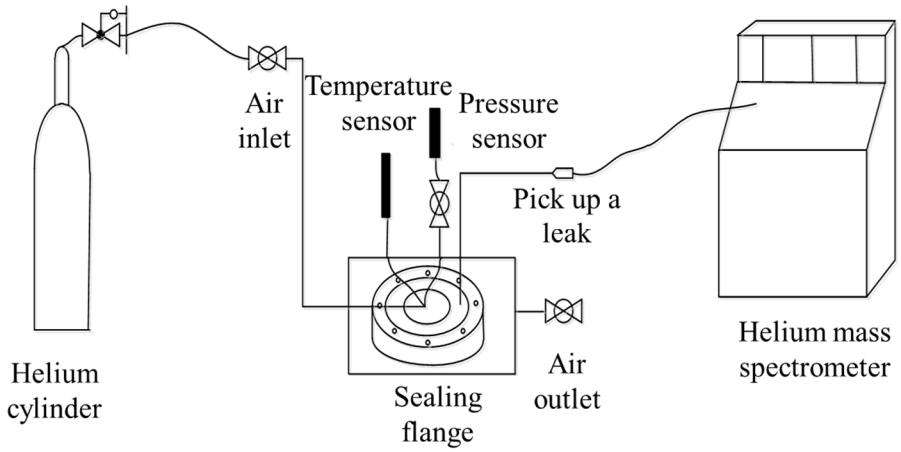


Figure 5. Detection device of leakage rate

Put the rubber ring to be tested into the sealing flange, pressurize the flange structure with helium gas cylinder, monitor the pressure and temperature status in the sealing flange through the sensor, and measure the leakage rate of the rubber ring in the flange through the helium mass spectrometer leakage detector after reaching the ideal test conditions.

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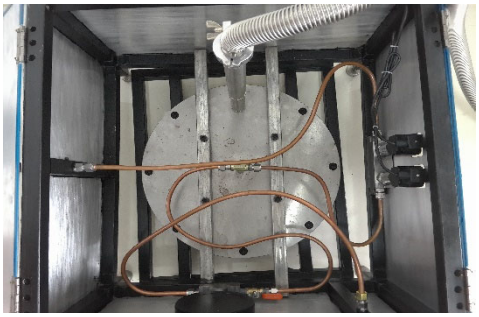
(a) Front view



(b) Top view

Figure 6. Combination sealing of flange

The internal structure of the sealing flange assembly is composed of three parts: the flange base, the ventilation tube and the leakage detection tube, and its metal material is stainless steel, as shown in Figure 6. The vent line and leak detector are seamlessly welded to the upper end cap of the flange base. The other end of the leak detector tube is connected to the leak detector port of the helium mass spectrometer leak detector [11]. The flange base is provided with two sealing slots. As shown in Figure 7, the size design of the sealing slot of the inner channel is determined according to the initial compression rate of the rubber ring (to be tested) of the inner channel. Small holes are opened in the middle of two rubber rings to connect with the leakage detection tube. A gas cavity is set in the center of flange base. A ventilation port is opened in the center of base end cover to communicate with the ventilation tube. The ventilation tube is composed of inflation tube, detection tube and exhaust tube. The inflation tube is connected with the output end of helium cylinder. The detection tube first passes through the temperature sensor and then passes through the pressure sensor. The other end of pressure sensor is connected with the exhaust tube. Spherical valves are installed at both the inflation port and the exhaust port.

Figure 7. Real figure of flange base

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(2) Detection principle of leakage rate

The section diagram of sealed flange combination is shown in Figure 8.

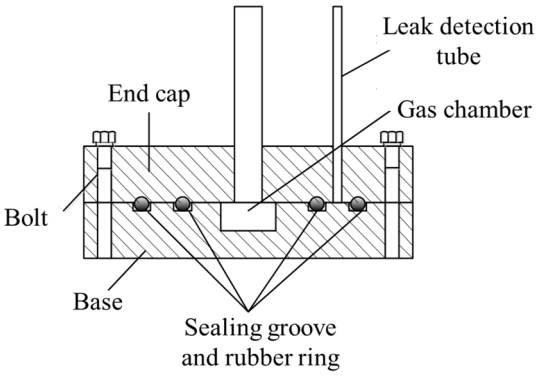

Figure 8. Cross section of sealing flange

Before measuring the leakage rate, first put the rubber ring to be tested and the rubber ring in the outer channel into the flanged structure base with the corresponding compression rate, and the end cover and base are firmly fastened by bolts. Open the inflation valve, the He-gas cylinder continuously transmits the high-pressure gas to the gas chamber, and the indication of the pressure sensor is the pressure value in the gas chamber. The center of the two rubber bands is the leakage detection area, which is connected to the leakage detection tube welded to the upper end cap of the flange base. Start the helium mass spectrometric leak detector to perform continuous vacuum pumping for the leak detector tube. Driven by the pressure difference, the helium molecules leak into the leakage detection area, which is then measured by the helium mass spectrometric leak detector.

5. TEST RESULTS AND ANALYSIS

To analyze the effect of initial compression rate and rubber aging on the sealing performance of rubber ring, the pressure of filling helium cylinder into the gas cavity is controlled to be 0.3MPa. According to the test results, the change trend of rubber ring leakage rate with equivalent storage time when the initial compression rate is 0.25 and the change trend of rubber ring leakage rate with initial compression rate after accelerated aging are made, and compared with the theoretical calculation results as shown in Figure 9 and 10. Under the same conditions, there are some differences between the test and numerical calculation results of rubber ring leakage rate, but they are on the same order of magnitude. The causes of errors are analyzed. On the one hand, the leakage rate model is established according to Roth leakage theory, the analysis and calculation process is based on certain assumptions, and the rubber aging prediction formula introduced in the leakage rate model is given empirically, resulting in certain errors in the calculation results; on the other hand, due to the limited processing accuracy of the leakage rate test device, and the impurity particles in the flange groove will affect the sealing performance of the rubber ring during the determination process, some errors are introduced into the determination results.

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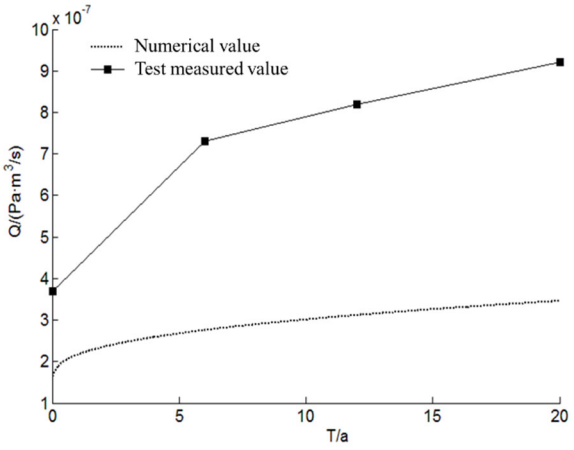

Figure 9. Leakage rate curve over time

It can be seen from Figure 9 that when the medium pressure and initial compression rate are constant, the leakage rate of rubber ring increases continuously with the extension of accelerated aging time. The leakage rate increases the fastest within the accelerated aging time of 0 ~ 8 days, and then gradually slows down. The law is consistent with the law obtained from the theoretical calculation in Section 2. In Figure 10, the leakage rate of rubber ring decreases significantly with the increase of initial compression rate, and the leakage rate decreases by an order of magnitude for each 5% increase of compression rate. This change trend is consistent with the numerical calculation results. It is concluded that increasing the initial compression rate can effectively reduce the leakage rate of rubber ring sealing structure and improve its sealing performance.

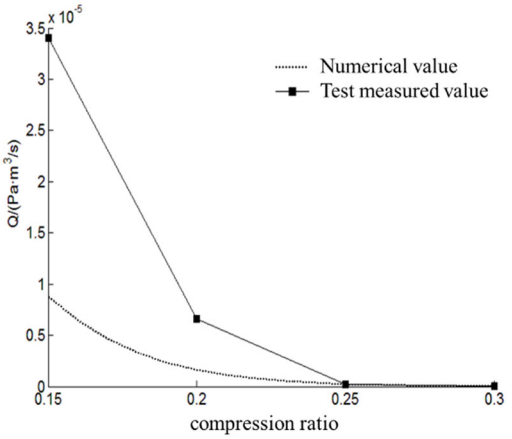

Figure 10. Leakage rate curve over initial compression ratio

6. CONCLUSION

In this paper, the leakage rate of SRM sealing structure under long-term storage is numerically calculated and analyzed. The rubber aging prediction model is introduced into Roth molecular flow leakage model, and the SRM sealing structure ground leakage rate model under long-term storage condition is established. The numerical calculation of the leakage rate of SRM sealing structure is carried out. The results show that the leakage rate of SRM rubber ring increases with the increase of storage time, the leakage rate at the early stage of storage increases rapidly with time, and then gradually slows down.

To verify the credibility of the numerical calculation results, the leakage rate of rubber O-ring under long-term storage is determined by the method of experimental study in this paper.

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Considering the actual installation of rubber ring in SRM sealing structure and the influencing factors of leakage rate to be analyzed, a special fixture for accelerated storage and a leakage rate measurement device for flange structure are designed. The leakage test results show that the effect of initial compression rate and rubber aging on the sealing performance of rubber rings is consistent with the conclusion obtained from numerical calculation, and the test results and numerical calculation results of rubber ring leakage rate are on the same order of magnitude under the same conditions, thus verifying the credibility of numerical calculation.

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