Proceedings of the 2022 International Conference on Smart Manufacturing and Material Processing (SMMP2022), A. Nayyar (Ed.)

doi:10.3233/ATDE220826

A Review of the Development of Sealing Materials and Measurement and Control Simulation Technology for Typical Hypersonic Vehicle Positions

Yixiang GUO, Lifang CHEN [1] and Yuhang ZHOU
College of Mechanical and Electrical Engineering, Beijing University of Chemical, Technology, Beijing, China

Abstract. Hypersonic vehicles are an important development direction in aerospace, and their development will have a significant impact on world security, the development of cosmic space resources and related disciplines. Along with the rapid development of modern aircraft, landing gear is commonly used with retractable technology, which brings a series of problems, such as the design of landing gear hatch retraction heat sealing mechanism and the evaluation of air tightness. This paper takes the thermal sealing structure of the front main landing gear hatch of a vehicle as an example, reviews the progress of the analysis techniques of sealing material properties and sealing structure design for hypersonic vehicles at home and abroad, discusses the current status of the development and limitations of hatch thermal sealing technology, outlines and discusses the key technologies for design and analysis of hatch thermal sealing structure and the future development trend, and summarizes the test equipment and methods for identifying the performance of seals and sealing systems.

Keywords. Hypersonic vehicles, Sealing materials, Computer Aided Engineering, Control Technology

1. Introduction

The sealing of the hatch is an important safeguard to prevent air leakage or loss of pressure inside the hatch. For the hatch structure of aircraft landing gear, gas-tight seals can effectively block direct convection inside and outside the fuselage, reduce damage to the internal structure of the landing gear from high-temperature fluids, and guarantee a relatively stable working environment for the landing gear [1,2]. In the design of the hatch seal, the design of the seal and the selection of the seal form are crucial. Common hatch seals can be classified according to shape as: tubular or hollow tubular sealing belts, flat sealing belts, flap or claw sealing belts, diaphragm seals, inflatable tube or air tire type sealing belts, etc [3]. Among them, seals made of rubber are the most common. Natural rubber and synthetic rubber [4] present many unique physical and chemical properties, such as strong elasticity, large deformation, wear resistance and excellent barrier properties. In particular, the vulcanization of rubber and the use of additives

[1] Corresponding Author: Lifang Chen, e-mail: chenlf@mail.buct.edu.cn.

improve the mechanical and physical properties of the material for better aerospace applications. Therefore, spacecraft high-temperature heat sealing technology is recognized as a very important technology for the development of future spacecraft.

This paper outlines the progress of domestic and international research on thermal sealing technology, and the research institutions involved, mainly NASA and other research institutions in the United States abroad, and aerospace research institutions and related universities in China, have carried out research related to sealing materials, sealing structures, and leakage. It mainly includes thermal seal application technology, testing technology, and performance simulation technology [5-9], etc. The present study enables to obtain the latest overall overview of the development of high-temperature thermal seal technology.

2. Technical Development of Heat Sealing Applications

2.1 Progress in International Research

During the flight to and from the ground, the surface of the fuselage will experience a large temperature rise due to aerodynamic heating, and the vehicle must be protected by a thermal protection system with excellent performance to maintain the structural temperature within the allowable range. Especially for the opening part of the fuselage (The landing gear hatch sealing structure is shown in Figure 1), this part penetrates the fuselage bearing structure directly to the interior of the fuselage, and the requirements for sealing are more stringent. Therefore, more than two sealing components are usually set in this area, the outermost layer is the thermal barrier seal and the inner layer is the pneumatic seal. The main function of the first seal is to reduce the intrusion flow of hot air, and the main function of the air pressure seal is to prevent direct convection inside and outside the body and reduce the inflow of gas [10].

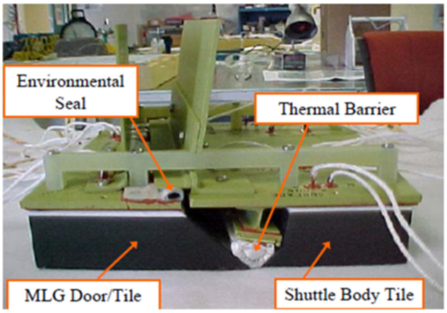


Figure 1. Landing gear hatch sealing structure diagram.

One of the new structural components of the thermal barrier seal is shown in Figure 2, which mainly consists of tubular spring, thermal insulation cotton, sleeve and ceramic fiber. The tubular spring is prepared from the high-temperature alloy Inconel, inserted into a sleeve woven from Nextel fibers, and finally covered externally with Nextel ceramic fiber fabric. The thermal barrier seals also include fiber braided tails that are bonded or mechanically attached to the sealing area with a pressure plate. The improved thermal barrier seal has an additional elastic element inside compared to the conventional one, which largely improves the seal's resilience at high temperatures and enhances the sealing performance.

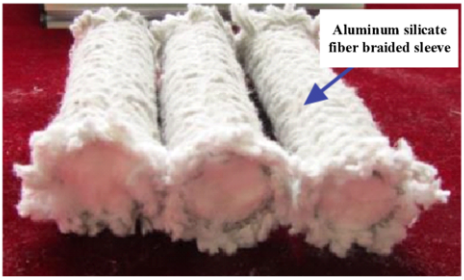


Figure 2. Schematic diagram of a typical thermal barrier seal structure.

The ambient pressure seal, shown in Figure 3, consists of a hollow tubular seal and a tailpiece, both made of silicone rubber and covered with Nomex fabric. The outer side of the tubular seal has through holes spaced 152.4 mm/each in the length direction, which allow the pressure of the seal to be released into the vacuum when the vehicle is in orbit.

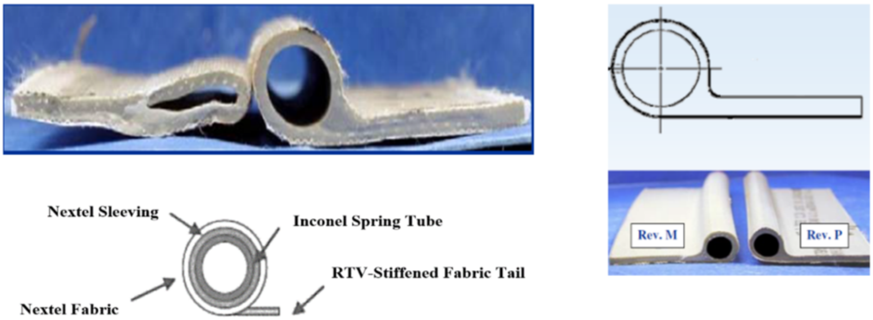


Figure 3. Schematic diagram of pneumatic seal structure.

The hatch seal has to meet both the sealing requirements during re-entry and the ability to adapt to the external environment during orbit, and requires the intervention of the thermal protection system (TPS) of the flight orbiter throughout [11,12]. The hatch sealing structure contact surface is very much, mainly there are opposite hatch contact at the seal, the seal between the hatch and the bulkhead wall, the seal between the hatch and the beam directly, the seal of the direct expansion joint of the hatch components. The position of the contact surface will inevitably bring about the reaction force of the elastic seal, and this force will also have some influence on the sealing effect. According to the data, the hatch is subjected to a reaction force of about 1.8 N/mm by the thermal barrier seal and the pneumatic seal during the opening and closing process, and this part of the load boundary condition should be included in the simulation to evaluate the overall structural deformation and then analyze and discuss the main control factors affecting the leakage volume.

Foreign research institutions have carried out a large number of theoretical analyses and experimental tests in the field of high-temperature heat sealing and thermal protection of aircraft, and have made certain research progress. Especially for the fuselage opening position similar to the hatch and mouth cover at the sealing leakage problem, the most important, the physical diagram of the hatch is shown in Figure 4, by the skin, cross and longitudinal beams, frame and locking structure and so on. A systematic modeling and theoretical analysis of actual pressure-holding doors was carried out in the literature [13], and the study showed that the mechanical junction structure of these doors is simple and flexible, but their unique sealing form requires more demanding structural stiffness, and the specific sealing structure is schematically shown in Figure 5.

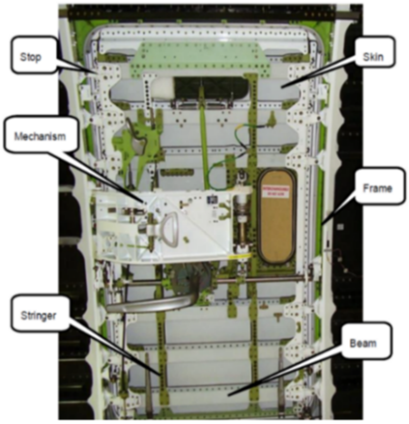


Figure 4. Physical drawing of the hatch.

Because its sealing structure is on the outside of the body, when the overall structural deformation of the door and pressure load increase, the leakage will be more obvious than other sealing positions of the body, especially at the upper rocker position. In order to reduce the self-weight of the door while ensuring good sealing performance, it is urgent to carry out research on hatch composites, which also has a certain reference value for the design of the sealing structure.

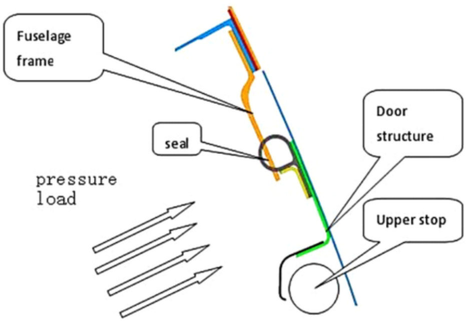


Figure 5. Schematic diagram of the upper seal of the horizontal sliding door.

2.2 Domestic Research Progress

In China, Chen Fu-kui and others from the China Aviation Industry Design Institute conducted research on the application of seal design for various port covers and hatches on aircraft. For non-pressure hatches, the choice of seals is mainly based on the size of the door and the frequency of opening. For hatches with frequent opening and large size, hollow tube seals are often used because there are fewer fixed points; For smaller doors or hatches with infrequent opening, flat serrated seals can be used, which are commonly used for various maintenance port covers and flat seals are also commonly used for aircraft fuselage seals. Inward-opening pressurized hatch, hollow tubular seals have been improved with the continuous development of sealing materials, and the sealing performance of hollow tubular seals depends mainly on the elasticity of the rubber compound. Later improvements in the use of hollow tube seals with sponge fillers improved the compressibility of the seals and obtained better overall sealing performance.

The sealing of the hatch honeycomb parts should take anti-corrosion measures, honeycomb parts butt usually first surface coating treatment after filling in the water-resistant sealant, through the glued honeycomb parts of the connection should be wet state assembly, to ensure the sealing requirements. The hatch opening outside the exposed skin, mouth frame, rib plate and other structural parts, in the first row of fasteners connected more sealant sealing riveting. If the hatch is a sandwich structure, the middle cavity should be equipped with ventilation and drainage holes, and the ventilation is sealed by riveting or the cavity is filled with polyester foam. During the takeoff and landing phase of the aircraft, the landing gear area will be subjected to a large number of corrosive media (water, sand and dust, sulfur dioxide from tire friction, etc.), and all the seals of the landing gear area have taken relevant anti-corrosion measures to improve the reliability and stability of the sealing structure.

Furthermore, the large opening hatch represents a typical class of large space structures and mechanisms that can accommodate a variety of loads in the ground preparation phase, launch and liftoff phase, on-orbit cruise phase, return segment, and landing and descent phases. The overall structural pressure-bearing design requirements of the hatch, the thermal protection system design and thermal sealing technology, the repeated spreading and closing technology, the hatch locking mechanism and unlocking technology, and a series of key technology solutions can be more widely applied to the Space Shuttle, re-entry vehicles and various air and space reusable vehicles to improve the overall safety of the vehicle's full flight phase.

3. Heat Seal Materials Testing Technology

3.1 Progress in International Research

In 1991, NASA proposed ceramic wafer seals; In 1998, NASA evaluated the feasibility of thermal barrier seals at extreme transient temperatures [14], which verified the initial feasibility of carbon fiber braided rope in a 2500°F (~1370°C) sealing environment through flow, compression, and combustion tests, both of which were designed to be flexible and lightweight, and could operate at higher temperatures (2200°F) in stable operation, these seal concepts are the starting point for NASA's third generation of high-temperature seals to carry out under-mission planning and testing. In 2000, NASA designed a high-temperature baseline seal for use at its rudder and wing in the X-38 vehicle design session [15], which produced permanent deformation in a test at a peak temperature of 1900°F (~1038°C) for 7 minutes, meeting the one-time service life requirement for a high-temperature heat seal of a rubber seal. In 2005, NASA conducted an environmental seal test for the main door of the space shuttle landing gear [16], which specifically tested the leakage characteristics of the seal at different locations of the hatch, whether the mounting plate was slotted or not, and whether the seal was with support rounding, and obtained the seal leakage law of the P-seal under different conditions from the perspective of the test, where the variation of the seal leakage with the compression rate is shown in Figure 6.

From the figure, it can be seen that as the percentage of compression rate increases, the overall trend of leakage produces a decrease, with a sudden change at a compression rate of 25%. Among them, the best compression interval is 5%-25%, the compression rate is controlled within this interval, the best sealing effect. In 2006, NASA studied braided metal spring tubes in thermal barrier seals [17], and the thermal barrier seal material and metal spring tubes are shown in Figure 7. Its main purpose as an elastic structural support for the seal is to enhance the seal resilience at high temperatures [18] and effectively prevent the seal from crushing to produce permanent deformation, leading to seal failure. Based on the test data, it can be concluded that the baseline seal does not meet the strict design requirements for future vehicle use, and it was found in the tests that the high-temperature seal reaching its elastic limit could potentially lead to the re-entry of the re-entry vehicle into the atmosphere by leaking into harmful high-temperature gases, forcing the fuselage bottom system components to be exposed to excessive temperatures for a long time. Improved properties of the spring tube assembly can improve the seal resilience and thus control the leakage flow through high temperature compression tests [19-23].

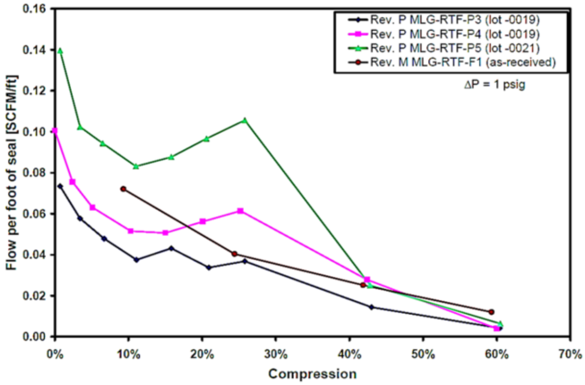
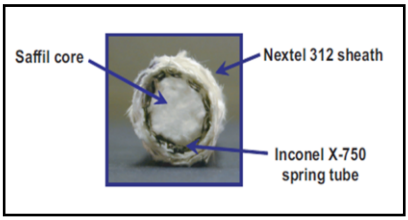
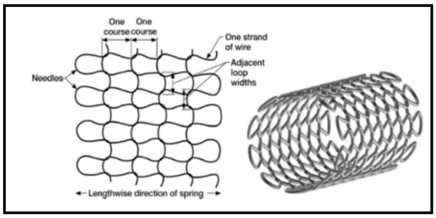


Figure 6. △P=1psig seal leakage diagram.



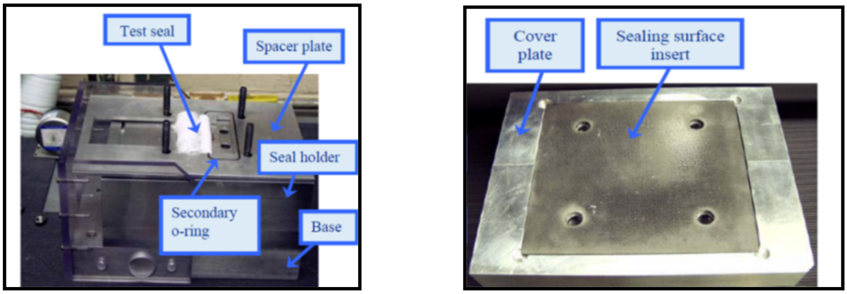
(a) Thermal barrier sealing rope structure.



(b) Braided metal spring tube structure.

Figure 7. Schematic diagram of the thermal barrier seal structure.

In 2007, NASA conducted and evaluated a relevant experimental study for spring tube insulation and an innovative wafer sealing system under relevant hypersonic test conditions (temperature, pressure, etc.) [24], and the specific test setup is shown in Figure 8. The test results showed that Nextel 440 seals had better load retention than Nextel 312, with load retention of 35%-40% and 19%-20% for the two samples to be tested, respectively, and an average reduction in leakage values of about 10%-20% for specimen 440, due to the slightly higher filling density of 440 compared to 312. In addition, high-temperature alloy seals suitable for dynamic sealing applications have been optimized by finite element techniques [25-32].



(a) Schematic diagram of test seal holder, spacer, and test sample.

(b) Schematic diagram of leakage fixture cover plate and sealing surface.

Figure 8. Schematic diagram of spring tube insulation sealing device.

Tracking NASA's research data on high-temperature heat sealing, NASA public information in 1989 involved the study of the Space Shuttle's Thermal Protection System (TPS), indicating that this agency's research in this area started earlier and initially grasped the general laws of sealing and leakage, laying a certain foundation for later scholars' research. In the period from 2000 to 2004, the main research was carried out for the thermal barrier seal rope (baseline seal) to investigate the influence of different properties and working conditions of the rope on the seal. One year later, NASA immediately started the research work on air pressure seal (environmental seal) to analyze the seal leakage characteristics of rubber P-ring under different compression rate and differential pressure conditions, and the flow of the research phase is shown in Figure 9.

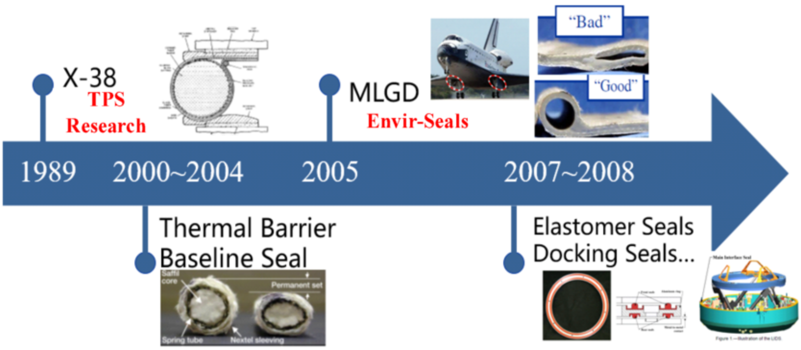


Figure 9. NASA Heat Seal Research Progress.

Three types of studies were conducted on the hatch heat seal, namely, the effect of whether the P-ring is dipped in rubber on the seal, the problem of permanent deformation of the P-ring at different locations of the hatch, the analysis of the effect of whether the P-ring is perforated on the leakage, and the analysis of other influencing factors.

(1) According to whether the P-ring is dipped in rubber or not, there are two kinds of seals, one is Rev. The test results show that: the seal dipped in rubber is more rigid, and the seal stress is too large during the compression process of hatch opening and closing, and the resulting problem is that the effective deformation range becomes narrow. In the process of designing the compression rate at a later stage, it is necessary to ensure that the seal works within the effective range to prevent the seal from deforming too much to produce permanent deformation and losing rebound capability leading to seal failure.

(2) Exploring the deformation of the seal in different positions of the hatch seal sub ring, the structure is shown in Figure 10. It can be seen from the figure that the deformation of the rocker support hinge position is larger and is an obvious leak sensitive point. The other positions of the hatch (front section, rear section, and inside and outside) also produce some deformation, but basically within the theoretical values. To evaluate the sealing performance of the hatch, it is necessary to consider the influence of structural deformation as well as thermal deformation on leakage from the overall structure.

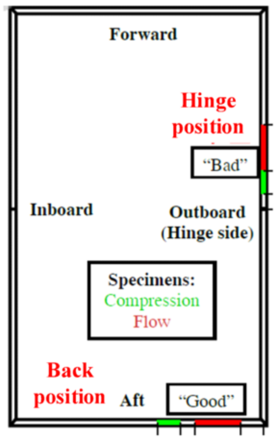


Figure 10. Deformation of seals at different locations of the hatch.

(3) With regard to whether the P-ring is perforated on the outside, two operating conditions were analyzed. For the different operating phases of the vehicle (ascent and descent) the internal and external pressures are different, and the direction of fluid leakage is also different. In the ascent phase, the inner pressure is higher, the air holes are opened and the seal is connected to the atmosphere; In the descent phase, under the action of the outer pressure, the air holes are inflated causing the seal to expand, which increases the contact stress of the seal and helps the seal to seal. The fluid leakage path is shown in Figure 11.

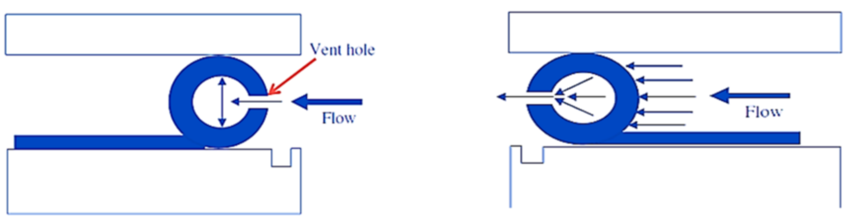


Figure 11. Fluid Leakage Path during Rise and Fall Phase.

To sum up, it is very important to carry out thermal seal test, which can provide qualitative and quantitative guidance for the design of hatch structure; the experimental test needs to be fully aligned with the actual working conditions to ensure the reference value of the final results; at the same time, the accuracy of the test research should be high, and the test should be repeatable for the later reproduction.

3.2 Domestic Research Progress

Domestic research institutions in the field of high-temperature thermal seal testing technology are mainly carried out in the following three aspects. Firstly, experimental tests are conducted for different sealing materials to evaluate the performance of seals in the field; Secondly, numerical calculations are used to simulate and analyze the sealing characteristics with the help of third-party finite element software; Thirdly, research is conducted for the unique properties of sealing materials, such as elastic rubber seals, high-temperature baseline sealing ropes, etc. In 2012, Liu Wei et al. conducted compression experiments on the overall structure for two models of hatch seal belts, the physical seal belt test pieces are shown in Figure 12, and the test data are shown in Figure 13, and the fitted model was brought into the finite element calculation to obtain the implicit response relationship between the secondary contact force of the door body and the door frame [33]. By analyzing the relationship between metal O-ring seal contact width and compression rate, domestic scholars Yanjun Liu et al. predicted that the contact width increases with the compression rate within a certain range, and the metal O-ring collapses when the compression rate exceeds the limit [34], and the seal structure is schematically shown in Figure 14.

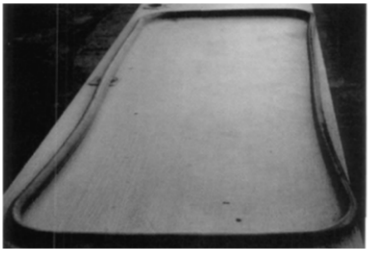


Figure 12. Physical diagram of the test piece of sealing tape.

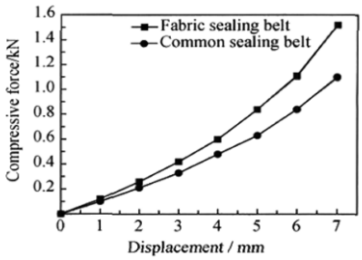


Figure 13. Load-deformation test curves of two types of sealing belts.

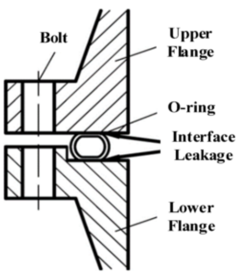


Figure 14. Schematic diagram of metal O-ring seal structure.

For the study of the law of resilience of elastic elements, it is necessary to conduct repeated compression tests under different operating conditions and prepare spring-like curves as shown in Figure 15. The results show that the rebound decay rate is closely related to the size of the spring wire diameter, 0.15 mm wire diameter at 33% compression, the rebound change rate is 0.6% after 7 repeated loads, and under the same loading conditions, the rebound decay rate of 0.2 mm wire diameter reaches 8.67% [35], the rebound decay rate of the elastic element is influenced by the compression amount, and the front view of the compressed condition is shown in Figure 16.

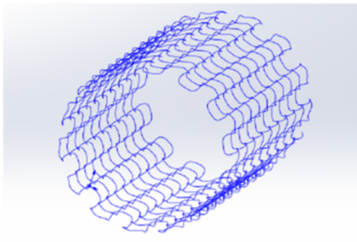


Figure 15. S braided spring tube model.

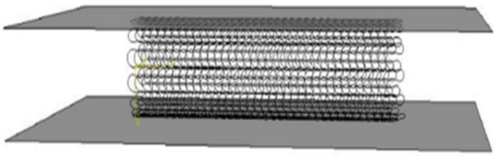


Figure 16. Front view of braided spring tube under pressure.

For the study of nonlinear contact problems of superelastomers, the study is analyzed by simulation with the help of ANSYS software, going through the process of modeling, Mold checking and modifying to derive the deformation of the seal at different compression rates. This part of the work is only a theoretical analysis and calculation, for the actual working conditions, the seal situation is more complex and the results of the analysis are bound to have errors when compared with the actual situation [36-38]. Therefore, in order to avoid the traditional three-dimensional finite element analysis method, the force situation of the seal is usually transformed into a plane stress problem, and the force required to compress the seal per unit length is found, and the compression force is equated to the pressure applied to the seal position that is the hatch seal load, and this method improves the calculation accuracy and seal load calculation efficiency [39-42].

4. Heat Seal Performance Simulation Technology

4.1 Progress in International Research

On January 28, 1986, the U.S. space shuttle Challenger exploded and burned 73 seconds after ignition and liftoff, killing all seven astronauts on board, making it the greatest tragedy in the history of spaceflight, and the reason for this tragedy was the faulty sealing ring of the solid rocket booster [43]. For the material of the seal, the commonly used materials are mainly fluoroelastomer, silicone rubber, fluorosilicone rubber, etc. Silicone rubber has excellent resistance to high and low temperatures, using temperatures between -70°C and 250°C. Considering the poor wear resistance of the rubber material, the fabric wrapping is used to reduce its damage and wear [44]. However, with the rapid development of spaceflight technology and the continuous improvement of spacecraft operating performance and requirements, the operating temperature of all parts of the spacecraft increases, which can easily lead to the sealing position being partially or fully higher than the normal operating temperature of the seal, and the old sealing solutions and materials cannot meet the existing sealing performance requirements, which leads to the failure of the sealing mechanism, leakage of the sealing medium, and other problems [45].

Especially the aircraft landing gear system in the landing phase, can effectively reduce the impact load with the ground, slow down the flight speed, can avoid the aircraft vibration and broken ring structure, so it is vital to improve the reliability of the landing gear system, one of the important aspects is to improve the reliability of the landing gear hatch seals. Landing gear hatch seals insulate the landing gear from high temperatures and also reduce the inflow of gases to prevent convection inside and outside the airframe; if the seals fail, they reduce the strength, stiffness, and performance of the landing gear structure, thereby endangering the safety and reliability of the aircraft [46]. Therefore, for the complex nonlinear mechanical properties of hatch seals, it becomes necessary to theoretically analyze their forces and deformations by means of finite element techniques, etc. [47].

4.2 Domestic Research Progress

The vehicle landing gear is the weakest mechanism, which is highly susceptible to leakage problems with serious consequences [48-49]. In 2020, Kaiyang Xiao et al. studied the sealing characteristics of the hatch of the manned module in the near space, focusing on the compression simulation analysis of the P-type rubber seal of the hatch, and the seal installation form is shown in Figure 17. The main study is on the law of the variation of the seal contact width and contact stress of the primary and secondary sealing surfaces with the hatch gap and hatch travel, while the total leakage model of the P-type rubber seal is derived by drawing on the ROTH leakage model, and finally the steady-state leakage value is calculated and compared with the hatch seal test to verify the validity of the model [50]. Among them, the ROTH given mechanism model is shown in Figure 18. For this model, the rough part of the sealing surface can be considered as consisting of flat equilateral corner cones that are flattened, and the air leakage channels are formed between the corner cones, and the slots of the leakage channels are the leakage cell slots [51-52].

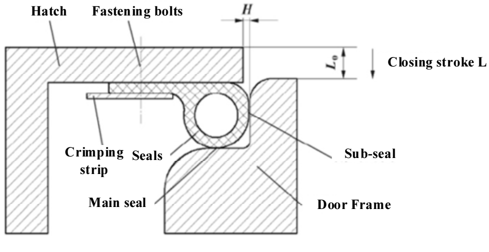


Figure 17. Schematic diagram of hatch seal installation.

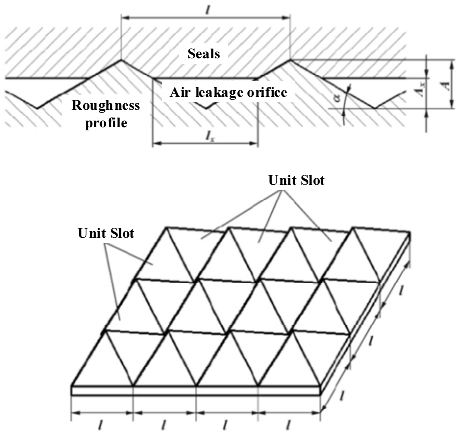


Figure 18. Schematic diagram of the hatch seal leakage channel.

In Figure 18, the total flow conductance of the seal is the result of connecting all unit slots in series and parallel in the seal area, and the unit slot flow conductance C_k [53] is shown in equation (1) and expressed as:

$$C_k = \frac{4}{3} v_{av} \frac{A^2 (\frac{A_x}{A})^3}{4(1+1/\cos\alpha)} \frac{1}{1-0.36(A_x/A)} \tag{1}$$

where A is the difference between the peak and valley heights of the unit trough; A_x is the penetration depth; α is the angle of the unit trough; v_{av} is the average velocity of the gas molecules; v_{av} is calculated in equation [54] (2):

$$v_{av} = 1.45 \times 10^4 \sqrt{\frac{T}{M}} \tag{2}$$

where T is the thermodynamic temperature and M is the molar mass. The penetration depth A_x/A is a function of the sealing pressure p_w and the gasket sealing coefficient R [55], as shown in equation (3):

$$\frac{A_x}{A} = e^{-\frac{p_w}{R}} \tag{3}$$

The re-entry vehicle in the return phase is extremely fast, the air is rapidly compressed, the boundary layer pressure is much larger than the pressure inside the seal structure, the great pressure difference drives the hot airflow through the seal structure, in the design process of the thermal seal structure need to consider the analysis of the force thermal environment, the selection of thermal seal materials, the seal material compression resilience and friction wear anti-corrosion properties, and finally complete the design of the complete thermal seal structure [56-58], the design method and process as shown in Figure 19.

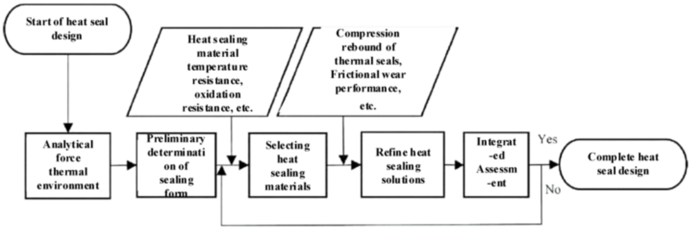
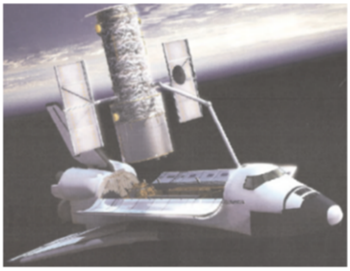
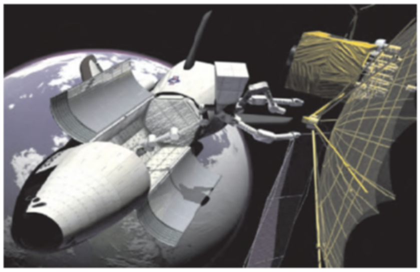


Figure 19. Flow chart of flight vehicle heat seal design.

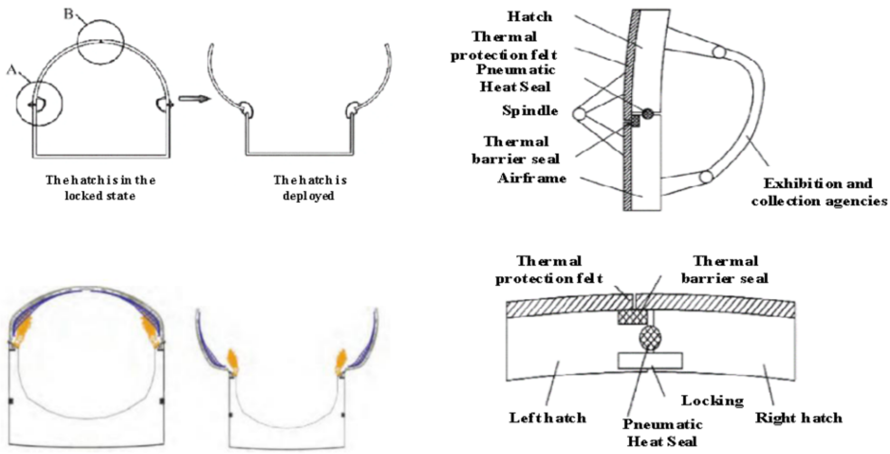
In addition, Baojiang Li et al. in Shanghai proposed key technologies such as overall design technology, thermal protection and thermal sealing technology, and repeated locking and unlocking for such structures in a comparative analysis of domestic and international research results on large-opening hatch technology for round-trip spacecraft [59]. For the payload bay hatch and sealing structure, see Figure 20, mainly consists of left and right hatches hinged on both sides of the center fuselage, which are locked to the centerline of the fuselage pair by a mechanical locking mechanism, and the centerline of the hatch as well as the surrounding gap are sealed by heat and pressure, and each hatch is equipped with a mechanism to drive the hatch to open or close laterally, which consists of a drive unit and six rotating actuators.



(a) Space shuttle hatch deployment schematic.



(b) Schematic of X-37B orbital test hatch deployment.



(c) Hatch opening and closing state. (d) Hatch connection position sealing structure.

Figure 20. Schematic diagram of the payload bay hatch and sealing structure.

The overall structure of the hatch tends to use composite materials for integral molding, which on the one hand helps to improve the rigidity and strength of the hatch, and on the other hand reduces the weight of the hatch. The hatch insulation material is generally glued directly to the hatch surface with the help of adhesive, and for the edge part most of the flexible materials are used for heat sealing [60-63]. In order to ensure that the temperature inside the load bay is at a reasonable level, so the hatch sealing structure mostly uses two seals to achieve the design solution. Thermal barrier seals reduce the temperature from 700°C to less than 120°C, and pneumatic thermal seals reduce the temperature from 120°C to less than 50°C. Heat barrier seal belongs to high temperature dynamic seal, generally for the internal heat insulation core, outer fiber heat insulation sheath and middle elastic element combination structure, air pressure heat seal mainly to achieve low temperature sealing, generally for the rubber material with certain temperature resistance to meet the ability of temperature resistance, heat insulation and sealing at the same time, Table 1 shows the summary of high temperature resistant heat insulation materials for typical aircraft.

Table 1. Thermal protection materials for typical aircraft.

Aircraft	Ultra-high temperature thermal protection materials	Large area thermal protection materials
X-51A	SiO2, carbon/carbon, tungsten (W)	Reuse of insulation, surface insulation mats, ablative materials
X-43A	Silicon carbide, tungsten	Aluminum Reinforced Thermal Barrier
X-33	CMC	Flexible insulation blanket(FBI)
X-34	SIR CAThermal insulation tiles	Advanced flexible reusable insulation blanket(AFRSI)
X-38	CMC,SiC Wall plate	SPFI

For hypersonic vehicles, due to their special operating environment and extreme conditions, they can be divided into five phases according to their functions and loads: ground preparation phase, launch phase, in-orbit segment, return segment and landing segment. The hatch state and the main load bearing for each phase are shown in Table 2, and the process requires consideration of multiple design constraints and multiple functional requirements.

Table 2. Functional profile analysis of the payload bay hatch at different stages of the mission.

Mission Phase	Main functional roles	Load bearing
Ground stage	Open with the help of auxiliary tooling	Ground operating loads and environmental conditions
Launch phase	Closed position, reliable locking	Carrier load, vibration, quasi-static load, differential pressure inside and outside the cabin
In-orbit operation phase	Hatch unlocking and unfolding, multiple spreading and closing in orbit	Space environment load (vacuum, high and low temperature, UV irradiation) variable orbit impact load
Return Phase	Closed position, reliable locking	Pneumatic power, pneumatic heat load, noise
Landing phase	Closed position, reliable locking	Landing shock load

5. Conclusion

To sum up, in the field of sealing and leakage, sealing is relative while leakage is absolute. It is essential to keep the leakage within the safe range by adopting certain technical means. At the same time, relevant experimental tests need to be conducted to verify the simulation results and ensure the accuracy of the results. In terms of test validation, foreign research institutions, mainly NASA, have carried out thermal compression tests (to identify changes in the resilience of seals with temperature, pressure, number of load cycles and prolonged static load), seal leakage flow tests (to identify changes in leakage flow with differential pressure, compression force, gap size, before and after wear or compression, and friction surface condition), high temperature dynamic seal test (to identify the thermal endurance in the corresponding environment, the wear effect due to the movement of the control surface, the effect of compression force and gap size, and to establish a database for pneumatic thermodynamic analysis), the compatibility test between the seal and the control surface material, the thermal wear test, and the thermal acoustic vibration test. In order to adapt to the development of hypersonic vehicles in the new environment, the following further work is needed in the research of hatch heat sealing structures.

(1) Research work on technical means and equipment for leak detection in orbiting vehicles;

(2) Investigation of the sealing retention capacity of heat-sealed structures within a certain range of deformation;

(3) Stability and longevity of heat seals under suitable materials and structures exposed to environmental loads in space for long periods of time;

(4) The coordination and cooperation between the heat sealing mechanism and the movement stroke of the spreading and closing mechanism and the locking mechanism, and the design and manufacture of reusable heat seals.

References

[1] Jinjin Xu. Design of aircraft landing gear hatch linkage mechanism and air tightness research. Nanjing University of Aeronautics and Astronautics, 2016.

[2] Chuntu Qiu, Zhenzhong Chen. Research on thermal structure design analysis techniques for hypersonic vehicles. Aircraft Design, 2012, 32 (06): 6-14.

[3] Fukui Chen, Huibing Zhang. An introduction to the sealing of aircraft hatch. Shandong Industrial Technology, 2013, {4} (12): 31.

[4] Xiaofang Li, Xiaoxiang Yang. Hyperelastic intrinsic model of rubber materials. Elastomers, 2005, {4} (01): 50-58.

[5] Dunlap P, Steinetz BM, Demange JJ. Advanced Control Surface Seal Development at NASA GRC for Future Space Launch Vehicles. 2003.

[6] Qinzhi Liu, Zhe Wang. Research on the technical requirements of civil aircraft structural sealing design. Aviation Standardization and Quality, 2017, {4} (01): 15-18.

[7] Wang LY, Wang JH, Yang BY. Dynamic sealing technology for hypersonic vehicle control surfaces. Aerospace Materials Technology, 2016, 46 (03): 1-6.

[8] DEMANGE JJ. Advanced control surface seal development for future space vehicles. NASA 20040182408, 2003 NASA Seal/Secondary Air System Workshop, Nov. 5-6, 2003.

[9] Steinetz BM. Seal Technology for Hypersonic Vehicle and Propulsion: An Overview. 2008.

[10] Fan, Li, Shuhao Wang, Jiangtao Chen, Guanghui Zhao, Huanguang Yu. Typical heat sealing structures for aircraft. Aerospace Materials Technology, 2013, 43 (01): 20-25.

[11] Martin AD,Abella RJ. Application of the Cost–Risk Network method to the thermal protection system of the Space Shuttle. Structure & Infrastructure Engineering, 2006, 2: 231-245.

[12] Fu JH, Graves GR. Thermal environments for space Shuttle payloads. AIAA - 85 - 6058, 1985.

[13] Liu H. A structural design comparison of metallic and composite aircraft pressure retaining doors. cranfield university, 2012.
[14] Steinetz BM, Dunlap P. Feasibility Assessment of Thermal Barrier Seals for Extreme Transient Temperatures. Journal of Propulsion and Power, 1998, 16 (2): 347-356.
[15] Dunlap, Patrick H, Steinetz BM, et al. Rudder/Fin Seal Investigations for the X-38 Re-Entry Vehicle. Aiaa Journal, 2001.
[16] Finkbeiner J, Dunlap P, Steinetz B, et al. Investigations of Shuttle Main Landing Gear Door Environmental Seals//41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. 2005.
[17] Taylor SC, Demange JJ, Dunlap P, et al. Further Investigations of High Temperature Knitted Spring Tubes for Advanced Control Surface Seal Applications. Aiaa Journal, 2006.
[18] Quankun Ba. Research on the performance testing method of high temperature seal. Beijing University of Chemical Technology, 2019.
[19] Demange JJ, Dunlap PH, Steinetz BM. Improved Seals for High Temperature Airframe Applications. Aiaa Journal, 2013.
[20] Glass D, Dirling R, Croop H, et al. Materials Development for Hypersonic Flight Vehicles// Aiaa/ahi Space Planes & Hypersonic Systems & Technologies Conference. 2013.
[21] Dunlap P, Steinetz BM, Demange JJ, et al. Toward an Improved Hypersonic Engine Seal. 2003.
[22] PHD Jr, Steinetz BM, Curry DM, et al. Investigations of a Control Surface Seal for Reentry Vehicles. Journal of Spacecraft and Rockets, 2003, 40 (4): p.570-583.
[23] Oswald JJ, Mullen RL, Dunlap P, et al. Modeling and Evaluation of Canted Coil Springs as High Temperature Seal Preloading Devices. 2004.
[24] Demange JJ, Dunlap PH, Steinetz BM, et al. An Evaluation of High Temperature Airframe Seals for Advanced Hypersonic Vehicles. aiaa journal, 2007.
[25] Mutharasan R, Steinetz BM, Tao X, et al.Development of braided rope seals for hypersonic engine applications Flow modeling. Journal of Propulsion and Power, 1993, 9 (3): 456-456.
[26] Steinetz BM, Melis ME, Orletski D, et al.High temperature NASP engine seal development. National Aeronautics&Space Administration Report, 1991.
[27] Adams ML, Olsen A, Darolia R, et al. High-Temperature Braided Rope Seals for Static Sealing Applications. Journal of Propulsion and Power, 1996, 13 (5).
[28] Finkbeiner JR, Dunlap P, Steinetz BM, et al.On the Development of a Unique Arc Jet Test Apparatus for Control Surface Seal Evaluations. 2004.
[29] Taylor SC, Demange JJ, Dunlap P, et al. Further Investigations of High Temperature Knitted Spring Tubes for Advanced Control Surface Seal Applications. Aiaa Journal, 2006.
[30] Demange JJ, Bott RJ, Dunlap PH. Investigation of the Mechanical Performance of Compliant Thermal Barriers. 2011.
[31] Dunlap, Patrick H, Steinetz BM, et al.Investigations of Control Surface Seals for Re-Entry Vehicles. 2002.
[32] Demange JJ, Dunlap PH, Steinetz BM. Advanced Control Surface Seal Development for Future Space Vehicles. 2003.
[33] Liu W, Liu CQ, Zhao XB, Xi BA, Yue Zu F. Study on the airtight reliability of aircraft hatch sealing structure. Materials Engineering, 2012, {4} (04): 47-51.
[34] Yanjun Liu, Guofeng Wu. Leakage model study of metal O-ring seal structure. Lubrication and sealing, 2019, 44 (09): 19-24.
[35] Li CN. Analysis and design of mechanical properties of elastic elements for heat sealing structures. Harbin Institute of Technology, 2020.
[36] Tongjiang Xu. Finite element analysis of O-shaped seal based on ANSYS. Shandong University, 2012.
[37] Yuchao Ke. Research on key performance and molding process of aviation rubber sealing structure. Tsinghua University, 2016.
[38] Xu JJ. Simulation analysis of contact behavior of hatch seals. Science and Technology Perspectives, 2018, {4} (16): 202+211.
[39] Aimin Guo, Weiwei Liu, Bo Peng, Di Wu, Jin Yin. Decoupling solution method for hatch seal load. Missile and Space Launch Technology, 2018, {4} (04): 18-21.
[40] Saifeng Dai. Research on aircraft hatch sealing requirements. Science and Technology Innovation, 2018, {4} (17): 56-57.
[41] Ying Ma. Aircraft hatch seal design research . Value Engineering, 2011, 30 (28): 29-30.
[42] Zenghui Wang. Simulation optimization design of aircraft hatch sealing tape. Special Rubber Products, 2019, 40 (01): 46-51.
[43] Naihong Wang. Seal ring failure leads to an aerospace tragedy. Quality and Reliability, 1986, {4} (04): 45-46.
[44] Yang Bai, Yang Pan. Analytical study on the hatch sealing structure of large wide-body passenger aircraft. Structural Engineering Committee of Chinese Society of Mechanics, Inner Mongolia University

of Science and Technology, Editorial Committee of Engineering Mechanics of Chinese Society of Mechanics, Department of Civil Engineering, Tsinghua University, etc., 2016: 4.
[45] Liu S, Yanjin Man, Weimeng Ma, Hui Yang, Zhaopu Guo. Study on the effect of compression rate and seal pressure difference on high temperature dynamic seal performance. China Aerospace Third Professional Information Network, China Association of Science and Technology Aero-engine Industry - Academia Consortium (preparation). Proceedings of the 40th Technical Exchange Meeting of the Third Professional Information Network of China Aerospace and the 4th Joint Conference of Air and Space Power - S10 engine internal and external flow integration related technology, 2019: 5.
[46] Zhe Wang. Aircraft structural sealing and failure repair. Civil Aircraft Design and Research, 2014, {4} (03): 73-76.
[47] Feng Huang, Ruosi Liu, Yuchao Ke, Chengxiang Li, Baofeng Dou, Huan Luo, Xuefeng Yao. Finite element simulation of compression behavior of hatch rubber seals. Aviation manufacturing technology, 2013, {4} (06): 83-88.
[48] Che Z. Landing gear bay, the death of the space shuttle . Knowledge is power, 2003, {4} (04): 24-25.
[49] Feng YL, Fang X. Analysis method of relative displacement of aircraft hatch structure. Applied Mathematical Mechanics, 2014, 35 (S1): 95-98.
[50] Kaiyang Xiao, Xiaoxiao Yuan, TY Wu, Jian Wu. Study on the sealing characteristics of the hatch of a manned module in near space. Lubrication and sealing, 2020, 45 (04): 118-124.
[51] Xiaoxiao Yuan, Kaiyang Xiao, Jian Wu. Hatch design based on manned vehicle in near space. Manned Spaceflight, 2018, 24 (02): 218-226.
[52] Xia Yang. The latest design of space shuttle seals. Vacuum and Cryogenics, 1991, {4} (02): 53-54.
[53] ROTH A. Vacuum technology. Beijing: Machinery Industry Press, 1979.
[54] Zhenghang Wen. Research on spacecraft seal analysis and in-orbit leakage detection technology. National University of Defense Technology, 2012.
[55] YG Bai, Ruping Pu. Leakage calculation of low vacuum tapered seals. Hydraulic and Pneumatic, 2012, {4} (05): 23-26.
[56] ZF Wang, Y Gao, XL Xu, ZW Gao, YC Gong, J Chen. Design methods and performance evaluation of high-temperature heat seals for spacecraft. Journal of Astronautics, 2018, 39 (07): 793-800.
[57] Shuo Han. Design and experimental verification of high-temperature heat seal structure. Harbin Institute of Technology, 2019.
[58] Zujun Peng. Design and analysis of high temperature dynamic seal structure. Harbin Institute of Technology, 2011.
[59] Baojiang Li, Jiming Shao, Changhuan Wang, Peng Huang. The key technology of large opening hatch for space shuttle vehicle and its solution. Journal of Aeronautics, 2016, 37 (S1): 8-15.
[60] W Lu, Q Zhong, JR Huang, HL Fan. Study on heat leakage in the sealed compartment of manned spacecraft. Journal of Astronautics, 2012, 33 (02): 145-152.
[61] Xuewen Sun. Hypersonic aerodynamic thermal prediction and thermal protection material/structure response study. University of Science and Technology Beijing, 2020.
[62] Bo Qiu. Numerical simulation study on the vortex structure and thermal environment inside the transverse slit of hypersonic vehicle. China Aerodynamic Research and Development Center, 2015.
[63] CN Li. Analysis and design of mechanical properties of elastic elements for heat sealing structures. Harbin Institute of Technology, 2020.