STUDY ON GAS PERMEATION CHARACTERISTICS OF 3D BRAIDED SEAL

JIAO Yanan 1, JING Yuanyuan1 and ZHANG Shihao 1

1 Key laboratory of Advanced Textile Composites, Ministry of Education, Tianjin Polytechnic University, Tianjin 300387, China
Email: jiaoyn@tjpu.edu.cn

Keywords: Thermal seals; 3D braiding; Structure design; Gas permeation; Computational modeling

ABSTRACT

The airtight of the three-dimensional braided preform as sealing material is studied in this paper. Connecting to actual situations, the braided sealing of six samples with fiber volume fraction of 50% were prepared by quartz fiber, which are 3D 4-directional structure, 3D 5-directional structure with different monofilament diameters and braiding angles. The gas leaking experiment was carried out. The gas permeability of the three kinds of structures on different pressure and different compression ratio is calculated and compared. The Results show that in the same volume fraction, the larger the braiding angle is, the larger the gas permeation is in the range of the same pressure difference with better the airtightness. Moreover, at the same compression rate, the monofilament is more compact, which increases the difficulty of the airflow passing through the sealing element. According to the improved permeability formula, the permeability of the seal with a single wire diameter of 7μm is reduced by a factor of 71.2% compared with that of a single wire diameter of 14μm. Comparing with measured and predicted gas permeation, the comparison showed that the predictions are in good agreement well with the experimental data.

1 INTRODUCTION

High temperature seals are required for advanced hypersonic airframe applications to avoid a lot of hot air leaking into the internal structure. High temperature sealing technology is the key technology of hypersonic aircraft [1, 2]. X-51A Waverider hypersonic flight failed the first test just because the thermal seal between the rear of the fuel-cooled engine and its vehicle mounted nozzle was not as tight as it needed to be. This caused some of the hot gases that should have provided thrust to leak into the rear of the cruiser [3]. NASA Glenn Research Center (GRC) became involved in the development of high temperature structural seals in the late 1980s and early 1990s during the National Aerospace Plane (NASP) program. In order to minimize core flow leakage around variable geometry of Advanced hypersonic propulsion system with variable flow path geometry, there are two main types of high temperature seals: ceramic seal and braided rope structure seal. But the ceramic pieces are brittle, whose compression is poor, which can not be used for high temperature seals at the corner. Through the study of scholars on the braided fiber rope seal test and theoretical research shows that, in meeting the requirements of sealing elasticity, the braided fiber rope seal can only adapt to the small changes in the gap of high temperature environment [4, 5]. Then a more flexible thermal barrier was developed. The baseline seal consisted of an Inconel X-750 spring tube stuffed with Saffil batting and over braided with two layers of Nextel 312 ceramic sleeving. Dunlap et al. [6] conducted a series of experimental studies. Research indicates that, after exposure at 1038°C for 7 min, the braided rope seal will be permanently deformed and loss of elasticity, which directly affects the safety and reliability of the aircraft during service. Figure 1 shows the spring tube thermal barrier and thermal barrier permanent set. Therefore, it is necessary to develop new high temperature sealing structure and carry out a large number of system research work.

3D braided preforms using high-performance fibers was receiving great attention as a result of a number of advantages [7-9]. Compliant seals are required high temperature, low-leakage to mitigate thermal stresses and control between structures. For the use of thermal seal properties, a new type of thermal seal with 3D braided structure was introduced [10]. In this study, the new structure heat seal is
designed. The gas permeation of 3D braided seals with different diameter of monofilament and braiding angle at room temperature was studied. According to Darcy’s Law, we present a computational model based on K-C equation and Kozeny theory for prediction [11]. The comparison showed that the predictions are in good agreement well with the experimental data. By analyzing the influencing factors of the gas permeation of the three-dimensional sealing structure, the structural design basis for the heat seal is provided.

![Figure 1: Spring tube thermal barrier and thermal barrier permanent set](image)

## 2 EXPERIMENT

### 2.1 Materials

The change in high-temperature seal performance is closely related to material properties. Ordinary rubber seals or metal seals can not meet the requirements of sealing and insulation at the same time, therefore, the choice of good temperature resistance of the material plays an important role in the high-temperature seal. Quartz fiber is a kind of the high-performance inorganic fibers with SiO$_2$ content more than 99.99%. Quartz fiber diameter is generally often only a few microns to tens of microns, acid-resistant and alkali-resistant (except KOH), light weight and high strength, good insulation and compression resilience, softening temperature of 1700 °C, and its superior temperature resistance is determined by the inherent temperature of SiO$_2$, which was used generally in 600 ~ 1050 °C with long-term. At high temperatures, quartz fibers do not shrink like high silica fibers, and at 1000 °C for 1000 h, the degradations is no more than 1.5%. This paper chooses 190tex hollow quartz glass fiber yarn, which was made by Hubei Felicity Quartz Glass Fiber Co., Ltd. Compared with solid quartz fibers, the hollow quartz fiber reinforced material reduces the dielectric constant and dielectric loss of the material further due to hollow (similar to pores), with low conductivity, light weight, high strength, high rigidity, suitable for light structural materials, insulation materials, the main parameters shown in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Linear density (tex)</th>
<th>Fibre density (g/cm$^3$)</th>
<th>Filament diameter (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B quartz fiber</td>
<td>95</td>
<td>2.2</td>
<td>9~14</td>
</tr>
<tr>
<td>Hollow quartz fiber</td>
<td>190</td>
<td>2.2</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Table 1. Parameter tables of 3D braided seals

### 2.2 Braided seal specimen

3D braiding seals were produced by the four-step 1×1 braiding technique using the 3D braided machine at the Institute of Composite Materials of Tianjin Polytechnic University (China). Six seal specimens (Figure 2) were made using 190 tex and 95 tex quartz fiber bundles. Three-dimensional braid surface structure of six seal specimens was shown in Figure 2 and specifications of test samples were labelled in Table 2, which is used to calculate the gas permeation of 3D braided seals in the subsequent sections.
<table>
<thead>
<tr>
<th>Sample number</th>
<th>structure</th>
<th>Yarn fineness(tex)</th>
<th>length(mm)</th>
<th>Fiber volume fraction / (%)</th>
<th>Braiding angle/ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D4A1</td>
<td>3D four-direction</td>
<td>190×2</td>
<td>300.00</td>
<td>50</td>
<td>19.95</td>
</tr>
<tr>
<td>D4A2</td>
<td>3D four-direction</td>
<td>190×2</td>
<td>300.00</td>
<td>50</td>
<td>24.35</td>
</tr>
<tr>
<td>D4A3</td>
<td>3D four-direction</td>
<td>190×2</td>
<td>300.00</td>
<td>50</td>
<td>30</td>
</tr>
<tr>
<td>D4A4</td>
<td>3D four-direction</td>
<td>190×2</td>
<td>300.00</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>D4A5</td>
<td>3D four-direction</td>
<td>95×4</td>
<td>300.00</td>
<td>50</td>
<td>29.1</td>
</tr>
<tr>
<td>D5A1</td>
<td>3D five-direction</td>
<td>95×4</td>
<td>300.00</td>
<td>50</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 2. Parameter tables of 3D braided seals

Figure 2: Three - dimensional braid surface structure of six seal specimens

2.3 Flow measurement

Since there are no definite standards of flow tests for 3D braided seal, the test procedures are conducted according to the standard of GB/T 25077-2010/ISO 9053:1991 and ASTM C522-03 (reapproved 2009). Flow test is carried out at room temperature, as shown schematically in Figure 3 [11]. Seal specimens were mounted in a specially developed test fixture, which were leak tested at various pressure conditions in the range of 0.01 - 0.15MPa and different amounts of linear compression. Air flows through the gap between the cartridge and the cover plate, passes through the seal, and then
flows out of the top of the fixture (Figure 3(b)). A flow meter upstream of the flow fixture measures the amount of flow that passes through the test seal. The flow meter has a range of 0–100 standard liters per minute (L/min) and accuracy of 1% of full scale. Test conditions and parameters are listed in Table 3.

![Diagram of flow fixture](image)

**Figure 3. Schematic of the flow fixture. (a) Flow fixture. (b) Isometric. (c) Cross section**

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Compression Ratio / (%)</th>
<th>Differential pressure/ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D4A1</td>
<td></td>
<td>0.01, 0.03,</td>
</tr>
<tr>
<td>D4A2</td>
<td></td>
<td>0.05, 0.07,</td>
</tr>
<tr>
<td>D4A3</td>
<td>10%</td>
<td>0.1, 0.12,</td>
</tr>
<tr>
<td>D4A4</td>
<td>20%</td>
<td>0.15, 0.17</td>
</tr>
<tr>
<td>D5A1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Test conditions and parameters

### 2.4 Gas permeation equation of 3D braided seals

A computational model based on K-C equation and Kozeny theory for prediction was presented in previous studies [12]. The permeation of gas through the 3D braided sealing strips can be expressed as follows:

\[ q_v = \frac{d_s^2 \phi_s^2}{30(1-\phi_s)^2} \frac{A}{2\mu L} \left( \frac{p_1^2 - p_2^2}{p_2} \right) (1) \]

\[ q_v = \frac{\Omega_1}{\Omega_2} \frac{d_s^2 \phi_s^2}{30(1-\phi_s)^2} \frac{A}{2\mu L} \left( \frac{p_1^2 - p_2^2}{p_2} \right) (2) \]

Where \( c_s \) is a dimensionless constant only relating to specific surface of 3D braided seals, \( \phi_s \) is porosity of 3D braided seals, \( d_s \) is the diameter of fiber of 3D braided seals, \( \mu \) is viscosity, which approximate to \( 1.79 \times 10^{-5} \) Pa-s, \( T \) is the thickness of 3D braided seal, \( P \) is pressure (MPa), \( \Omega_1 \) is the specific surface of 3D four-directional braided seals, \( \Omega_2 \) is the specific surface of 3D five-directional braided seals.
3 RESULT AND DISCUSSION

3.1 Effect of braided angle on gas permeation of three-dimensional braided seal

![Graph showing gas permeation and differential pressure](image)

**Figure 4(a):** Compression ratio 10% on the gas permeation of 3D braiding seals with different braiding angle

![Graph showing gas permeation and differential pressure](image)

**Figure 4(b):** Compression ratio 20% on the gas permeation of 3D braiding seals with different braiding angle

Figure 4(a) is the volume of 50%, three-dimensional structure of the direction of the four, respectively, the angle of knitting is 20°, 25°, 30°, 35°, the compression rate of 10% gas permeation and pressure difference curve. From this picture, the gas permeation of the four kinds of samples increases gradually with the differential pressure, and the change trend is consistent. Between 0.01MPa and 0.05MPa, the gas permeation of the four kinds of braided samples is approximately equal. However, between 0.05MPa and 0.17MPa, with the increase of braiding angle, the gas permeation of 3D braided seal is decreasing. In addition, between 0.05MPa and 0.17MPa, the gas permeation of each sample was more obvious than that of 0.05MPa before and after 0.17MPa. 35° of specimens compared with the 20°, the overall volume of the gas permeation decreased by 33.3%. Because of under the same volume fraction, the greater the braiding angle, the larger the specific surface. Three dimensional braided seal...
in the braiding angle of 20°, 25°, 30°, 35°, according to the formula (1) calculated by the specific surface were 2.16, 2.23, 2.35, respectively. For the porous structure of the material, the greater the specific surface is, the greater the blocking effect of the fluid, so the increase of three-dimensional braided seal angle to help increase the tightness.

Figure 4(a) is the volume of 50%, three-dimensional structure of the direction of the four, respectively, the angle of knitting is 20°, 25°, 30°, 35°, the compression rate of 10% gas permeation and pressure difference curve. From this picture, now the four specimen due to horizontal compression more, structure has reached a relatively close degree, so the airflow through the internal pore channel sample closed and difference of air tightness between the samples gradually decreases. Especially before the 0.09 MPa, the gas permeation the four samples was not very different. With the increase of the pressure difference, the 3D braided seal with the braiding angle of 35° still exhibits better air tightness and the gas permeation decreased by 16.6% compared with the braiding angle of 20°. It is shown that in the same volume fraction, the larger the braiding angle is, the larger the gas permeation is in the range of the same pressure difference with better the air tightness.

### 3.2 Effect of different diameter of monofilament on gas permeation of three-dimensional braided seal

![Graph](image)

Figure.5(a) compression ratio 10%, 20% on the gas permeation of 3D four-direction braiding seals with different diameter of single filaments

![Graph](image)

Figure.5(b) compression ratio 10%, 20% on the gas permeation of 3D five-direction braiding seals with different diameter of single filaments
As shown in Figure 5(a), 5(b) is in the 10%, 20% compression rate, in the same fiber volume fraction and structure, the different filament diameter on the gas permeation of the seal. From the picture, at the same fiber volume fraction, with the increase of the pressure difference, the volumetric flow rate of the four-directional and five-directional 3D braided seals showed an upward trend. At the same structure, the better performance of the three-dimensional four-directional braided seal of the filament diameter is better. At the differential pressure is 0.15MPa, the diameter of the single wire diameter of 7.5\(\mu\)m seal is smaller than that of the single wire diameter of 14\(\mu\)m, and the gas permeation is reduced by as much as 53.6%. In the 3D five direction structure, the gas permeation of 7.5\(\mu\)m sample comparing with the 14\(\mu\)m sample is reduced by 41%. The influence of monofilament diameter on the air tightness is more significant than the braiding angle. The reason is that when the monofilament diameter is smaller, the permeability of the three-dimensional braided seals is lower. The fiber volume fraction is the same, so that monofilament of the braided seals requires more. At the same compression rate, the monofilament is more compact, which increases the difficulty of the airflow passing through the sealing element. According to the improved permeability formula, the permeability of the seal with a single wire diameter of 7\(\mu\)m is reduced by a factor of 71.2% compared with that of a single wire diameter of 14 \(\mu\)m.

### 3.3 Comparison of measured and predicted gas permeation

![Figure 6(a). Seal D4A1 measured gas permeation compared to predictions](image1)

![Figure 6(b). Seal D4A2 measured gas permeation compared to predictions](image2)
Figure 6(c). Seal D4A3 measured gas permeation compared to predictions

Figure 6(d). Seal D4A4 measured gas permeation compared to predictions

Figure 6(e). Seal D4A5 measured gas permeation compared to predictions
From these pictures, we can see that the predicted values of all the samples are in good agreement with the measured values. The average value of six samples of differential pressure, gas permeation in all the average error between prediction and measurement is less than 10%, especially when the pressure is 0.01MPa to 0.12MPa, the average minimum error is 0.2%. After the differential pressure exceeds 0.17MPa, the predicted value is generally larger than the measured value. Analysing the reason, When the differential pressure increases to a certain extent, the gas permeation of measurement does not increase as much as the predicted result and gradually tends to a slow increase, indicating that the effect of the differential pressure on the gas permeation increasing gradually within a certain range and then decreases.

4 CONCLUSIONS

The gas permeation of the seals decrease with the increase of the braiding angle at same fiber volume fraction, the braiding structure and the monofilament diameter. In the case of a compression ratio of 10%, the sample with a braiding angle of 35° is reduced by an average of 33.3%. At the compression rate 10%, the braiding angle of 35° sample comparing with 20° reduced by 16.6%.

The airtight property of the seals is better with the finer the monofilament diameter, at same fiber volume fraction, the braiding angle and the braiding structure. When the differential pressure is 0.15MPa, and the seal of the monofilament diameter is 7.5μm, the gas permeation is reduced by 53.6% compared with monofilament diameter of 14μm in the three-dimensional four-direction structure. In the three-dimensional five-direction structure, the gas permeation reduced by 41%. And the influence of the monofilament diameter on the gas permeation of the seal is more significant. Through further comparison, it is shown that the model can be used to predict the gas permeation of the seal at different differential pressure.

ACKNOWLEDGEMENTS

Supported by Seed Foundation of Tianjin University (No.15ZCZDGX00340)

REFERENCES


References


