Research on the total leakage rate leak detection technology of the large spacecraft

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Abstract. The spacecraft is becoming bigger and bigger. This development trend brings us a strict challenge for the leak detection of spacecrafts, especially for the total leakage rate leak detection. So it is important to study the total leakage rate leak detection technology of the large spacecraft. In this paper, an idea on large flexible accumulation chamber was provided to overcome this strict challenge. But at the same time it also brings two key problems to be solved. That is how to build the large flexible accumulation chamber for accommodating the large spacecraft and whether the mixed helium gas concentration on the height direction in this flexible accumulation chamber is uniform because helium is lighter than air. The feasibility on building the large flexible accumulation chamber for the total leakage rate leak detection of the large spacecraft was firstly analyzed. Secondly, the mixed helium gas distributing rules on the height direction in the large accumulation chamber was also given from the theoretic analysis. Finally, a large flexible accumulation chamber was built for the total leakage rate leak detection of the large spacecraft and the six times repeatability tests were also finished. The results here indicated that the six times repeatability tests owned a well consistency and the large flexible accumulation chamber was suitable for the total leakage rate leak detection of the large spacecraft.

1. Introduction

With the development of the space technology, the spacecraft is becoming bigger and bigger. Nowadays the height of some spacecrafts is up to ten meters. This development trend brings us a strict challenge for the leak detection of spacecrafts, especially for the total leakage rate leak detection. As we all know, the non-vacuum accumulation method and vacuum method are both used for the total leakage rate leak detection of the spacecraft [1-4]. Among them, the non-vacuum accumulation method is widely used because of the low cost. But this method often needs a sealed rigid chamber. There are some problems for building the sealed rigid chamber, such as long building period and high building cost. So it is impossible to build a sealed rigid chamber for the total leakage rate leak detection of the large spacecraft. In practice, the traditional method is to divide the large spacecraft into several parts and make these parts leak detection respectively. But it cannot provide the actual total leakage rate. In this paper, an idea on large flexible accumulation chamber was provided to solve this difficult problem. The flexible accumulation chamber is also an effective method for the total leakage rate leak detection of the spacecraft [5-8]. The principle is to build a sealed flexible bag which can accommodate the large spacecraft firstly, then open the bag by various methods. How to build the large flexible accumulation chamber is a difficult problem. At the same time, there is also a key
problem that whether the mixed helium gas concentration in this flexible accumulation chamber is uniform from the height direction because of the gravity. In this paper, the two problems are both analyzed. Finally, a large flexible accumulation chamber was built for the total leakage rate leak detection of the large spacecraft and the six repeatability tests were also finished.

2. Building the large flexible accumulation chamber
The key to build the large flexible accumulation chamber is to open the sealed flexible bag. Now the open style is focused on the below two methods, namely the framework method and the hanging method (showed by figure 1 and figure 2 respectively). The specific operation steps of the framework method were as follows. The framework was installed firstly. Then the spacecraft was covered with the framework and a flexible film bag was put outside of the framework. Finally, the flexible film bag was sealed. The hanging method often consists of the flexible film bag, the string and chain wheels. Its operation steps were correspondingly simple. The chain wheels were fixed on the house firstly. Then a flexible film bag was hanged by strings with the help of the chain wheels. Finally, the flexible film bag was also sealed. The framework method owns the stable shape and the volume change in the leak detection process is little. Now NASA often uses this method. The hanging method owns the instable shape and large volume change. In China, some institutes use this method.

The framework used by NASA cannot be moved without the crane. It is also fixed, inner of the flexible bag, so this method is often discommodious in engineering. There is no framework for the hanging method. So this method can move expediently. But it needs an appropriate house to hang the sealed flexible bag. In this paper, a novel scheme was given. The framework consists of four pillars (showed by figure 3) with an extension-type rail on the top. The four pillars is liquid pressure and can ascend and descend expediently. The extension-type rail can also spread and fold expediently. The novel scheme of the large flexible accumulation chamber was showed by figure 4. There was a portiere in the front of the flexible bag and the large spacecraft can be in and out. Contrast to the other scheme, this flexible accumulation chamber can be moved expediently and was independent of the house. So this scheme owns better adaptability in engineering. The picture of the manufactured liquid pressure pillar was showed by figure 5.

Figure 1. The picture of the framework method used by NASA.

Figure 2. The picture of the hanging method.

Figure 3. The sketch map of the liquid pressure pillars.

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The uniformity of the mixed helium gas

The distributing rule on the density of the gas molecule with the height is as follows

\[ n = n_0 e^{-\frac{mgz}{RT}} = n_0 e^{-\frac{Mez}{RT}} \]  

(1)

where \( n \) is the density of the gas molecule, \( n_0 \) is the density of the gas molecule with the height \( z=0 \), \( m \) is the mass of the gas molecule, \( k \) is the Boltzmann constant, \( M \) is the molar mass of the gas molecule, \( g \) is the gravity, \( z \) is the gas height, \( R \) is the gas constant, \( T \) is the temperature.

The mixed helium gas concentration \( Y_{he} \) can be given by

\[ Y_{he} = \frac{n_{he}}{n_{he} + n_{air}} \]  

(2)

Combining with the equation (1) and equation (2), the following equation can be obtained

\[ \frac{Y_{he,z}}{Y_{he,0}} = \frac{n_{he,z} \left( n_{he,0} + n_{air,0} \right)}{n_{he,0} \left( n_{he,z} + n_{air,z} \right)} \]  

(3)

Assume that the density of the air is \( N \) times than helium with height \( z=0 \), namely

\[ n_{air,0} = N n_{he,0} \]  

(4)

Substituting the equation (1) and equation (4) into equation (3), it can be given by

\[ \frac{Y_{he,z}}{Y_{he,0}} = \frac{N + 1}{1 + N e^{\frac{gMZ}{RT}}(M_{he} - M_{air})} \]  

(5)

In the process of the leak detection, the helium concentration is only ppm order of magnitude. That is to say, \( N \) is often large, so the equation (5) can be described by

\[ \frac{Y_{he,z}}{Y_{he,0}} \approx \frac{1}{N + 1} \approx \frac{1}{N + 1} e^{\frac{gMZ}{RT}(M_{he} - M_{air})} \]  

(6)

According to equation (6), we can gain the relationship between the helium relative concentration and the different height. When the temperature is 293K, the relationship was showed in table 1. The detailed parameter values were as follows: \( g = 9.8m/s^2 \), \( R = 8.314J/(mol \cdot K) \), \( T = 293K \), \( M_{air} = 29g/mol \), \( M_{he} = 4g/mol \).
Table 1. Helium relative concentration with different height.

| Height (m) | Helium relative concentration (%) |
|------------|----------------------------------|
| 5          | 100.05%                          |
| 10         | 100.10%                          |
| 15         | 100.14%                          |
| 20         | 100.19%                          |
| 25         | 100.24%                          |
| 30         | 100.29%                          |
| 35         | 100.34%                          |
| 40         | 100.39%                          |
| 45         | 100.44%                          |

From table 1, we can find that even if the height is 30 meter, the relative concentration has only 100.29% and the relative error is only about 0.29% which can be ignored. That is to say, the thermal motion of helium molecule plays a major role compared with the gravity from the motion mechanism. So helium cannot be layered in evidence from the height direction because of the gravity.

4. Repeatability tests
A large flexible accumulation chamber showed by figure 6 was built and the size is about 5.5m(L) ×5.5m(W)×12m(H). A channel leak connecting to a gas cylinder (showed by figure 7) as the tested object was firstly calibrated by the metrology organization and the total leakage rate is $2.77 \times 10^{-7} \text{Pa} \cdot \text{m}^3/\text{s}$. Then the six times repeatability tests were made with this large flexible accumulation chamber. The process is similar to document [8] and the actual calculation equation is as follows

$$Q = \frac{w \times (u_2 - u_1)}{t (u_3 - u_2)}$$  \hspace{1cm} (7)

where $Q$ is the total leakage rate of the tested object, $u_1$, $u_2$, $u_3$ are the initial value, final value and sample value respectively, $w$ is the sample helium gas quantity, and $t$ is the accumulated time. The results were shown in table 2.

![Figure 6. Picture of the built flexible accumulation chamber.](image)

![Figure 7. Picture of the channel leak connecting to a gas cylinder as the tested object.](image)
From the above analyses, we can obtain:

5. Conclusions

From the above analyses, we can obtain:

- Helium cannot be layered in evidence from the height direction because of the gravity and can quickly diffuse.
- The large flexible accumulation chamber proposed here owns a good stability, accurate testing results and is suitable for the total leakage rate leak detection of the large spacecraft.

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References

[1] Underwood S and Lvovsky O 2003 40th Space Congress(Huntsville) 312
[2] Underwood S and Lvovsky O 2007 NASA-20070022572
[3] Dario B and Michele C 2007 58th International Astronautical Congress(Hyderabad) 115
[4] Underwood S and Lvovsky O 1998 20th Space Simulation Conference(Boston) 445
[5] Manganaro JL and HollingerDL 1967 NASA-19670028318
[6] Manganaro JL and HollingerDL 1968 NASA-19680015289
[7] Information on http://terra.nasa.gov/events/terraphotos5.php
[8] Wang Y, Shao R P, Yan R X, Sun L C, Li Z and Sun W 2012 Chinese Journalof Vacuum Scienceand Technology 32 118-122