IOP Conf. Series: Materials Science and Engineering **269** (2017) 012002 doi:10.1088/1757-899X/269/1/012002

Research on the Total Leakage Rate Test of the Spacecraft and its Uncertainty Evaluation

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Abstract. Leak testing is the major type of non destructive testing for spacecrafts and the sealing performance of the spacecraft is an important parameter to evaluate the quality of the spacecraft. So it is necessary to study the total leakage rate test of the spacecraft and its uncertainty evaluation. In this paper, the basic principle of the total leakage rate test of the spacecraft was analyzed firstly from the theoretical aspect. Secondly, the various influencing factors on the results of total leakage rate test had been systemically analyzed. Finally, through the uncertainty evaluation theory, the uncertainty components induced by these influencing factors were respectively quantified and combined. And the expanded uncertainty of the result of total leakage rate test was given.

1. Introduction

As we all know, leak testing is the major type of non destructive testing for spacecrafts and the sealing performance of the spacecraft is an important parameter to evaluate the quality of the spacecraft. A tiny leak may cause huge loss. So, in the AIT process of the spacecraft, it needs the strict leak testing for spacecrafts [1]. Nowadays, the non-vacuum accumulation leak testing method and vacuum leak testing method are widely used for testing the total leakage rate of spacecrafts, such as the hermetic cabin, propulsion pipeline system. The vacuum leak testing method is often used for Russian spacecrafts. But the above two kinds of method are both used for American spacecrafts [2]. Generally speaking, the non-vacuum accumulation leak testing method is used for spacecrafts which have low leakage rate demand, such as satellites and Node 1 of International Space Station [2-4]. While the vacuum leak testing method is used for these spacecrafts which have high leakage rate demand, such as Airlock Module and Laboratory Module of ISS [2]. In China，the total leakage rate test mainly adopts the non-vacuum accumulation leak testing method. Its testing system often includes accumulation chamber, leak detector, atmospheric reference gas, leaking gas sampling system and leakage rate calibration system. The basic principle is that: Helium gas is filled into the spacecraft using the Helium filling device. And the spacecraft is placed into the accumulation chamber. The initial value u_1 of the spacecraft is firstly measured with the leak detector, and after the accumulation time t, the final value u_2 is also measured. In order to quantify the total leakage rate of the spacecraft, a quantitative helium gas w is filled into the accumulation chamber, and the sampling value u_3 is measured after the gas in the accumulation chamber is mixed homogeneously. So the total leakage rate of the spacecraft Q is

$$Q = \frac{w(u_2 - u_1)}{t(u_3 - u_2)} \tag{1}$$

The sketch of the non-vacuum accumulation leak testing method is shown in figure 1.

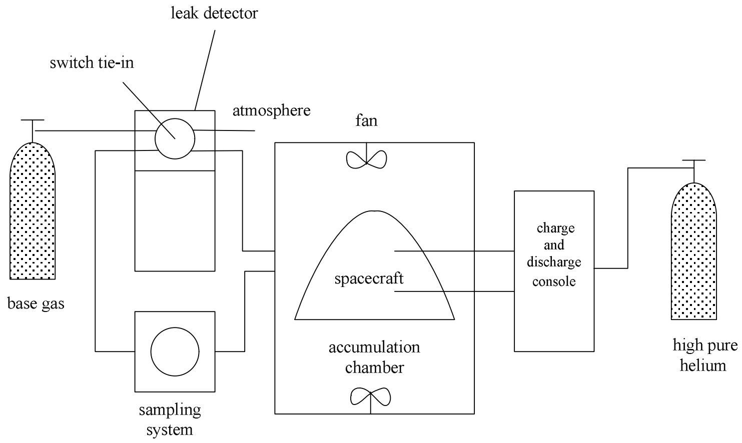

Figure 1. The sketch of the non-vacuum accumulation leak testing method.

All of the previous papers mainly focused on the application of kinds of leak testing methods but rarely referred to the uncertainty evaluation [2-4]. This paper tries to give the uncertainty evaluation process of the leak testing result.

2. Theoretical research on the non-vacuum accumulation leak testing method

The helium gas flow rate entering into the leak detector is

$$Q_{He} = \gamma Q_z = \gamma p_e S_z \tag{2}$$

where Q_z is the inlet mixed gas flow of the leak detector, S_z is the pumping speed of the leak detector, γ is the concentration of the mixed gas and p_e is the inlet pressure of the leak detector.

By literature [5], the measured value *u* of leak detector can be described by

$$u = kp_e S_z \gamma \tag{3}$$

where *u* is the measured value of the leak detector, k is the amplificatory factor of the leak detector. p_e can be adjusted by a fine adjustment valve. When p_e is fixed, the pumping speed S_z is also fixed.

Usually, k, p_e, S_z can be fixed, so the measured value of the leak detector is proportional to the measured helium concentration of the mixed gas.

Equation 3 can also be expressed by

$$u_i = kp_e S_z \gamma_i \quad (i = 1, 2, 3) \tag{4}$$

where i is free index, and denotes the initial value, final value and sampling value respectively.

The total leakage rate of the spacecraft *Q* can be described by

$$Q = \frac{p_{atm} V(\gamma_2 - \gamma_1)}{t} \tag{5}$$

where p_{atm} is atmospheric pressure, V is the effective volume which equals to the difference volume between the accumulation chamber and the spacecraft, γ_2, γ_1 denote the final and initial helium concentration in the accumulation chamber respectively and t is the accumulation time.

Because the total leakage rate of the spacecraft is very small and the effective volume is big, the pressure in the accumulation chamber changes little and almost equals to p_{atm}.

After accumulation time *t*, the accumulation chamber is filled by quantitative helium gas $w = p_0V_0$, then the helium concentration changes from γ_2 to γ_3. So we can obtain.

$$\frac{p_0V_0}{p_{atm}V} = \gamma_3 - \gamma_2 \tag{6}$$

From equations 5, 6, the total leakage rate of the spacecraft can be obtained by

$$Q = \frac{p_0V_0(\gamma_2 - \gamma_1)}{t(\gamma_3 - \gamma_2)} \tag{7}$$

With equation 4, the concentration can be instead by the measured value of the leak detector and we can obtain

$$Q = \frac{p_0V_0(u_2 - u_1)}{t(u_3 - u_2)} = \frac{w(u_2 - u_1)}{t(u_3 - u_2)} \tag{8}$$

The above derivation process is the quantitative principle of the non-vacuum accumulation leak testing method.

3. The analysis on uncertainty resources of the test results

Through the above analysis, the influence factors of the non-vacuum accumulation leak testing method are shown as figure 2. Among them, the white parts are the systemic factors and the yellow part is the random factor.

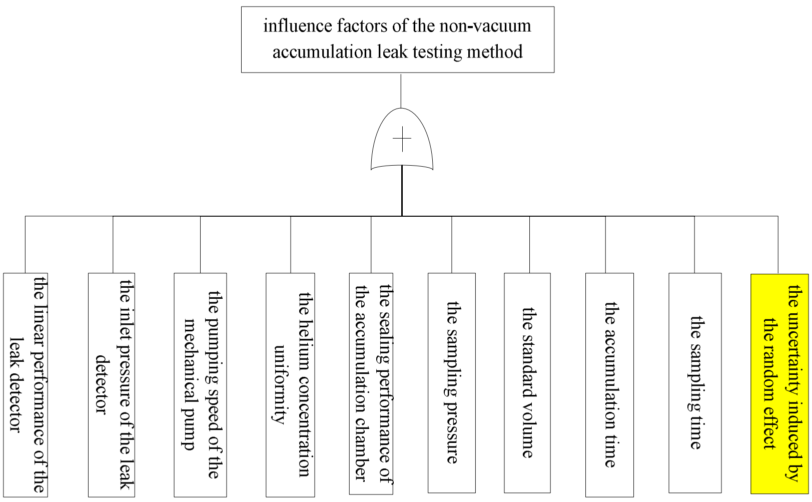

Figure 2. The influence factors of the non-vacuum accumulation leak testing method.

4. Uncertainty evaluation of the test result

4.1 Evaluation of the uncertainty induced by the systemic effect

4.1.1 Uncertainty component induced by the linear performance of the leak detector. With the type B evaluation method, the uncertainty component induced by the linear performance of the leak detector is about 5% [6].

4.1.2 Uncertainty component induced by the inlet pressure of the leak detector. In order to study the inlet pressure change of the leak detector, the following experiments are made in 30 minutes and the test data are shown in table 1.

Table 1. The test data of the inlet pressure change of the leak detector.

Number	The test value (Pa)	Maximum value (Pa)	Minimum value (Pa)	Average value (Pa)	Change value (Pa)	Relative change value
1	29.10, 28.54, 29.66, 27.98	29.66	27.98	28.82	1.68	5.83%
2	29.10, 28.54, 29.66, 27.98	29.66	27.98	28.82	1.68	5.83%

From table 1, the uncertainty component induced by the inlet pressure of the leak detector is $5.83\% / \sqrt{3} = 3.37\%$ if the hypothesis of uniform distribution is adopted.

4.1.3 Uncertainty component induced by the pumping speed of the mechanical pump. From the linear relationship between the inlet pressure and pumping speed, the relative change rate between them can be seen as the same. So the uncertainty component induced by the pumping speed of the mechanical pump is also 3.37%.

4.1.4 Uncertainty component induced by the helium concentration uniformity in the accumulation chamber. From the literature [7], the maximum deviation caused by the helium concentration uniformity is about 4.45%. So the uncertainty component induced by the helium concentration uniformity is $4.45\% / \sqrt{3} = 2.57\%$ if the hypothesis of uniform distribution is adopted.

4.1.5 Uncertainty component induced by the sealing performance of the accumulation chamber. In the design process of the accumulation chamber, the sealing performance usually demands that the pressure drop is less than 300Pa when the gas of 2KPa pressure is filled into the accumulation chamber. In practice, its sealing performance is often better than this demand. Conservatively, the design value is adopted to evaluate the uncertainty component induced by the sealing performance of the accumulation chamber. That is $300 / (100000 \times \sqrt{3}) = 0.17\%$. So the uncertainty component induced by the sealing performance of the accumulation chamber is 0.17%.

4.1.6 Uncertainty component induced by the sampling pressure. The level of the pressure sensor is 0.1, namely the corresponding relative error is 0.1%. So the uncertainty component induced by the sampling pressure is $0.1\% / \sqrt{3} = 0.06\%$ if the hypothesis of uniform distribution is also adopted.

4.1.7 Uncertainty component induced by the standard volume. From the calibration document, the uncertainty component induced by the standard volume is 0.001%.

4.1.8 Uncertainty component induced by the accumulation time. Usually the accumulation time of non-vacuum accumulation leak testing method is about 24 hours, while its error can be controlled in minute range, so the uncertainty component induced by the accumulation time is less than 0.1%. Conservatively, the uncertainty component induced by the accumulation time can be adopted by 0.1%.

4.1.9 Uncertainty component induced by the sampling time. From the literature [1], the uncertainty component induced by the sampling time is 2%.

From the above analysis, it can be found that the uncertainty component induced by the linear performance of the leak detector was biggest. So if we want to improve the correctness of the testing result, the most effective way is to improve the leak detector. The uncertainty induced by the systemic effect is

$$\begin{aligned} u_{Br} &= \sqrt{5\%^2 + 3.37\%^2 + 3.37\%^2 + 2.57\%^2 + 0.17\%^2 + 0.06\%^2 + 0.001\%^2 + 0.1\%^2 + 2\%^2} \\ &= 7.64\% \end{aligned} \tag{9}$$

4.2 Evaluation of the uncertainty induced by the random effect.

A tested object was tested by the non-vacuum accumulation leak testing method and the six results were given in table 2.

Table 2. The test results.

Number	1	2	3	4	5	6
Leakage rate ($Pa \cdot m^3/s$)	1.86×10^{-5}	1.65×10^{-5}	1.98×10^{-5}	1.82×10^{-5}	1.92×10^{-5}	2.00×10^{-5}

So, the arithmetic average value is $\bar{Q} = \frac{1}{n}\sum_{i=1}^{n} Q_i = 1.87\times10^{-5}$.

The standard deviation is $s(Q) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(Q_i - \bar{Q})^2} = 0.1284\times10^{-5}$.

The standard uncertainty is $u_A(\bar{Q}) = \frac{s(Q)}{\sqrt{n}} = 0.05244\times10^{-5}$.

The relative standard uncertainty is $u_{Ar}(\bar{Q}) = \frac{u_A(\bar{Q})}{\bar{Q}}\times100\% = 2.8\%$.

4.3 The combined standard uncertainty

$$u_{cr} = \sqrt{{u_{Br}}^2 + {u_{Ar}}^2} = \sqrt{7.64\%^2 + 2.8\%^2} = 8.14\% \tag{10}$$

4.4 The expanded uncertainty

$U = ku_c = 2\times8.14\% = 16.28\%$ $k = 2$, where k is the coverage factor.

5. Conclusion

In this paper, the basic principle of the total leakage rate test of the spacecraft was analyzed firstly from the theoretical aspect. Secondly, the various influencing factors on the results of total leakage rate test had been systemically analyzed. Finally, through the uncertainty evaluation theory, the uncertainty components induced by these influencing factors were respectively quantified and combined. And the expanded uncertainty of the result of total leakage rate test was given. The results indicated that the non-vacuum accumulation leak testing method was accurate enough to test the total leakage rate of the spacecraft and the expanded uncertainty of the testing result was only about 16.28%(k=2).

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Acknowledgements

This work was supported by the National Natural Science Foundation of China through Grant Number U1537109 and National Defence Technique Foundation of China through Grant Number JSJL2015203B019.