The estimation method of time of on-orbit spacecraft cabin decompression based on effective circulation area

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Abstract. This paper presented a method to estimate the pressure relief time of spacecraft cabin by testing a single component in the airway. Comparison between the theoretical prediction and experimental measurement indicates that there exits two methods which can effectively predict the pressure relief time of spacecrafts: measuring the effective flow area each single component or direct measurement of the effective flow area of the pressure relief system composed of single component. It also should be noted that the latter one can bring about a smaller error. Therefore, when conditions were met, the measurement and calculation of the system composed of components could more accurately predict the time required for the spacecraft pressure to drop to the target point.

1. Introduction
Pressure relief function is an important function of pressure control system of spacecraft with sealed cabin, and pressure relief time was one of the key indicators of spacecraft cabin pressure relief [1-4]. Subject to design boundary conditions such as installation location, safety, reliability, life and operability, the cabin pressure relief system was composed of a number of manual, electronic control valves and pipelines through series and parallel. The pressure relief path was zigzag, criss cross, the cross-sectional area was variable [5]. The estimation error of flow resistance was large because the common empirical formula was difficult to estimate the complex and changeable flow passage, and the pressure relief parameters calculated were difficult to be used in engineering design. Therefore, the effective pressure relief parameters were obtained through pressure relief tests, and the spacecraft body was usually placed in a large vacuum container in engineering [6-9]. But the method requires all piping and products were installed in place before the test, which needed a longer time. If the estimated test results were wrong before the test, a lot of resources will be consumed after several iterations of trial-design-retest.

Therefore, this paper presents a method to estimate the pressure relief time of spacecraft cabin by test, combining the measured flow capacity with the empirical formula. The method could shorten test cycle, reduced the number of trial iterations, saved test resources.

2. Test principle

2.1. System equivalent testing principle
The external cabin pressure of a spacecraft in orbit is \(P_{\text{out}} \leq 1.33 \times 10^{-6} \text{kPa}\), when the pressure is released from inside (\(P_{\text{in}} \approx 100 \text{kPa}\)) to outside meet \(P_{\text{out}}/P_{\text{in}}<0.528\), so the process of the pressure relief from...
inside to outside through the spacecraft pressure relief system could be regarded as the supercritical state. If the pressure relief system of the spacecraft was equivalent to a pressure relief hole with area and no thickness installed in the cabin, as long as the equivalent pressure relief hole area was obtained, the pressure relief time and other parameters of the supercritical state of the cabin could be calculated. The complex gas circuit of the pressure relief system could be simplified into a series and parallel composition of several pipelines and valve products. By setting up the test platform, the equivalent cross-sectional area of single pipeline and valve could be measured in the supercritical condition. The equivalent cross-sectional area of the whole system can be obtained by calculating the equivalent area in series and parallel. In this way, the pressure relief time of spacecraft cabin could be obtained through test and calculation of single product.

2.2. Thermodynamic analysis of pressure relief process
Spacecraft pressure relief was a variable process of vacuum exhaust from pressure-tight cabin. In engineering, it was usually treated by isothermal process or adiabatic process. When a gas was discharged into a vacuum, it expanded to do work, and the temperature dropped sharply and caused the temperature of the bulkhead near the pressure relief port to drop. The metal used in the cabin had better thermal conductivity, as the pressure relief progresses, the heat transferred from the pressure relief port was gradually balanced with the heat transferred from other parts of the bulkhead to the pressure relief port. Spacecraft shells and loads were mostly metal components. Large space stations, in particular, could weigh tens of tons. But that air was usually in the hundreds of kilograms, the heat capacity of spacecraft was much larger than that of air. After the local temperature of the pressure relief port was balanced with the whole cabin, the temperature had little effect on the whole cabin temperature, so the pressure relief of spacecraft in orbit could be analyzed by isothermal process. Figure 1 was the temperature curves of the pressure relief test process of a certain type of large cabin, the figure 1 illustrated the change of pressure relief port and whole tank temperature. Therefore, when the test design and result analysis were carried out in this paper, they were simplified according to the temperature process.

![Figure 1](image)

**Figure 1.** The temperature changes in large cabin vacuum pressure relief process.

2.3. Principle of equivalent cross section test
The single machine of equivalent test was worked in the supercritical flow. According to the method shown in figure 1, the pressure-tight cabin, products and vacuum tank needed to be set up. But it required higher quality equipment and the general laboratory was difficult to meet the demands [5,6]. So, the equivalent method in figure 2 was used in this paper. In the early stage of the re-pressure of the vacuum tank, the test was carried out in the supercritical state with the ratio of internal and external
pressure less than 0.528.

![Figure 2](image1.png)

**Figure 2.** Schematic diagram of testing methods of common pressure relief time.

The complex pressure of cabin could be simplified to isothermal and constant volume process under supercritical condition [10].

\[
t = \frac{V}{\mu ACR\sqrt{T}} \left( \frac{P_2 - P_1}{P_s} \right)
\]

(1)

Where \( t \) is repressing time, \( A \) is repressing the equivalent cross-sectional area of the product which was tested, \( V \) is repressing vessel volume, \( P_1 \) is repressing the starting, \( P_2 \) is repressing the stopping pressure, \( P_s \) is repressing air supply pressure and \( T \) is repressing temperature. \( \mu, C \) and \( R \) are constants. When testing different products on the same platform, the product of the equivalent area \( A \) and the repressing time \( t \) is a definite value. So an approximate standard leak could be made by measuring the repressing time, used

\[
A_t=t=A_s\tau_s
\]

(2)

The equivalent flow area of the tested machine could be got by calculating. This method could avoid the influence of empirical coefficients in the formula.

3. Test equipment and results

3.1. Test equipment

![Figure 3](image2.png)

**Figure 3.** Schematic diagram of test platform.
Figure 3 is a schematic diagram of the test platform. The pressure outside the vacuum tank was normal pressure. Therefore, when the pressure in the tank did not exceed 50 kPaA, the repressing airflow was supercritical state. In this paper, the repressing process from 1 kPaA to 20 kPaA was analyzed and calculated.

Electronic pressure relief valves, manual pressure relief valves and vacuum pipelines of aerospace products were selected to build the test platform. These products were widely used in real spacecraft. During the test, the entrances and exits were also set according to the gas flow direction equipped in real spacecraft. The standard hole diameter for testing was selected to be 50 mm, which was directly installed on the bulkhead of vacuum tank. In order to avoid the influence of valve on product testing, the gate valve with a diameter of 150 mm was selected as the control valve of pressure relief path.

3.2. Experimental procedure
The vacuum tank recharge processes from 1 kPaA to 20 kPaA were timed using only the standard hole, the valves and the pipe. Then the valves and the pipe were connected as one pipe system, the same recharge processes from 1 kPaA to 20 kPaA was timed using the pipe system. The test results are shown in table 1.

| No. | Name                          | Recharge time | Equivalent circulation area |
|-----|-------------------------------|---------------|-----------------------------|
| 1   | Standard hole                 | 58s           | 1962.5 mm²                  |
| 2   | the electronically controlled relief valve | 118           | 964.4 mm²                  |
| 3   | the manual relief valve        | 185           | 618.4 mm²                  |
| 4   | the pipeline                  | 184           | 615.1 mm²                  |
| 5   | the pipe system               | 289           | 393.8 mm²                  |

4. Analysis of the results

4.1. Calculation of equivalent circulation area
The equivalent circulation areas calculated by formula 2 was shown in table 1 according to recharge time of the vacuum tank. The equivalent circulation area of the pipe system $S_{ec}$, which was established by connecting the electronically controlled relief valve $S_1$, the manual relief valve $S_2$ and the pipeline in series $S_3$, was 397.5 mm². It is in accordance with the experimental measurement value of 393.8 mm².

$$\frac{1}{S_{ec}} = \frac{1}{S_1} + \frac{1}{S_2} + \frac{1}{S_3} \quad (3)$$

4.2. Pressure relief time calculation
Compared with the surface of the spacecraft cabin, the surface area of the pressure relief system is usually very small. The spacecraft cabin is usually made of metallic material with good thermal conductivity. Therefore, the spacecraft cabin could be treated as an isothermal process when it is decompressing on orbit. According to the pressure relief data of some Chinese spacecrafts, the temperature change of the cabin before and after pressure relief was less than 1 K, so the pressure relief of spacecrafts could be calculated approximately according to the isothermal process.

The on-orbit spacecrafts operate in a vacuum environment and the pressure relief process was in a supercritical state. The volumes of certain on-orbit spacecrafts are constant. According to Figure 1, temperature does not change much and the pressure relief process can be regarded as isothermal process. Therefore the pressure change of a cabin in a supercritical case in this paper is simplified to an isothermal constant volume process and the following formulas were applicable.

Volume flow rate $Q$ [11,12] can be expressed as
\[ Q = -\frac{1}{\rho} \cdot \frac{dm}{dt} = -\frac{V}{kRT \rho} \cdot \frac{dP}{dt} \quad (4) \]

In isentropic steady flow volume flow rate \( Q \) [11,12] can also be expressed as

\[ Q = 7.3 \times 10^{-3} S P \sqrt{\left(\frac{P_e}{P_s}\right)^{\frac{2}{k}} - 1} \cdot \frac{273}{T} \quad (5) \]

According to formulas (4) and (5), \( dt \) is expressed as formula (6).

\[ dt = -5.217 \frac{V}{kS} \sqrt{\frac{273}{T}} \cdot \frac{dP}{P^\frac{k-1}{2k}} \quad (6) \]

Integral operation is used to obtain cabin pressure relief time \( t \) [11,12], which is expressed as

\[ t = \frac{2k}{k-1} \left[ \left(\frac{P_e}{P_s}\right)^\frac{2k}{k-1} - 1 \right] \left(5.217 \frac{V}{kS} \sqrt{\frac{273}{T}}\right) \quad (7) \]

Temperature in ShenZhou-7 with 2 astronauts was controlled at 22.7°C in thermal tests [13], accordingly the air temperature was controlled at 23°C±0.5°C in this experiment. Adiabatic index \( k \) is considered as a fixed value at 23°C and under normal pressure. Therefore it takes 1.4 in this paper. \( V \) is the volume of the spacecraft cabin, \( S \) is the equivalent flow area of the relief channel, \( T \) is the absolute temperature, \( P_s \) is the initial pressure of the relief, and \( P_e \) is the pressure at the end of the relief.

The time of the cabin with a volume 90 m³ decompressing from 97 kPa to 27 kPa is 1136s, which is got by substituting the test data of table 2 (line 2,line 3 and line 4) into formulas (3) and (4). The time of the same process by substituting the test data of table 2 (line 5) into formula (3) is 1147 s.

In the course of Chinese spacecraft test, similar electronic pressure relief valves, manual pressure relief valves and pipelines are connected in series as pressure relief channels. After conversion, it takes about 1200s for the pressure relief system to complete the same pressure relief process.

| No | Test conditions | Equivalent flow area | Time | Remarks |
|----|----------------|----------------------|------|---------|
| 1  | Measuring the Equivalent Area of a Single Machine and Calculating the Equivalent Area of the System | 397.5 mm² | 1136s | The product is not ready |
| 2  | Measuring Equivalent Area of the pipe System | 393.8 mm² | 1149s | The product is ready |
| 3  | Measured data | - | 1200s | - |

The calculation methods and the results were compared in table 2. The results show that both methods can accurately predict the pressure relief time, but method 2 is more accurate. The measurement and calculation errors are smaller by using the pipe system for calculation, when the valves and pipes are ready. If they are not ready, the relief time can be effectively predicted by measuring the equivalent flow area of valves and pipes at different time or location.
5. Conclusion
The method of estimating the decompression time of spacecraft cabin by valves and pipes test was presented in this paper. The decompression time of a spacecraft can be effectively predicted by measuring both the equivalent area of the unit (valves and pipes) and the pipe-system. By comparing the calculated results with the measured results, the error of the latter method is smaller. Further research will be carried out on relationship between equivalent area and pipe-system. And then the decompression time of spacecraft cabin will be estimated more quickly and precisely.

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