

Pumping speed of cryopump for xenon

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Abstract: The xenon pumping speed testing system of the large-diameter external cryopump was designed to meet the plume test requirements for prototype electric propulsion. The flowmeter method was utilized to measure the xenon pumping speed. The test results show that the averaged effective pumping speed of double-cryopumps is 52 200 L/s, and that of single-cryopump is 27 100 L/s. The pumping speed ratio of two configurations is 1.93. It can be concluded that the pumping speed has in linear relationship with the number of cryopump, and the coefficient is irrelevant with the gas type. The averaged effective pumping speed of xenon is less than its nominal pumping speed, and the averaged pumping efficiency is 0.83. Under the identical inflow conditions, the averaged effective pumping speed ratio of nitrogen is 0.53, slightly less than the theoretical pumping speed ratio of 0.55. Consequently, it can be concluded that results assessment of large-diameter external cryopump design index can guide the engineering application, showing certain reference significance.

Key words: vacuum; plume; large-diameter external cryopump; xenon; pumping speed test

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The plume effect experimental system (PES) developed by the Beijing University of Aeronautics and Astronautics is a multipurpose testing apparatus. It is mainly used to test the plume effects of chemical propulsion and electric propulsion for aerospace attitude and orbit control engine^[1]. The horizontal cylindrical vacuum chamber has the inner diameter and length of 5.2 m and 12.6 m^[2], respectively. All the required vacuum environments are obtained by the vacuum acquisition system^[3]. The coarse vacuum pumping system is mainly composed of the roots pumps, the high vacuum pumping system is mainly composed of the large-diameter external cryopumps, and the ultra high vacuum pumping system is mainly composed of the internal cryopumps (including liquid nitrogen heat sink and liquid helium heat sink).

At present, the electric propulsion has become one of the main trends of space propulsion

technology. The electric ion propulsion mainly uses xenon as the working medium^[4-10]. Generally speaking, an electric ion thruster whose thrust is on the order of mN has a xenon volume flow rate of 14 mL/min under standard condition. During the tests, the dynamic vacuum degree in the chamber is required less than 5×10^{-3} Pa to ensure the measurement accuracy. In order to decrease the interference as much as possible, the tests should be performed without the heat sink. The PES only relies on the external type cryopump to maintain high dynamic vacuum degree.

As an important parameter of the external type cryopump, the pumping rate is not only related with the kind of gas, but also with the volume and installation position of the vacuum chamber. To improve the accuracy of the electric propulsion plume tests, the actual xenon pumping rate of the external type cryopump should

No.	Device	Performance index
1	Vacuum chamber	Inner diameter $\phi 5.2$ m, length 12.6 m.
2	Coarse vacuum pumping system	Two roots pumps each of which is composed of a WSU2001FC frequency conversion roots pump and a SP630 screw pump. The ultimate vacuum is better than 5 Pa.
3	High vacuum pumping system	Two 1250-type large-diameter external cryopumps, two TW1600 molecular pumps, a SL300 molecular pump, a SV40BI rotary vane pump. The ultimate vacuum is better than 5×10^{-5} Pa.
4	Xenon source	Stored in the xenon bottle, 99.999% purity, pressure 3 MPa, pressure reducing valve, gas supply pressure 0.2 MPa.
5	Flowmeter	Range 0~15 mL/min, calibration gas nitrogen, xenon conversion coefficient 1.431.
6	Hot cathode ionization gauge	Range $6 \times 10^{-8} - 1 \times 10^{-1}$ Pa, calibration gas is nitrogen, xenon conversion coefficient 2.71.

of 1250 mm, the national standard on the pumping speed measurement has not yet formulated.

Present paper used the flowmeter method to measure the xenon pumping speed. During the tests, the volume flow rate of the filled gas was taken as the standard value. External cryopump was started normally. When the chamber pressure was operating at or near the ultimate pressure, the pumping speed measurement was started. The xenon at a certain pressure and volume flow rate was injected into the chamber. The pressures at the specific positions in the chamber were measured using the hot cathode ionization gauge. When the chamber pressure was held at a constant value more than 10 min, the pressure was recorded, and imputed into the following equation to calculate the pumping speed of the external cryopump:

$$S = \frac{Q}{p - p_0} \quad (1)$$

where S is the pumping speed of the external cryopump (L/s); Q is the actual xenon flow rate ((Pa · L)/s), $Q = \frac{q_v \times 101325}{1000 \times 60}$; where q_v is the actual volume flow rate of the xenon (mL/min); p is the equilibrium pressure in the chamber at a certain volume flow rate (Pa); p_0 is the back pressure in the chamber (Pa).

The testing system adopted the CS200A-type mass flow controller whose effective range was 0~15 mL/min, response time ≤ 1 s, accuracy $\leq 0.5\%$. The mass flow controller was calibrated using the nitrogen. When it was used to control the xenon volume flow rate, the flowmeter reading should be modified using the following equation:

$$q_v = \sigma_1 q_0 \quad (2)$$

Where σ_1 is the correction coefficient, taken as $\sigma_1 = 1.431$; q_0 is the visual volume flow rate of the flowmeter (mL/min).

The DL-7 type vacuum gauge made in Peking University was used to measure the vacuum degree. Three ZJ12-type hot cathode ionization gauges whose effective range is $6 \times 10^{-8} - 1 \times 10^{-1}$ Pa were installed on the vacuum chamber.

At low pressure, the number of the positive ions ionized from the gas molecules is usually proportional to the density of the gas molecules. The hot cathode ionization gauge adopted this principle to measure the vacuum degree. Because the ionization gauge are selective for gas, the ionization potential for different gases are different, resulting in the existence of indication error.

At the factory, the ionization gauge used the nitrogen as the calibration medium. When the vacuum degree under the xenon environment was measured, the reading should be revised using the following equation:

$$p = \frac{p_2}{\sigma_2} \quad (3)$$

Where σ_2 is the xenon correction coefficient, taken as $\sigma_2 = 2.71$; p_2 is the visual pressure of the vacuum gauge (Pa).

2 Results and discussions

Figure 2 shows the photograph of the xenon pumping speed testing system. The xenon pumping speed was tested using double-cryopump and single-cryopump, separately, and compared to the nitrogen pumping speed.

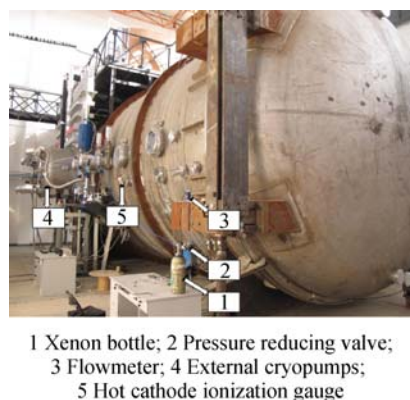


Fig. 2 Photograph of the xenon pumping speed testing system

2.1 Nitrogen pumping speed tests

To acquire the actual pumping speed ratio of the xenon to nitrogen, the nitrogen pumping speed was tested in advance. The nitrogen with a purity of 99.999% was supplied using the high-pressure nitrogen cylinder.

Two external cryopumps were started. When the chamber pressure reached 4.7×10^{-5} Pa, the nitrogen pumping speed was tested. The nitrogen volume flow rate ranged from 1–10 mL/min, and the testing results are shown in Fig. 3. With the increase in the nitrogen volume flow rate, the chamber equilibrium pressure increased gradually. The effective pumping speed of the double-cryopumps fluctuated in the range of 88 900~107 000 L/s, and the average effective pumping speed was 96 300 L/s. The effective pumping speed of the single-cryopump fluctuated in the range of 44 400~53 600 L/s, and the average effective pumping speed was 49 900 L/s. The effective pumping speed of double-cryopump was 1.93 times of that of single-cryopump. It can be considered that the pumping speed is proportional with the number of the pumps. The nominal pumping speed of the single-cryopump was 60 000 L/s (tested by the nitrogen at the factory) which was larger than its effective pumping speed. The average pumping efficiency of the external cryopump was 0.83, and the main reasons are as follows:

1) Effect of the flow state. At the factory, the nominal pumping speed was tested using the test cover, and the gas was viscous flow. While in the effective pumping speed measurement, the gas was molecular flow. The flow conductance in the molecular flow state was less than that in the viscous flow state, resulting in the decrease of the effective pumping speed of the external cryopump.

2) Effects of the vacuum chamber volume and installation position. The vacuum chamber volume in the effective pumping speed measurement was much larger than that in the nominal pumping speed measurement. Furthermore, the installation position of the external cryopump was some distance away from the relief port, resulting in the decrease of the gas space. The gas molecules requires more time to randomly arrive the condensing plate of the external cryopump, which decreased the effective pumping speed.

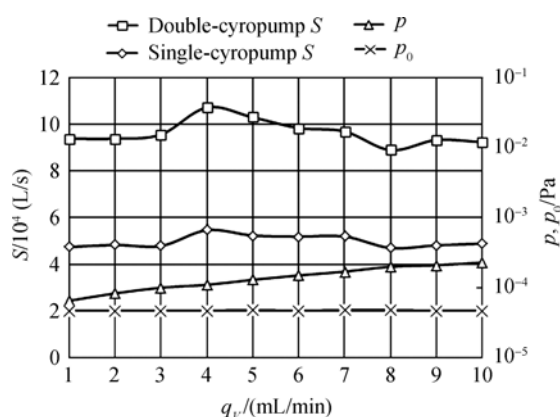


Fig. 3 Nitrogen pumping speed of the external cryopump

2.2 Xenon pumping speed tests

When the chamber pressure reached 1.9×10^{-5} Pa, the pumping speed of double-cryopump was tested, and the xenon volume flow rate ranged from 1–15 mL/min, as shown in Fig. 4. It can be seen that with the xenon volume flow rate increasing, the chamber equilibrium pressure increased gradually. The effective pumping speed of the single-cryopump fluctuated in the range of 46 300~58 300 L/s, and the average effective pumping speed was 52 200 L/s. When the chamber pressure reached 3.5×10^{-5} Pa, the pumping speed of single-cryopump was tested, and the testing results are shown in Fig. 5. The effective pumping speed of the single-cryopump fluctuated in the range of 24 700~29 200 L/s, and the average effective pumping speed was 27 100 L/s. The effective pumping speed of double-cryopumps was also 1.93 times as that of single-cryopump. It also can be considered that the number of the cryopumps has the linear superposition on the pumping speed, and the superposition coefficient is independent on the kind of the gas.

2.3 Pumping performance comparison of xenon and nitrogen

Figure 6 shows the xenon and nitrogen pumping speeds, respectively. It can be seen that under the identical gas volume flow rate, the nitrogen pumping speed is much larger than the xenon pumping speed. The effective pumping

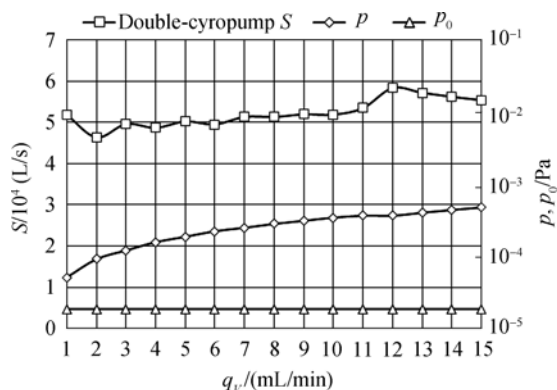


Fig. 4 Xenon pumping speed of the double-cryopump

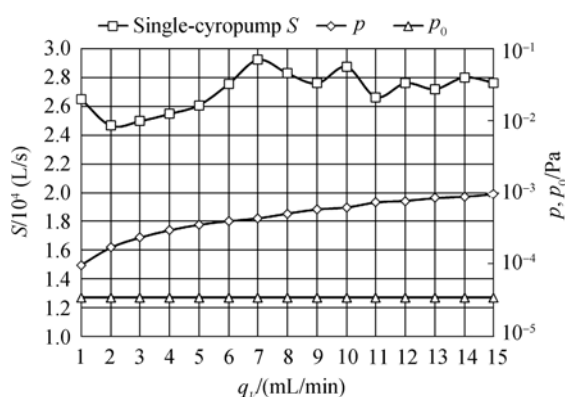


Fig. 5 Xenon pumping speed of the single-cryopump

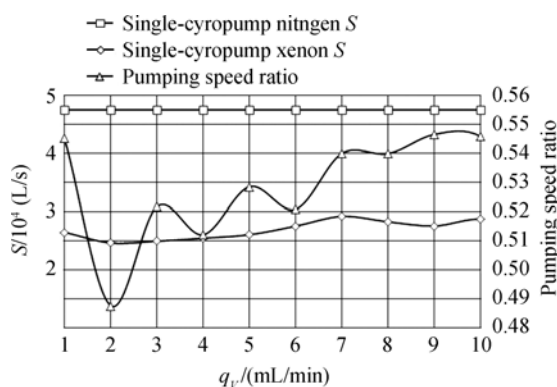


Fig. 6 Xenon and nitrogen pumping speed comparison

speed ratio fluctuates in the range of 0.49 ~ 0.55, and the average effective pumping speed ratio is 0.53.

The ideal pumping speed of the external cryopump under the molecular flow condition is calculated as follows^[16-19]:

$$S_m = 3.64 \times 10^4 A \sqrt{T/M} \quad (4)$$

Where A is the cold plate adsorption area of the external cryopump (m^2); T is the absolute

temperature of the pumping gas (K); M is the molar mass of the pumping gas, 28 g/mol for nitrogen, 131.3 g/mol for xenon.

Equation 4 has shown that in the external cryopump, the pumping speed of the condensation-adsorbed molecules is proportional to the square root of the temperature, and inversely proportional to the square root of the gas molar mass. Under the identical gas volume flow rate, the actual effective pumping speed ratio of the xenon to nitrogen is 0.53 which is slightly less than the theoretical value of 0.55.

3 Conclusion

A xenon pumping speed testing system of the large-diameter external cryopump was designed. The xenon pumping speed of the 1250-type large-diameter external cryopump was measured using the flowmeter method, and compared with the nitrogen pumping speed. Some main conclusions are obtained as follows:

1) The average effective nitrogen pumping speed of the single-cryopump is 49 900 L/s, which is lower than the nominal pumping speed of 60 000 L/s. The average pumping efficiency is 0.83.

2) The average effective xenon pumping speeds of the double-cryopumps and single-cryopump are 52 200 L/s and 27 100 L/s, respectively.

3) The average effective pumping speed of the double-cryopumps is 1.93 times as that of the single-cryopump. The number of the cryopumps has the linear superposition on the pumping speed, and the superposition coefficient is independent on the kind of the gas.

4) Under the identical gas volume flow rate, the xenon pumping speed is much less than the nitrogen pumping speed. The average effective pumping speed ratio is 0.53, which is slightly less than the theoretical value of 0.55.

The test results show that the pumping speed of the large-diameter external cryopump is mainly related with the kind of the pumped gas. Furthermore, the vacuum chamber volume and the installation position of the cryopump also

have some effects on the pumping speed. These conclusions have some reference significance to evaluate the design index of the external cryo-pump and guide the engineering application.

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