Numerical Simulation and Design of a Lunar Sample Unsealing and Processing Equipment

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Abstract. Lunar Sample Unsealing and Processing Equipment (LSUPE) is an equipment which is used to vacuum unseal the Vacuum Lunar Sample Container (VLSC) and to take pictures, weigh and process lunar samples. LSUPE is mainly composed of four parts, the transfer chamber, operate chamber, unseal chamber and gas purification system. The operate chamber needs to maintain a high-purity nitrogen environment all the times to prevent samples from being polluted by the atmosphere which affects subsequent analysis of the samples. The unseal chamber switches vacuum environment to high-purity nitrogen environment. The high-purity nitrogen environment ensures that the sample is not contaminated after unsealing, and the vacuum environment ensures that the VLSC can be unsealed. In order to ensure that the water and oxygen concentration indexes in the two chambers meet the requirements at all times after the lunar sample is unsealed, this paper gives the LSUPE simulation design process, and establishes a simulation calculation model for the water and oxygen concentration. The calculation results show that the internal water and oxygen concentrations of LSUPE are better than 10ppm in any state, which meets the requirements for storage and processing lunar samples.

1. Introduction
Since the 1960s and 1970s, the United States and the former Soviet Union have conducted many lunar sampling missions, such as the ‘Luna’ lunar sampling mission by the former Soviet Union and the ‘Apollo’ lunar sampling mission by the United States. After the sampling mission, large numbers of lunar samples have been collected which provides important research basis for the study of extraterrestrial resources, the evolution of the universe, the structure of matter, the origin of life and other major basic frontier scientific issues. China also proposed the mission of Chang’e lunar exploration, and proposed a three-step strategy [1] to achieve ‘encircle, fall, and return’. As the last step of the ‘three-step’ strategy, realizing the task of unmanned automatic sampling is the final goal of the third phase of the lunar exploration project [2]

Before the lunar dust samples are collected, they have been existed on the lunar surface for billions of years. When the samples return to the earth and contact the earth’s atmosphere, chemical reactions may occur. For example, the iron in the samples reacts with the oxygen in the air to produce iron oxides, minerals in the sample and water in the air react to form clay [3]. Chemical reactions affect the characteristics of the lunar sample and are of a great obstacle to the subsequent in-situ lunar sample analysis. Therefore, it is necessary to design an equipment that can ensure the water and oxygen contacting the samples are less than 10ppm, and the earth atmosphere will not pollute the samples.
According to the above requirements, LSUPE is designed. It is the core equipment in China's lunar sample laboratory, mainly used for unsealing and processing lunar samples. Lunar samples and operating devices are directly placed inside LSUPE to provide a high-purity nitrogen environment for lunar samples to ensure the lunar samples will not be contaminated by the earth’s atmosphere after unsealed.

2. Composition and function of LSUPE

LSUPE is mainly composed of 4 parts, transfer chamber, operate chamber, unseal chamber and gas purification system, as figure 1 shown.

![Figure 1 Lunar sample unsealing and processing equipment composition diagram](image)

The transfer chamber is the entrance and exit of the vacuum lunar sample container, tools, instruments and sample processing equipment. The transfer chamber is connected with the operate chamber by the door between two chambers. The operate chamber provides a high-purity nitrogen environment for separating and weighing the lunar sample to prevent the lunar sample from being oxidized. The operate chamber is also connected with the unseal chamber by the door between the two chambers. The unseal chamber mainly provides a vacuum environment for unsealing the vacuum lunar sample container. The gas purification system is used to establish and maintain high-purity nitrogen environment and micro-adjust pressure in the operation zone. The gas purification system connects the operate chamber by tubes to provide high purified nitrogen.

3. Analysis of water and oxygen concentration in operate chamber

After unsealing, the lunar sample is photographed, sampled, and weighed in the operate chamber. The gas in the operate chamber directly contacts the sample, so its water and oxygen concentration directly affect the sample contamination. In the initial stage of establishing high-purity nitrogen environment, the atmosphere in the operating chamber needs to be replaced by high-purity nitrogen. When the replacing process is balanced, the water and oxygen concentrations in the operate chamber are below 10ppm everywhere, so the sample will not be affected by water or oxygen in the atmosphere.

The nitrogen circulation interface of the operate chamber is shown in Figure 2. It adopts a top-in and bottom-out layout, that is, high-purity nitrogen flows in from the top inlet and out from the bottom outlet. In order to simulate the distribution of water and oxygen concentration in the operate chamber better, the structure, instruments, equipment and irrelevant interfaces in the chamber are simplified and only the inlet and outlet of high-purity nitrogen are retained. The computational meshing method is polyhedral mesh method [4-5]. In simulation calculation with FLUENT, the turbulence model is selected as k-omega, gas property is selected to be high-purity nitrogen containing 1ppm water and oxygen, and the outlet is set as the outflow boundary condition [6-7].
Figure 2 The gas inlet and outlet layout calculation model of the operating chamber

According to the working capacity of the circulating fan, the inlet air flow is set to be 90 m³/h for simulation calculation. Figure 3 shows water and oxygen concentration change over time during the purification cycle. It can be seen from the figure that establishing a high-purity nitrogen environment in the operate cabin, that is, the water and oxygen concentration is reduced to 10 ppm, takes about 10 hours. After 12.5 hours of purification, the water and oxygen concentration in the chamber is as low as 0.02 ppm and reaches a stable condition, which is suitable for lunar sample processing operations.

![Figure 2](image1)

Figure 3 When the purification system turns on, the water and oxygen concentrations decrease with time. When it goes 12.5 hrs, the water and oxygen concentrations stabilize after reaching 0.02 ppm

When the water and oxygen concentration in LSUPE is stable, the highest point of the water and oxygen concentration is located on the side wall of the high-purity nitrogen inlet, where the oxygen concentration is 0.05 ppm and water concentration is 0.05 ppm, as figure 4 shown. In design, the water and oxygen concentration sensors can be installed close to this position to monitor the water and oxygen concentration in the operation chamber in real time. In addition, an alarm system can be installed to send out an alarm when the water or oxygen concentration exceeds 10 ppm, so the experimenter take emergency measures to protect the samples from contamination.
4. After unsealing, air concentration design

Since the sampling work is performed on the surface of the moon in the pressure of $1 \times 10^{-9} \text{Pa} \cdot \text{m}^3/\text{s}$\textsuperscript{[8-9]}, the internal pressure of the vacuum lunar sample container is about to be $1 \times 10^{-9} \text{Pa} \cdot \text{m}^3/\text{s}$ in theory. Taking into account the leakage rate of the sealing container on the way back, the outgassing of the material and the lunar sample, the gas penetration through the material, and the time to return to the ground, the internal pressure of the vacuum lunar sample container is estimated to be $10^{-2} \sim 20 \text{Pa}$\textsuperscript{[10]}. Therefore, the lowest pressure of the unseal chamber is designed to be $10^{-3} \text{Pa}$.

After unsealing the VLSC, open the valve between the operate chamber and the unseal chamber. The high-purity nitrogen in the operate chamber enters the unseal chamber through the valve. When the pressure on both sides is equalized and reaches an atmospheric pressure, the maximum water and oxygen concentration in the LSUPE are less than requirements to avoid sample contamination.

The calculation grid is still selected as a polyhedral grid. The turbulence model is selected as k-omega model in FLUENT, and the gas property is selected as nitrogen. The inlet gas content is high-purity nitrogen, containing 1ppm water and 1ppm oxygen. The outlet is set as outflow boundary condition.

Simulation result shows that when the valve opens, the water and oxygen concentration (calculated as a whole set) rises shortly, and the maximum concentration is 0.09ppm. As the gas purification unit works, in 106 seconds, the water and oxygen concentration drop to 0.08ppm, the maximum water and oxygen concentration does not exceed 10ppm, which meet the requirements of lunar sample storage and processing, and will not pollute lunar samples.
5. Conclusion
According to China’s lunar sample unsealing and sample processing requirements, a proposal which is suitable for China's subdivision, vacuum unsealing and nitrogen environmental protection was proposed. And an environmental simulation analysis on the scheme is carried out, which includes the sensor installation location and the correctness of the design. Through the analysis above, the LSUPE can meet the requirements of unsealing and sample processing.

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