Analysis of the Vacuum Chamber Based on the Environmental Simulation Experiment of the Lunar Surface

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Abstract. The vacuum chamber based on the environmental simulation experiment of the lunar surface mainly provides the simulation space for the comprehensive environmental effect tests such as vacuum, low temperature, irradiation and charged dust, and provides the interface for the relevant environmental sources, in-situ testing instruments, etc. In this paper, a set of vacuum chamber for the experiment is provided, and the finite element analysis, surface temperature analysis and radiation dose analysis of the chamber are carried out. The analysis results provide a guarantee for the experiment and a reference for the related research work.

1. Foreword
With the planning and development of the future manned lunar exploration mission in China, it is necessary to carry out the research work of lunar surface environment simulation experiment technology [1]. The lunar surface environment simulation experiment is mainly used to simulate the comprehensive environment and effects of various factors on the lunar surface, such as vacuum, low temperature, electronic radiation, ultraviolet radiation, X-ray radiation, charged dust, etc, and carry out scientific research on the physical theory and effect of lunar surface dust, dust plasma, etc.

The vacuum chamber (VC) is one of the main subsystems of the experimental equipment, which provides simulation space for the comprehensive environmental effect test of the lunar surface, such as vacuum, low temperature, electronic radiation, ultraviolet radiation, X-ray radiation, charged dust, etc [2], and provides interfaces for relevant environmental sources, in-situ testing instruments. In the process of the experiment, the VC is in the environment of vacuum, low temperature, irradiation and dust, so it needs to carry out the finite element analysis, surface temperature analysis, radiation dose analysis to verify whether it meets the requirements of the experimental environment. As long as we pay attention to the protection and cleaning, the dust will not affect the VC, so this paper will not discuss.

2. Structure of VC
According to the experimental requirements, the VC is designed to be vertical, with an inner diameter of φ4m and a straight section of 5m high, supported by six supports. The test piece and personnel enter and exit through the φ3 m gate on the side. Shroud, guide rail and lifting points are installed inside the VC, and interfaces are provided for the thermal system, vacuum system, measurement and control system, relevant environmental sources, in-situ testing instruments, etc [3,4]. Its structure is shown in Figure 1.
3. Finite element analysis
The structure of VC is complex, so the traditional mechanical analysis method can’t be used to analyse it. However, the finite element method has its unique advantages in the analysis of stress, displacement and anti-instability ability of large VC [2].

Next, we build the finite element model of the VC, and carry out stress analysis, displacement analysis and buckling analysis.

3.1. Applied load
After modeling, set the boundary conditions of the model, constrain the six degrees of freedom of the supports, and set the load conditions of the model:

1) Apply 5 tons of test piece load evenly on the guide rail of the VC;
2) Apply 7 tons of shroud load evenly on the inner wall of the VC;
3) Apply 1 ton of low cryogenic pump load on each Dn500 interface flange;
4) Apply 1 ton load on lifting points;
5) Apply 0.8 ton load on each Dn1100 interface flange;
6) The loading directions described above are all vertical downward, and define the weight of the VC itself;
7) Since the VC is in the vacuum state during the experiment, an external pressure of 0.1MPa is applied to it.

Additional material properties for the model: the material of supports and stiffeners is Q345, and the material of other structures is S30408.

3.2. Stress analysis results
The overall stress distribution of the VC and the location of the maximum stress are shown in Figure 2. The maximum stress is 102 MPa, which appears above the joint of DN1100 interface flange and cylinder, and is lower than the yield strength of S30408 by 205 MPa [5].

3.3. Displacement analysis results
The overall displacement distribution and the position of the maximum displacement of the VC are shown in Figure 3. The maximum deformation displacement is 1.36 mm, which appears on the left side of φ3 m gate.
3.4. Buckling analysis results

The VC belongs to external pressure vessel. There are two main failure modes of external pressure vessel: one is the failure caused by insufficient strength, that is, when the compressive stress of the shell reaches the yield strength of the material, the vessel structure will be damaged, but this failure mode is rare; the other is that the shell loses its original shape due to insufficient rigidity, resulting in instability (buckling). For thin-walled vessel, the instability always occurs before the strength failure, so the stability calculation is the primary problem to be considered for the thin-walled vessel [6,7].

Under the given load of the project, extract the natural frequency and mode of the model, conduct linear buckling analysis, and obtain the corresponding critical instability factor of 26.504, as shown in Figure 4. The main load corresponding to the buckling mode is 0.1 MPa external pressure, so the critical load of the VC \( P = 0.1 \times 26.504 = 2.6504 \) MPa. Through the linear buckling analysis above, it can be seen that the instability of the structure will not occur under the existing conditions.

4. Surface temperature analysis

The low temperature environment is one of the essential simulation environment conditions in the lunar surface environment simulation experiment equipment [8]. The experimental equipment uses shroud to simulate the cold black environment in space, and provides 100 K low temperature background for the experiment by injecting liquid nitrogen into the shroud. There is a low temperature background formed by shroud in the lower half and bottom of the equipment: the effective space of the cylinder shroud is \( \Phi 3500 \text{ mm} \times 3100 \text{ mm} \). The structure and location of shroud are shown in Figure 5.
Next, we will analyse the temperature effect of shroud on the VC. The grid model of heat radiation is shown in Figure 6.

![Figure 6. Grid model of heat radiation.](image)

When the natural convection heat transfer coefficient $h=2 \text{ W/(M}^2\text{K)}$ (ventilation condition is poor) [9], the calculation results are shown in Figure 7. The surface temperature of the lower part of the VC is close to the ambient temperature of 300 K due to the radiation proof screen. The upper part faces the inner wall of the shroud directly, the surface temperature decreases obviously, and the lowest temperature is 280 K (about 7 °C).

When the natural convection heat transfer coefficient $h=5 \text{ W/(M}^2\text{K)}$ (the ventilation condition is general), the calculation result is shown in Figure 8. The minimum temperature of the surface of the VC is 290 K (about 17 °C). Compared with the working condition with poor ventilation condition, the heat transfer efficiency between the VC and the environment is higher, so the temperature is improved.

![Figure 7. Cloud chart of thermal radiation effect, h=2 W/(M}^2\text{K).](image)

![Figure 8. Cloud chart of thermal radiation effect, h=5 W/(M}^2\text{K).](image)

According to the above analysis, when the ventilation condition is poor, the minimum temperature of the VC is 280 K (about 7 °C); when the ventilation condition is general, the minimum temperature of the VC is 290 K (about 17 °C).
5. Radiation dose analysis

5.1. Set conditions for the model
In the simulation experiment of lunar surface environment, the radiation source is 200 keV electron source and 80 keV X-ray. Because the dose rate of X-ray is three orders of magnitude lower than that of the electron source, this paper only analyses the electron source with high dose rate.

The electronic source is installed on the side of the VC, and the angle between its axis and the axis of the VC is 45°. The simulation of the irradiation area is shown in Figure 9.

![Figure 9. Irradiation area of electron source.](image)

The model conditions of the electronic source are:
1) The range of electron energy is 30-200 keV, and the error of output energy stability is less than ±0.5%;
2) The maximum current intensity is 15 mA, and the minimum regulation current precision of filament is ≤0.1 mA;
3) The size of irradiation surface is 1000 mm * 1000 mm, which is about 3500 mm away from the exit of electron beam.

5.2. Dose rate distribution
The ionizing radiation produced by the electron source is calculated by FLUKA software, and the secondary radiation produced by the electron source is also calculated. Three different ways are used to represent the radiation dose rate distribution inside and outside the VC.

The first is the longitudinal section, and the dose rate distribution of the longitudinal section where the incident angle is located is shown in Figure 10.

![Figure 10. Dose rate distribution of longitudinal section, mSv/h.](image)
The second is the transverse section. Take the transverse section of the key position of the VC for analysis. See Figure 11 for the detailed position and table 1 for the dose rate distribution of each height.

**Figure 11.** Location of transverse section.

**Table 1.** Dose rate distribution of transverse section.

| Height (mm) | Dose rate outside VC (mSv/h) | Dose rate in VC (Sv/h) | Dose rate distribution |
|-------------|------------------------------|------------------------|------------------------|
| 730         | 0-10                         | 1-10                   |                        |
| 2400        | 0-10                         | 1-100                  |                        |
The third is the circumferential section. The dose rate distribution in different radius sections is shown in Figure 12-Figure 14. In the figure, the x-axis is the height and the y-axis is the angle.

**Figure 12.** Dose rate distribution of R=7000 mm, mSv/h.

**Figure 13.** Dose rate distribution of R=5000 mm, mSv/h.

**Figure 14.** Dose rate distribution of R=3500 mm, mSv/h.
5.3. Analysis of calculation results
The radiation of VC mainly comes from 200 keV electron source, and the radiation dose rate level in VC is 1-100 Sv/h. Because the stainless steel wall of the VC attenuates the radiation of 200 keV electron greatly, the radiation dose rate level outside the VC is 1-10 mSv/h.

6. Conclusion
This paper introduces a set of VC used in the environmental simulation experiment of the lunar surface, and analyses it. The analysis contents include: stress analysis, displacement analysis, buckling analysis, surface temperature analysis, radiation dose analysis. The analysis results are as follows:
1) The maximum stress of the VC is 102 MPa, which appears above the joint of DN1100 interface flange and cylinder, which is lower than the yield strength of S30408 by 205MPa;
2) The maximum deformation displacement is 1.36 mm, which appears on the left side of φ3 m gate;
3) The critical load of the VC is P=2.6504 MPa, which is greater than the main load of 0.1 MPa external pressure. Therefore, under the existing working conditions, the structural instability will not occur;
4) When the ventilation condition is poor, the minimum temperature of the VC is 280 K (about 7 ℃);
5) The radiation dose rate level in the VC is 1-100 Sv/h, and the radiation dose rate level outside the VC is 1-10 mSv/h.

In conclusion, the VC meets the requirements of the environmental simulation experiment of the lunar surface, which provides a guarantee for the experiment, and the analysis results provide a reference for the related research work [10].

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