Analysis of Gas State in Venus Surface Environment Simulation System

Gao Wen, Yang Xiaoning, Wang Jing, Guo Qinliang, Lin Boying, Bi Yanqiang and Wu Yue
Beijing Institute of Spacecraft Environment Engineering, Beijing, 100094
18811772351@163.com

Abstract. Venus, as a terrestrial planet, not only has the closest distance to Earth in the solar system but also has similar size and mass to Earth, the detection on it has extremely high reference value for Earth and future research. While due to the high temperature, high pressure and weak acid environment on the surface of the planet, the landing detection is hindered. Based on comprehensive analysis and computation on the Venus surface environment simulation process and diffusion state of single-phase binary gas under high-temperature and high-pressure conditions, this article provides an optimization scheme, which would provide support for the establishment of future environmental simulation equipment.

1. Introduction
Venus is the closest planet in the solar system to Earth. The difference in radius and average density of Venus from Earth is only 5%, which indicates that the two planets have similarities in the main structure and composition. In contrast, in terms of atmospheric environment, the surface pressure of Venus is about 90 times that of Earth, and its main component is carbon dioxide, while the component of carbon dioxide in Earth's atmosphere is relatively low. According to the Venus observations, there are more active signs of volcanic activity on the surface of Venus, which indicates that convective motion exists within Venus, but there are still no signs that plate movements will be caused by this, and then planetary magnetic fields will be generated[1].

Venus is so close to Earth in mass and size, so probing Venus has important scientific significance for understanding the historical evolution of Earth. However, due to the extremely harsh environment of Venus, the Venus lander will face great challenges[2]. Before the Venus lander is launched, it needs to undergo a full environmental assessment to ensure the reliability of the mission. Therefore, simulating the Venus environment to evaluate the Venus lander is very important. The gas of the final state of the Venus environmental simulation system is high-temperature and high-pressure, and it is heated from normal temperature to high temperature to reach the required ambient temperature and pressure. Based on the actual two-component equation of state (EOS), this article analysed the gas state change process in the Venus environment simulation system.

2. Venus typical atmospheric environment
Pressure profile of Venus atmosphere [3]is shown in figure 1. The pressure of Venus atmosphere increases dramatically with decreasing altitude. The atmospheric pressure on the surface of Venus is about 90 atm [4].
Figure 1. Pressure Profile of Venus Atmosphere.

Temperature profile of Venus atmosphere [4] is shown in figure 2, and the temperature of Venus surface is about 740K. Therefore, the temperature and pressure, required to simulate the Venus atmospheric environment, are about 773K and 92bar and due to the complexity of the atmospheric composition, it is so difficult to simulate.

Figure 2. Temperature Profile of Venus Atmosphere.
The atmospheric composition table of Venus [1] is shown in table 1. In Venus atmosphere, CO₂ and N₂ account for 99.5%. When performing state analysis, CO₂ and N₂ are considered as the main factors for calculation.

**Table 1. Composition of the atmospheres of Venus [1].**

| Species                  | Venus            |
|--------------------------|------------------|
| Carbon dioxide           | 0.96             |
| Nitrogen                 | 0.035            |
| Argon                    | 0.00007          |
| Neon                     | 0.000005         |
| Water vapor              | 30 parts per million |
| Heavy water (HDO)        | 3 parts per million |
| Sulphur dioxide          | 150 parts per million |
| Carbonyl sulfide         | 4 parts per million |
| Carbon monoxide          | 0.00004          |
| Hydrogen chloride        | 0.5 parts per million |
| Hydrogen fluoride        | 0.005 parts per million |
| Atomic oxygen            | trace            |
| Hydroxyl                 | trace            |
| Atomic hydrogen          | trace            |

3. Typical Venus Surface Environment Simulation System Process

In order to reach the temperature and pressure of Venus surface, the container needs to have a certain pressure $P_1$ when the temperature is raised, so that it can reach the temperature and pressure after the temperature is raised. To reach $P_1$ from normal pressure conditions, it is necessary to use a pump to pump premix container to the container to achieve the purpose of compressing the volume and boosting the pressure. Simple system process is shown in figure 3.

![Figure 3. Simple system process.](image1)
4. Gas state analysis

4.1. Theory of actual gas state calculation

The gas composition can be regarded as a mixed gas of 96.5% CO$_2$ and 3.5% N$_2$ [5], and due to the large temperature and pressure, the gas is not ideal gas.

Research shows that there is a certain similarity in the thermodynamic properties of various substances, and the contrast equation of state (EOS) is a general equation of state for various substances expressed using dimensionless contrast parameters [6].

\[
p_r = \frac{p}{p_c} \tag{1}
\]

\[
T_r = \frac{T}{T_c} \tag{2}
\]

\[
\nu_r = \frac{\nu}{\nu_c} = \frac{\nu_m}{\nu_{mc}} \tag{3}
\]

\[
z = \frac{p\nu_m}{RT} \tag{4}
\]

Among them, the comparison parameters $p_r, T_r$ and $\nu_r$ are the ratios of the parameters at each point and the same parameters at the critical point, and the compression factor is the ratio of the actual gas volume to the ideal gas volume. After experiments on various gases, a general compression factor graph is obtained, so in the calculation, reading graph or iterative method is used to obtain the compression factor.

The calculation of the actual mixture needs to be simplified, and the virtual critical constant method is used to treat the mixture as a pure substance. This method was proposed by W.B. Kay [7], and the following is the Kay rule:

\[
T_{pc} = y_1T_{c1} + y_2T_{c2} + \cdots = \sum y_iT_{ci} \tag{5}
\]

\[
P_{pc} = y_1P_{c1} + y_2P_{c2} + \cdots = \sum y_iP_{ci} \tag{6}
\]

Virtual contrast parameter [7]:

\[
T_{pr} = \frac{T}{T_{pc}} \tag{7}
\]

\[
P_{pr} = \frac{P}{P_{pc}} \tag{8}
\]

4.2. Gas state analysis

4.2.1. Calculate the total amount of gas: Calculate the mixed gas compression factor $Z_m$ in this state by the virtual critical constant method to calculate the overall amount of mixed gas and obtain the amount of each component gas [7].

\[
Z = \frac{1}{1-h} - \frac{A}{B} \left( \frac{h}{1+h} \right) \tag{9}
\]

\[
h = b \frac{\nu}{z} \tag{10}
\]

where $A$ and $B$ can be calculated by:

\[
\frac{A}{B} = \frac{4.934}{TP_r^{1.9}} \tag{11}
\]

\[
B = \frac{0.08664P_{pc}}{TP_pr} \tag{12}
\]

The iterative process is: preset the initial value of the compression factor $Z_0$, substitute it into equation (9) to calculate $h_0$, and then pass equation (10) to obtain $Z_1$, and calculate the difference $\Delta Z = |Z_{k+1} - Z_k|$ to verify whether it is less than the setting $\epsilon$, if it is smaller, then output $Z = Z_{k+1}$, otherwise continue to iterate until the result meets the requirement. The process of iteratively calculate is shown in figure 4.
4.2.2. **Iteratively calculate** $P_1$ **by the molar amount of gas.** Consistent with the above, when calculating $P_1$, the calculation of the relative volume is relatively tedious, so here we use the preset $Z_{m_0}$, calculate $P_{m_0}$, and then calculate $T_{r_0}$ and $P_{r_0}$ to obtain $\Delta Z = |Z_{m_{k+1}} - Z_{m_k}|$, verify whether it is less than the setting $\varepsilon$, if it is smaller, output the result $Z = Z_{m_{k+1}}$, otherwise continue iterating until the result meets the requirement. The process of iteratively calculate is shown in figure 5.

**Table 2.** the amount and mass of each gas component.

| No | Composition | mol    | Molar mass | Mass(g)    |
|----|-------------|--------|------------|------------|
| 1  | CO$_2$      | 1307   | 44         | 57508      |
| 2  | N$_2$       | 47.40  | 28         | 1327.2     |
| 3  | SO$_2$      | 0.2438 | 64         | 15.6032    |
| 4  | COS         | 0.0691 | 60         | 4.146      |
| 5  | H$_2$O      | 0.0406 | 18         | 0.7308     |
| 6  | CO          | 0.0163 | 28         | 0.4564     |
| 7  | H$_2$S      | 0.0027 | 34         | 0.0918     |
| 8  | HCl         | 0.000677 | 36.5  | 0.024711   |
| 9  | HF          | 0.00000339 | 20  | 0.0000678   |
|    | Gas mixture | 1354.77318 | /    | 58856.25298 |
The calculation result $Z_1=0.8451$, $P_1=3.0289\text{MPa}=30.289\text{bar}$, and the reserve pressure before the temperature rise of the simulation process in the reference [5] is $500\text{psi}=3.45\text{Mpa}$, and the error rate is 12.2%.

Calculation result $Z_2=0.9966$, $V_0=33.6261m^3$, which is about 35 times of the container.

5. Conclusion
Venus environment simulation technology is of great significance to the success of the Venus landing mission. Based on the actual two-component equation of state, this article calculates the gas state at each stage of the Venus environment simulation system and obtains the temperature and pressure parameters of the gas at each stage. It provides a basis for the typical process design of the Venus simulation system.

References
[1] Fredric W. Taylor et al. 2018 Venus: The Atmosphere, Climate, Surface, Interior and Near-Space Environment of an Earth-Like Planet. *J Space Sci Rev* 214 35
[2] JIAO Weixin. 2018 Future deep space exploration and related space environmental simulation. *J Spacecraft Environment Engineering* 35 103
[3] Hou Jianwen. 2015 *Deep space Exploration-Venus Exploration* (Beijing National Defence Industry Press)
[4] Vladimir A. Krasnopolsky. 2012 A photochemical model for the Venus atmosphere at 47–112 km. *J Icarus* 218 230
[5] Kremic T et al. Extreme Environment Simulation - Current and New Capabilities to Simulate Venus and other Planetary Bodies, 2014 IEEE Aerospace, 2014 (https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140013390.pdf)
[6] Zhou Yan. 2014 *Engineering Thermodynamics* (Beijing Chemical Industry Press)
[7] Yujiazi. 2016 *Chemical Thermodynamics* (Beijing Chemical Industry Press)