Oxygen concentration control in extra-vehicular activity (EVA) of manned spacecraft

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Abstract: The oxygen concentration control in the extra-vehicular activity is important for the safety of astronauts and the success of the extra-vehicular mission. This paper analyzes the influencing factors of the oxygen concentration, and the proposes verification test methods on the oxygen concentration limits at a low pressure. A model is built to simulate the variation of the oxygen concentration, and the partial pressure of the oxygen and the module pressure control scheme during the extra-vehicular activity are designed.

Key words: manned spacecraft; extravehicular activity(EVA); oxygen concentration control; combustibility test; flight safety

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0　Introduction

The technique of extra-vehicular activity (EVA) is one of the three basic techniques related with the manned spacecraft. The EVA technology is very complex，only the U.S.A，the former Soviet Union/Russia and China have completed the extra-vehicular activity successfully[1].

The airlock, which can isolate the sealed cabin from the vacuum environment in space, is a very important device in the EVA, when the astronauts enter the airlock first, and then, they wear the EVA spacesuits with pre-inhale oxygen, finally, the airlock gradually depresses to the vacuum state. The astronauts can achieve the EVA after opening the hatchdoor.

The pressure in the manned spacecraft is usually 101.3 kPa，while the pressure in the EVA spacesuit is 30~40 kPa. In order to avoid the decompression sickness, the astronauts have to inhale oxygen and exhale nitrogen. The airlock makes the depressing process smooth and gentle, that will also prevent the decompression sickness.

Along with the airlock's pressure release, the oxygen inhaled and the nitrogen exhaled, the oxygen concentration in the airlock when the pressure is lower than 1 atm is higher than the safe value (21%~25%) when the pressure is 1 atm. Thus, there are risks with respect to the safety of the airlock oxygen environment.

For the safety of astronauts in the EVA and in order to reduce the risks in the airlock oxygen environment during the depressing/repressing processes, tests are carried out to obtain the safe oxygen concentration range at a low pressure, and the partial pressure of the oxygen and the module pressure control scheme in the EVA are proposed.

1　Oxygen concentration change in extra-vehicular activity

Fig. 1 shows the typical process of the extra-vehicular activity by using the airlock.

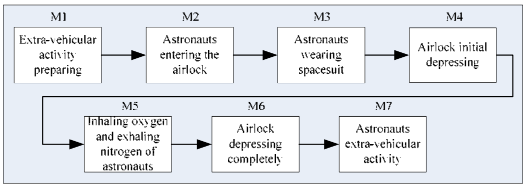

Fig. 1　The typical process of extra-vehicular activity

Assuming that initially, the volume of the airlock is V_0, the original airlock pressure is P_0, the partial pressure of the oxygen is Q_0, the oxygen concentration is D_0; after the initial depressing, the airlock pressure is P_1, the partial pressure of the oxygen is Q_1, the oxygen concentration is D_1; and after the oxygen inhaled and the nitrogen exhaled by astronauts, the airlock pressure is P_2, the partial pressure of the oxygen is Q_2, the oxygen concentration is D_2。Equation (1) shows how to calculate the oxygen concentration in the extra-vehicular activity.

$$D = Q / P \tag{1}$$

As the oxygen is released uniformly during the initial depressing stage, the oxygen concentration can be treated as invariable, i.e.

$$D_1 = D_0 \tag{2}$$

As the oxygen leaks from spacesuit continuously during the process of the oxygen inhaled and the nitrogen exhaled, the oxygen concentration rises continuously. Supposing that the amount of the oxygen produced during the process is ,

$$D_2 = Q_2 / P_2 = (Q_1 + V_1 / V_0) / (P_1 + V_1 / V_0) \tag{3}$$

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Equations (1)～(3) show how to calculate the oxygen concentration change during the extra-vehicular activity.

Consider the astronaut wearing spacesuit during the extra-vehicular activity as an example. Supposing that the volume of the airlock used for the extra-vehicular activity is 10 m^3, the leakage from the spacesuit is 1 L/(min·suit), the flow of the flushing using pure oxygen is 50 L/(min·time·suit), the rate of oxygen inhaled and the nitrogen exhaled are 0.5 L/min. The flushing time is about 5 min and the process of the oxygen inhaled and the nitrogen exhaled is about 30 min[2]. The curve of the oxygen concentration during the extra-vehicular activity is obtained as shown in Fig. 2.

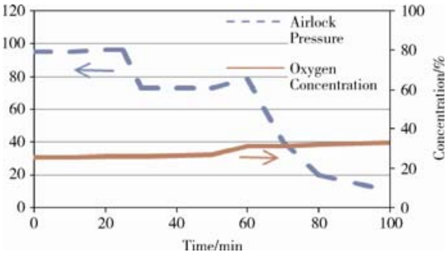

Fig. 2 The oxygen concentration and the airlock pressure in extra-vehicular activity

In the figure, the dash line refers to the change of the airlock pressure, and the solid line refers to the oxygen concentration.

It is shown that after the airlock's initial depressing and the oxygen inhaled and the nitrogen exhaled by astronauts, the oxygen concentration in the module would rise significantly from 25% to 31% at the low pressure of about 70 kPa,. The safety of the oxygen use at this pressure condition should be tested and verified.

2 The safety limit verification of oxygen concentration in extra-vehicular activity

For solving the fire control problem in the manned spacecraft induced by the oxygen concentration rising during the extra-vehicular activity, the oxygen concentration level inside the cabin at the key activity point in a series of extra-vehicular activities should be predicted according to the control model of the environmental pressure in the manned spacecraft cabin.

There will be no safety risk if the safety of the components, such as electrical equipment, cables and materials inside the manned spacecraft, is ensured under the predicted level of oxygen concentration. Otherwise, the oxygen concentration should be adjusted within the safety limit.

The oxygen concentration safety limit can be determined by the combustibility test of non-metal materials. First, the combustibility test should be performed for the non-metal materials inside the manned spacecraft under the normal pressure. The flammability, odor, offgassing, compatibility and the testing procedure for the materials in the combustion environment are given by NHB 8060.1 C [3].

Then, the material combustibility test is conducted under the oxygen concentration and the pressure circumstance of the extra-vehicular activities and the combustibility test results are compared with those under the normal air pressure environment. If the former test results are better than those in the normal air pressure condition, then the test condition will be considered as risk-free, and the reliability will be acceptable. Otherwise, the combustibility test will be performed again under the same pressure with a reduced oxygen concentration, until the test results about the spread speed of the flame, the combustion form, the carbide morphology, the flame colour, the flame size, and the others related factors, are similar to those in the normal air pressure environment, then the corresponding oxygen concentration value is taken as the safe value.

The operation case for the combustibility test can be chosen according to the calculated results of the concentration shown in section 1 of this paper. Three test samples are needed for a specific material. The flame down ramp mode can be adopted for the test, as the front edge of material decomposition is clear for determining the self-extinguishing position, which is the main advantage of the method. The test system is shown in Fig. 3.

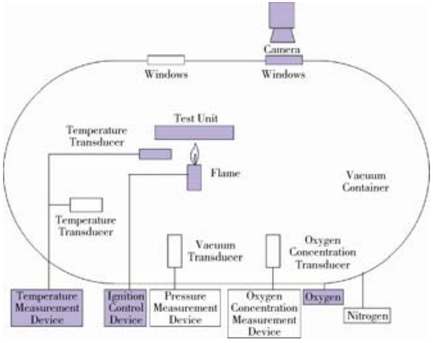

Fig. 3 The safety test system for low pressure and high oxygen concentration

A high power quartz lamp cluster is used as the ignition source, and the quartz lamp cluster consists of two 6 kW quartz lamps separated at a distance of 8 mm. The distance between the cluster and the sample is 15 mm. The sample temperature close to the lamp should be over 1 000 ℃, which exceeds the ignition temperature of common materials. The time for the ignition should be 30 seconds to guarantee a successful ignition.

The flame speed can be obtained by analyzing the temperature-time data given by the thermocouple measurements at points separated by intervals of 1 cm along the sample length direction on the sample surface in order, to judge the combustibility.

From the test results, the safe values of the oxygen concentration and the related curves can be obtained for different pressure conditions, to serve as a basis of the extra-vehicular oxygen concentration control procedure design.

The combustibility test for non-metal materials under microgravity environment should be performed if possible. The flame speed in microgravity environment generally reduces faster with the decrease of the pressure than it does in the normal gravity environment. Therefore, the material combustibility test results under the normal pressure condition can ensure the flight safety in microgravity environment.

3 The oxygen concentration control scheme

The oxygen concentration in the extra-vehicular activity when the pressure is lower than 1 atm is higher than the normal value. In order to ensure the safety of manned spacecraft, the oxygen concentration should be controlled within the safety limit.

Firstly, the oxygen concentration level inside the cabin at the key activity point in the series of extra-vehicular activities should be predicted. Secondly, an oxygen concentration control scheme should be in operation. The oxygen concentration should be controlled by adjusting the vehicle's pressure and the partial pressures of the oxygen, together with the filling of nitrogen. The series of extra-vehicular activities should be well designed and administered. Some factors should be considered，such as the operation time, the mode complexity, the manipulation, and the resource guarantee.

The pressure control system in a sealed module of the manned spacecraft is usually 101 kPa in the total pressure, with 21% of the oxygen percentage and 79% of the nitrogen percentage[4]. During the flight, the partial pressure of the oxygen would vary from 18 kPa to 24 kPa with the oxygen being consumed by astronauts.

According to equations (1)～(3), when the initial module pressure is 95 kPa, with the partial pressure of the oxygen at the high limit, the partial pressure of the oxygen would be up to 24 kPa and the oxygen concentration could reach 31% along with the airlock's depressing, the EVA spacesuit's oxygen flushing, and the astronauts' inhaling oxygen and exhaling nitrogen.

In order to avoid the potential danger of the high oxygen concentration at a low pressure in the extra-vehicular activity, the following control program could be adopted: firstly, the adjusting of the vehicle pressure and the partial pressure of the oxygen through depressing once or several times and refilling the nitrogen during the preparation of the extra-vehicular activity. Then start the formal procedure of the extra-vehicular activity. The partial pressure of the oxygen should be kept of no less than 17 kPa and the module pressure between 81 kPa and 99 kPa at the whole control process, in order to restrict the time of nitrogen refilling. Meanwhile, the module pressure rising as the result of the oxygen discharging would not exceed the high limit of 101 kPa in the extra-vehicular activity.

Fig. 4 indicates the process of the extra-vehicular activity with the oxygen concentration control scheme. The oxygen concentration would be pre-controlled before the airlock depressing and after the astronauts dressing their EVA spacesuits.

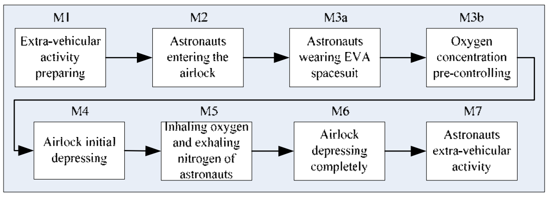

Fig. 4　The process of extra-vehicular activity with the oxygen concentration control scheme

Table 1 shows the comparison of the oxygen concentration in the module before and after adopting the oxygen concentration control scheme.

Table 1　The module pressure and the partial pressure of oxygen in extra-vehicular activity before and after the oxygen concentration control scheme

Task stage	Without the control scheme			With the control scheme implemented		
	Module pressure/kPa	The partial pressure of oxygen/kPa	Oxygen concentration/%	Module pressure/ kPa	The partial pressure of oxygen/kPa	Oxygen concentration/%
M2	95.0	24.0	25.2	95.0	24.0	25.2
M3a	96.0	25.0	26.0	96.0	25.0	26.0
M3b	96.0	25.0	26.0	98.0	17.0	17.7
M4	73.0	18.98	26.0	99.0	18.0	18.1
M5	78.3	24.28	31.0	73.0	13.2	18.1
M6a	40.1	12.5	31.2	40.0	9.6	24.0
M6b	2.1	0.724	34.0	2.1	0.504	24.0

The table demonstrates that the partial pressure of the oxygen following the extra-vehicular activity can be controlled effectively and will not exceed the range of the partial pressure of the oxygen at the normal module pressure, by the methods of pre-controlling of the module pressure and the partial pressure of the oxygen.

4 Conclusion

During the extra-vehicular activity, because of the oxygen inhaled and the nitrogen exhaled by the astronauts and the flow around the extra-vehicular spacesuit, the safety risks of the high oxygen concentration at a low pressure exist.

Through analysis of factors which affect the oxygen concentration during the extra-vehicular activity, and the verification of the oxygen concentration safety limits at the low pressure condition, a control scheme for the module pressure and the partial pressure of the oxygen in the extra-vehicular activity is proposed.

Different manned spacecraft's oxygen concentration safety limits can be determined by the fire test validation. Based on these limits, the level of the oxygen concentration can be reduced effectively by the pre-control scheme of filling the nitrogen during the extra-vehicular activity in the sealed module to ensure the astronaut's safety.

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载人航天器出舱活动氧气分压控制研究

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摘要：载人航天器出舱活动期间氧气分压控制是保证航天员安全和完成出舱任务的重要因素。文章通过对出舱过程中引起氧气分压变化的因素分析，进行了出舱活动低压情况下的氧气分压安全限的试验验证研究，建立了出舱活动氧气分压变化趋势仿真模型，并在此基础上确定了出舱活动阶段舱压和氧气分压的调控方案。

关键词：载人航天器；出舱活动；氧气分压；控制；可燃性试验；飞行安全

国际眺览

美展示新型宇宙飞船“猎户座”

据香港《星岛日报》7月4日报道，美国太空总署（NASA）展示了一架造价高达5亿美元的“猎户座”（Orion）宇宙飞船，外形和40多年前征月的“太阳神”太空舱相似，有望在将来送航天员上火星。

NASA预期“猎户座”在2014年首航，届时会以无人驾驶的试验形式展开，以时速3.2万km飞到离地球5 800 km的地方，比现在的国际太空站所处的轨道远15倍。

至于载人飞行预计在2019年展开，包括在2025年飞越小行星，以及飞到地球和月球之间引力的平衡点“拉格朗日点”（Lagrange point）。至于飞往最终目的地火星，则计划在2030年起进行。

“猎户座”本来是前总统小布什所制定的月球任务，称为“星座计划”（Constellation）的一部分；但奥巴马上台后，取消了“星座计划”，而主张集中在改进火箭技术。不久后，奥巴马又恢复了“猎户座”宇宙飞船的部分，使它成为国际太空站的“逃命汽车”工具。

据悉，“猎户座”宇宙飞船包括一个供航天员乘坐和运载货物的太空舱、一个推进和电力系统与其他设备的太空舱，以及载有另一个太空舱的“发射后放弃”（launch-abort）系统，作为万一推进火箭失效时的逃生装备。

（摘自2012-07-06中国新闻网）