Numerical Study of the Effects of Fluid Conductance and the Capacity of Negatively Pressured Cabin to the Process of Explosive Decompression

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Abstract. Explosive decompression is the rapid decompression process of aircraft in the sky caused by the damage of cabin which challenges the safety of people and equipment. The explosive decompression tester usually uses negative pressure reserve cabin technology. Numerical study was conducted to analyse the influence of the throttling and negative pressure reserve cabin volume on the explosive decompression process. The results show that as the throttle opening, the explosive decompression time decreases and the fluctuation amplitude of the two chambers after the pressure balance is enhanced; the volume of the negative pressure reserve cabin has little effects on the rate of explosive decompression and has no obvious influence on the fluctuation.

1. Introduction
At high altitudes, the air pressure is low. To ensure the safety of personnel and facility during the flight, the aircraft cabin will be artificially pressurized. Explosive decompression refers to the rapid pressure loss in the cabin caused by the direct contact of the air in and out of the cabin in the high air, which causes damage to personnel and equipment in the cabin.¹ ² Explosive decompression and its countermeasures are the challenges that aviation industry has to face. To research the explosive decompression process and its influences on the physiology and equipment, the simulator of this process is in need, which decompresses rapidly. The test cabin needs to decompress from 75.2kPa to 18.8kPa in 15s ³ ⁴, which can hardly be realized via vacuum pumps. The common method is to use negative pressure reserve cabin technology, which uses a bigger cabin with lower pressure connecting the test cabin to realize the rapid decompression ³ ⁴ ⁵. The parameters such as the connection type and the volume of each cabin have significant influence on explosive depression process, on which researches were done around the world.

Higgins established a mathematic model to describe the decompressing process of exposing to vacuum and conducted numerical study. ⁶⁻⁸ Sun conducted experimental and theoretical research to the pressure change of test cabin in explosive decompression and derived a formula of decompression time. The results show that the decompression time is proportional to the volume of the cabin and inversely proportional to the effective area of the decompression blast hole ⁹. Gao combined the fluid conductance equation with the gas thermodynamics theory, simplified the calculation with an isothermal process, and derived mathematical equations for the airflow balance between the cabins. The instantaneous pressure difference between the cabins is proportional to the initial pressure.
difference and the cabin volume, has an exponential relationship with the duration and an inverse relationship with the flow conductance of the connecting pipeline. [10]

Dynamic numerical simulation will be conducted to study the influence of throttling and the capacity of negatively pressured reserve cabin and provide guidance for the design of this type of equipment.

2. The influence of throttling on depression process

2.1. Mold and numerical method

A simulator with a test chamber volume $V_A$ of 7.2 m$^3$ was numerical studied. The initial pressure $p_{A0}$ of the chamber is 75.2 kPa, and the balance pressure $p$ is 18.8 kPa. The negative pressure reserve chamber volume $V_B$ is 400 m$^3$. The two chambers are connected by a $\varphi$1m × 2m pipe, as shown in Figure 1.

\[ p_{A0}V_A + p_{B0}V_B = p(V_A + V_B) \] (1)

The $p_{B0}$ was calculated to be 17.8 kPa. The simulator was meshed with unstructured meshes, as shown in Figure 2. The initial pressure of the two chambers, $p_{A0}$ and $p_{B0}$, were set by patch. Unsteady calculations of the decompression process were performed using Realizable $k-\varepsilon$ model.

2.2. Calculation results and analysis

The total pressure distributions at different times were obtained by calculation. The total pressure contours and of the three testers with the three throttle valve diameters of 900mm, 630mm and 450mm at 0.01s and 0.02s are shown in Figure 3, and the static pressure contours are in Figure 4.

![Figure 1. The simulator](image1)

![Figure 2. The meshing of the simulator](image2)
As can be seen from Figure 3, the high pressure air inside the test chamber quickly flows to the negative pressure reserve chamber during the decompression process. It can be found that as the valve closes, the decompression becomes significantly slower due to the flow resistance increases.

Comparing Figure 3 with Figure 4, it can be seen that there is a distinct low pressure zone at the rear of the throttle valve. After the airflow flows into the negative pressure reserve tank, eddy currents are also formed, resulting in a low pressure zone. It can be drawn that the kinetic energy loss of the system is mainly concentrated in the cabin loss caused by the throttle valve and the jet.

There is a distinct low pressure zone near the throttle valve. This is due to the formation of the vortex when air flow into the negative pressure reserve tank, mix with the low pressure gas and
decelerates, consuming its kinetic energy. As the throttle valve closes, the vortex at the rear of the throttle valve is enhanced, the conductance is reduced, and the flow loss is increased.

For the three throttle valves, the calculation was done until the decompression process was completed and the fluctuation was reduced to ±500 Pa. The development curve of the static pressure of the test chamber over time in the three decompression processes is shown in Figure 5.

![Figure 5. Development curves of static pressure of test chamber](image)

As can be seen from Figure 5, the test chamber’s static pressure drop rate increases significantly as the throttle valve opens. This is because the flow conductance is increased as the throttle valve is increased. Then the flow path resistance is reduced, and the gas flow is increased under the same conditions, which makes the decompression time reducing. The calculation results are in agreement with the theoretical values.

It’s obvious that pressure fluctuations of different amplitudes will occur after the pressures of the two chambers get equal. This is caused by the airflow impact. When the pressures of the two chambers get equal, the airflow rate is not zero, so the flow will continue, resulting in the gas pressure in the test chamber continuing to decrease, causing the lower pressure than the negative pressure reserve tank. Then gas backflow and wave formation. Fluctuations gradually decrease and disappear with the loss of gas mechanical energy. Comparing the three curves, the fluctuation intensity increases when the throttle valve becomes larger, and the fluctuation phenomenon is basically not observed when the throttle valve diameter is 450 mm. This is because the flow conductance of the connecting pipe is reduced as the throttle valve closes. And, the mechanical energy loss during the decompression process is increased, the kinetic energy of the gas is reduced after the pressure balance of the two chambers, and the fluctuation is reduced.

3. The influences of negative pressure reserve tank volume

It can be drawn from the derivation of the literature [10] that the negative pressure reserve volume $V_B$ has a significant impact on the decompression time. When design the test system, the test chamber volume $V_A$, the test chamber initial pressure $p_{A0}$ and the balance pressure $p$ are all specified by the design requirements. It can be seen from the formula (1) that the negative pressure reserve volume $V_B$ also has an influence on the initial two-chamber pressure difference $\Delta p_0$. In order to guide the design of the test equipment, the influences of the volume of the negative pressure reserve tank on the blasting decompression process were explored.

Four volumes of the negative pressure reserve tank were selected as $200\text{m}^3$, $400\text{m}^3$, $800\text{m}^3$ and $1200\text{m}^3$. In order to ensure that the same pressure is reached after decompression, the initial pressure of the reserve tank under each volume is calculated according to equation (1) as shown in Table 1.

| $V_B$/m$^3$ | 200  | 400  | 800  | 1200 |
|------------|------|------|------|------|
| $p_{B0}$/Pa | 16770| 17785| 18292| 18462|
To save computational resources, a 900 mm diameter throttle valve was uniformly selected. The pressure curves of each test chamber during decompression are shown in Figure 6. It can be seen from Figure 6 that the volume of the negative pressure reserve tank has little effect on the rate of blast decompression during the decompression phase, which is negligible. There is an impact in the fluctuation phase, but no obvious law.

![Figure 6](image_url)

**Figure 6.** Static pressure curves of test chambers with different negative pressure reserve tank

As shown in Figure 3, the affected area of the jet in the tank is smaller than the volume of the tank, so the volume of the negative pressure reserve tank will not significantly affect the decompression process.

4. **Conclusion**

Unsteady simulations of the explosive decompression process were carried out. The working conditions of different flow conductance and different negative pressure reserve tanks are studied. The influence of these parameters is explored. The conclusions are as follows.

(1) As the throttle valve opens, the flow conductance increases, the gas flow increases under the same conditions, so the explosive decompression time is reduced;

(2) During the explosive decompression process, pressure fluctuation of different amplitudes will occur when the pressures of the two chambers get equal;

(3) As the throttle valve closing, the flow conductance of the connecting pipe is reduced, and the mechanical energy loss during the decompression process is increased. After the pressure of the two chambers gets balanced, the kinetic energy of the gas is reduced, and then the fluctuation is reduced;

(4) The volume of the negative pressure reserve tank has little effect on the rate of blast decompression during the decompression phase. It has a influence during the fluctuation phase, but there is no obvious law.

**Reference**

[1] A G. Mathematical Model Research of Human Exposure to Vacuum[J]. Journal of the British Interplanetary Society. 2008, 28(2): 148-152.

[2] M R E. Rapid( Explosive) Decompression Emergencies in Pressure-Suited Subjects[R]. NASA, 1969.

[3] Xingrong S. Research on Rapid Decompression Test Technology for Airborne Equipment [J]. Environmental Technology. 2011, 33(2): 18-22.

[4] Dongchen Y, Huajun X, Bin Z, et al. Development of Experiment Chambers of Complex Low-pressure Environment [J]. Chinese Medical Equipment Journal. 2011, 32(12): 6-12.

[5] Demtrad. On the Decompression of a Punctured Pressurized Cabin in Vacuum Flight[J]. Jet Propulsion. 2006, 24(2): 112-123.

[6] M E. Rapid Decompression Emergencies in Pressure Suited Subjects[J]. Air Medical Journal. 2007, 28(1): 82-91.

[7] Pagani A, Carrera E. Gasdynamics of Rapid and Explosive Decompressions of Pressurized Aircraft Including Active Venting[J]. Advances in Aircraft and Spacecraft Science. 2016, 3(1):
[8] Higins. Simulation Model Research of Vacuum Exposure[J].
[9] Sun B, Xiao H, Yuan X. Effect of Cabin Decompression Time on Parameters of Emergency Oxygen Supply[J]. China Safety Science Journal. 2002, 2(5): 1-7.
[10] Gao H, Liu M, Wang J. Novel Technique to Rapidly Pump Spacecraft Cabin with Negatively Pressured Cabin and Its Theoretical Basis[J]. Chinese Journal of Vacuum Science and Technology. 2013, 33(12): 1191-1198.