Performance and Analysis of a Modular Vacuum Chamber For Explosive Decompression Testing

Introduction

Uncontrolled Decompression is a common aerospace industry term used to describe an unplanned depressurization of vessels that are occupied by people [1]. For example, this type of event could occur in an aircraft cabin, spacecraft, or submersible vehicle.

Uncontrolled Decompression events are often classified as *Gradual*, *Rapid* or *Explosive*. Explosive decompression is the fastest and dangerous of these events, typically occurring in 0.5 seconds or less [2]. Due to the speed at which explosive decompression occurs, it is the most challenging to simulate in a controlled environment and will be the primary focus of this white paper.

Explosive decompression can create dangerous situations that may stress critical systems on board a sealed vehicle. Simulating explosive decompression is a valuable worst-case stress test used by engineers and scientists to test and harden critical components.

Despite the common need for testing, purpose-built explosive decompression systems remain expensive and hard to find. Users are limited to purchasing a slow response altitude chamber, incorporating expensive high-power vacuum pumps, contracting out testing, or even forgoing real world testing entirely and settling for numerical simulations.

This report explores a way to use readily available vacuum components to build a fast-responce test chamber system capable of simulating explosive decompression.

Theory

Because decompression involves a drop in pressure from approximately atmospheric to well below atmospheric, it is typically simulated in a vacuum chamber. However, the speed limitations of vacuum pumps pose a challenge for anyone wishing to evacuate a test chamber fast enough to simulate explosive decompression. The system described below addresses this problem by utilizing a dual chamber configuration.

The two chambers used will be referred to as the *test chamber,* where the rapid decompression is created, and the *boost chamber*. The boost chamber acts as a vacuum reservoir that assists the vacuum pump in rapidly evacuating the test chamber. Figure 1 illustrates how the test and boost chambers are connected with their associated valving and pumping. The sequence of the explosive decompression test is:

1. V_1, V_2, V_3, and V_5 are closed and V_2 is opened, allowing the test chamber to be pumped down to the starting test pressure.
2. V_2 is closed and V_4 is opened, evacuating the boost chamber.
3. V_2 is closed and V_1 is opened to initiate the explosive decompression.
4. V_5 and V_3 are opened to vent and reset the system.

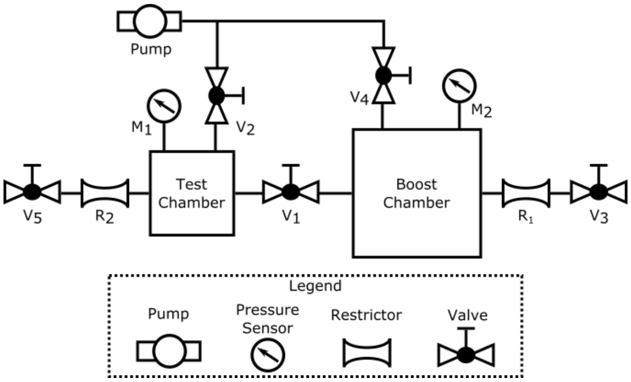

Figure 1: Explosive decompression test schematic.

In an explosive decompression test, the initial and final, targeted pressures of the test chamber are known. This leaves the initial pressure of the boost chamber to be calculated.

Using the Ideal Gas Law for the two chambers separated by V_1,

$$P_{t,i}V_t = n_t RT_{t,i}, \quad (1)$$

and

$$P_{b,i}V_b = n_b RT_{b,i}, \quad (2)$$

where, $P_{t,i}$ and $P_{b,i}$ are the initial pressures in the test and boost chambers, V_t and V_b are the volumes of the test and boost chamber, n_t and n_b are the number of moles of gas in the test and boost chambers, R is the gas constant, and $T_{t,i}$ and $T_{b,i}$ are the initial temperatures of the air in the test and boost chamber, respectively. After V_1 is opened the Ideal Gas Law gives

$$P_{s,f}V_s = n_s RT_{s,f}, \quad (3)$$

where, $P_{s,f}$ is the final pressure of the system (the test and boost chamber combined through V_1), V_s is the volume of the system, n_s is the number of moles of the system, and $T_{s,f}$ is the final temperature of the air in the system. Equation 3 can be rewritten using conservation of volume and mass,

$$P_{s,f}(V_b + V_t) = (n_b + n_t)RT_{s,f}. \quad (4)$$

Assuming an isothermal process from the initial to final state and substituting Equations 1 and 2 into Equation 4,

$$P_{s,f}(V_b + V_t) = (P_{b,i}V_b + P_{t,i}V_t). \quad (5)$$

Dividing Equation 5 by V_t and rearranging, we get the following relationship,

$$P_{t,i} - P_{s,f} = \frac{V_b}{V_t}(P_{s,f} - P_{b,i}). \quad (6)$$

Equation 6 shows that the relationship between the initial test chamber pressure and the final pressure of the system is proportional to the difference in pressure between the initial boost chamber pressure and the final pressure of the system. The constant of proportionality is the ratio of volumes between the boost and test chambers, V_b/V_t, which is defined as the boost ratio, b_r.

Because explosive decompression is of interest to applications that happen at altitude, the relationship between atmospheric pressure and height above sea level is needed. In this report the barometric model is used [3]. For altitudes between 0 and 11,000 m (36,089.24 ft) the pressure altitude relationship is

$$P = 101.29\left(\frac{288.15 - 0.00649h}{288.15}\right)^{5.26} \quad (7)$$

where h is the altitude above sea level in meters, and the pressure is calculated in kPa. For altitudes between 11,000 m and 25,000 m (82,021 ft), the following relation is used:

$$P = 22.65exp(1.73 - 0.000157h). \quad (8)$$

Test Setup

The goal of the test was to show that decompression of the test chamber meets the explosive decompression criterion of equilibrium in less than 0.5 seconds. An 8,000 to 60,000 ft decompression scenario was selected for the test.

The boost chamber and test chamber selected were the Ideal Vacuum 12x12 and 6x6 modular chambers, respectively. This configuration yields a boost ratio of approximately 9.5.

Implementation of Figure 1 was as follows:

- **M_1:** 1,000 Torr capacitance manometer
- **M_2:** Bourdon gauge
- **P_1:** SH-110 scroll pump
- **$V_{2\text{-}5}$:** Manual butterfly valve

For comparison, V_1 was switched between a pneumatic ISO-100 gate valve and an Ideal Vacuum KF-50 CommandValve (an electronic butterfly valve). These components are readily available and require no customization to accomplish the demonstrated testing.

The change in test chamber pressure was determined by using Equations 7 and 8 to relate altitude to pressure. The initial altitude in the test was 8,000 ft (2,438.4 m), which corresponds to 565.8 Torr (75.4 kPa). The final altitude was 60,000 ft (18,288 m), which when related to atmospheric pressure was 54.3 Torr (7.2 kPa). Using Equation 6, the boost chamber starting pressure was about 0.5 Torr (0.67 kPa).

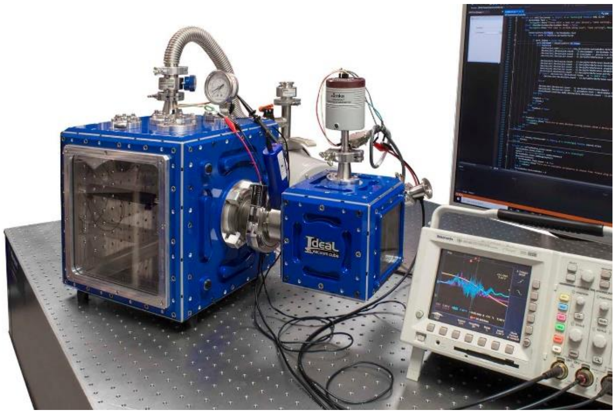

Figure 3: Explosive decompression test setup. Left-to-Right: 12x12 modular vacuum cube, the CommandValve electronic butterfly valve, and the 6x6 modular vacuum cube.

To measure the decompression time, the boost chamber was instrumented with two piezoelectric discs, along with the capacitance manometer. One disc was placed near the entrance of the boost chamber to capture the effect of the air rushing in from the test chamber. The second disc was positioned near the back of the boost chamber so an average response could be determined. The response from the discs were measured by a Tektronix TDS 3014B 100 MHz oscilloscope. Figure 3 shows the test setup.

The pressure in both chambers was measured using a 1,000 Torr capacitance manometer (note: the use of a second pressure transducer in Figure 1 was for automation/ease-of-use).

Test Routine:

1. V_1 and V_2 are open and the vacuum pump evacuates both chambers to the initial boost chamber pressure; 0.5 Torr in this case.
2. Close V_1 and open V_5 until the pressure rises to the initial condition for the test chamber; 565.8 Torr.
3. Open V_1 and collect the data.
4. Repeat steps 1 through 3 for as many experiments as needed.

Results

The first decompression test used the electronic butterfly valve as V_1 to separate the test and boost chamber. Figure 4 shows the results of the decompression. The time -20 ms to 0 ms is the time before the V_1 opening. The pressure is stable and the piezoelectric discs are producing 0 volts. V_1 opens and the piezoelectric disc in the path of the flow responds first, followed by the piezoelectric disc measuring the average response. The gauge follows after a 20 to 25 ms lag due to delayed response and conversion latency.

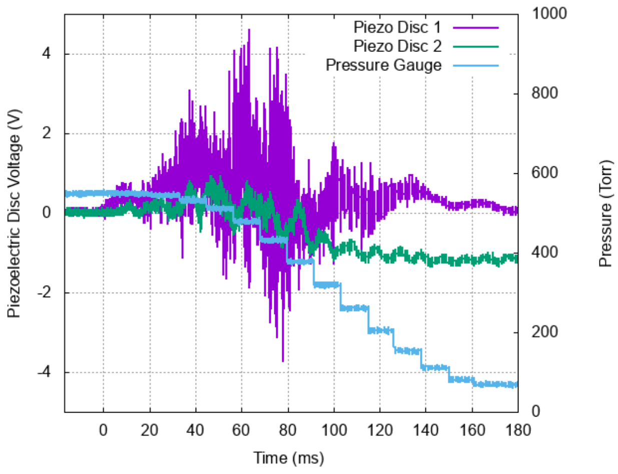

Figure 4: Trace showing the gauge and piezoelectric discs response to an 8,000 ft to 60,000 ft altitude increase. 160 ms marks the end of the decompression event.

At 160 ms the pressure has stabilized and the piezoelectric signals have subsided. This meets the goal of reaching equilibrium within 0.5 seconds (500 ms). The disc in the back of the chamber appeared to be deformed during the test because the voltage remained non-zero at equilibrium.

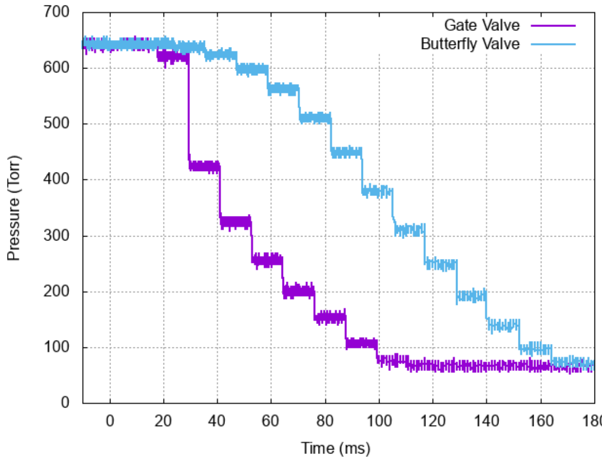

Figure 5: Comparison of ISO-100 pneumatic gate valve and KF-50 electronic butterfly valve as V_1 in the explosive decompression test setup. Data collection rate at gauge is 100 Hz, hence the stair-stepped plot.

After changing V_1 to an ISO-100 pneumatic gate valve, the test was repeated. The difference in time to equilibrium for each valve is shown in Figure 5, with the gate valve setup reaching equilibrium in about 100 ms, or 60 ms faster than the butterfly valve.

Discussion

With both the pneumatic gate valve and electronic butterfly valve meeting the goal of full pressure equilibrium within 0.5 s, this test and system configuration is appropriate for explosive decompression testing.

The faster response of the system using the pneumatic gate valve can be attributed to both its relatively larger cross section and its faster actuation speed. The more significant factor of these two is assumed to be the increased open speed of the gate valve.

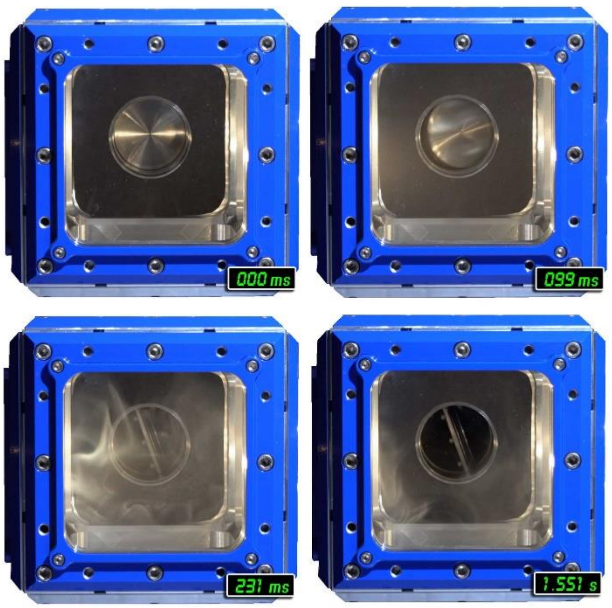

Figure 6: Water vapor rapidly condenses into a visible fog in about 100 ms of the test chamber undergoing explosive decompression. The chamber interior is slightly modified to highlight the sudden condensation and subsequent dissipation.

At the exact instant that the dump valve, V_1 opens, the momentary formation of a cloud was observed inside the test chamber, shown in Figure 6. This fog quickly dissipated as the chamber pressures equalized.

This instantaneous formation and evaporation of condensed water vapor upon decompression is a signature event documented in nearly all air-craft-related explosive decompressions (Figure 6).

Summary

Based on the time criterion for an explosive decompression event, the system described in this report was able to meet and exceed the set requirements. The use of modular chambers and common vacuum components allowed easy customization and reconfiguration throughout the system as the concept was tested and tuned for the desired response.

Figure 7: Off-the-shelf explosive decompression test system with test and boost chambers, electronic butterfly valves, capacitance manometers, gauge controller, and IDP-3 vacuum pump. The kit also includes assorted orifices for fine tuning the decompression speed (Ideal Vacuum Products Part Number P1010268).

Following the successful performance of the modular explosive decompression system, Ideal Vacuum has manufactured a replica kit, IVP Part No. P1010268, and made it available for purchase (Figure. 7). In addition to the critical components used in this report, the kit includes upgrades to enable thermal control, full system automation, and improved pressure measurement.

The system highlighted here may be adapted to a variety of test needs. For example, with modular Vacuum Cubes, the setup could be further upgraded to span wider pressure (altitude) jumps or support a larger test chamber, with the addition of boost chamber volume. An extensive assortment of feedthroughs and accessories are also available for expanding diagnostics, test piece control, or local environmental control capabilities. This allows users to build the experiment they need without being limited by the available hardware.

References

[1] Wikipedia Contributors, "Uncontrolled decompression," 24 September 2019. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Uncontrolled_decompression&oldid=916341251

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