Design and Performance Analysis of a CO_2 Ejection System for High-Powered Rockets

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The design and analysis of a compressed gas (CO2) ejection system to pressurize a high-powered rocket airframe is presented. Traditionally, burning black powder is utilized as the method of generating pressure inside the airframe. However, combustion releases very hot gasses, which endanger burning the electronics and flammable materials such as nylon parachutes within. CO2 ejection systems are preferred to burning black powder, because they utilize cold gases to generate pressure. The system presented utilizes a very small amount of black powder that is burned to generate pressure inside a closed chamber. The pressure generated accelerates a piston to release the compressed gas by puncturing the CO2 cartridges seal. The system is required to pressurize the airframe to 15 PSI under 2 seconds and puncture the cartridge at a specified time to be successful. The components and the assembly were modeled in Fusion 360 and machined from 6061-Aluminum. The necessary amount of black powder was calculated for piston to travel up to the cartridge seal using the ideal gas law. Theoretical value was tested to see if it was enough to puncture the canisters. Premature ejection was prevented by choosing a spring with right stiffness and size of CO2 cartridges were determined to reach desired pressure within the airframe to validate the system for use in a high-powered launch for the Spaceport America Cup 2023.

I. Nomenclature

A	=	Area
F	=	Force
h	=	Height
k	=	Spring rate
m	=	Number of Moles
$\dot{m}$	=	Mass Flow rate
P	=	Pressure
R	=	Gas constant
T	=	Temperature
V	=	Volume
W	=	Weight
Δx	=	Displacement of the spring from neutral position
γ	=	Specific Weight

II. Introduction

High-powered rockets can reach altitudes of tens of thousands of feet, with some launches exceeding 30,000 feet at apogee. A reliable recovery system is a necessary to safely decelerate the rocket to safe landing velocities and prevent a ballistic trajectory. Single- and dual-stage parachute deployment is the most common method of recovery used in high-powered rockets. These parachutes are carefully packed into the rocket airframe and are deployed by pressurizing the airframe, thereby causing sections of the rocket to separate at high velocities, pulling the parachutes out which can be seen at Figure 1 and b. Traditionally, deployment event is triggered by igniting a targeted volume of

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black powder with an electric charge, using the effects of rapid combustion to generate hot gasses to reach the necessary internal pressures. Black powder burns at temperatures around 800F [1], which, in the enclosed space of the airframe, yields a non-trivial rise in temperature, endangering the nylon parachutes, shock cord, and sensitive electronics of a non-sealed payload located near the black powder

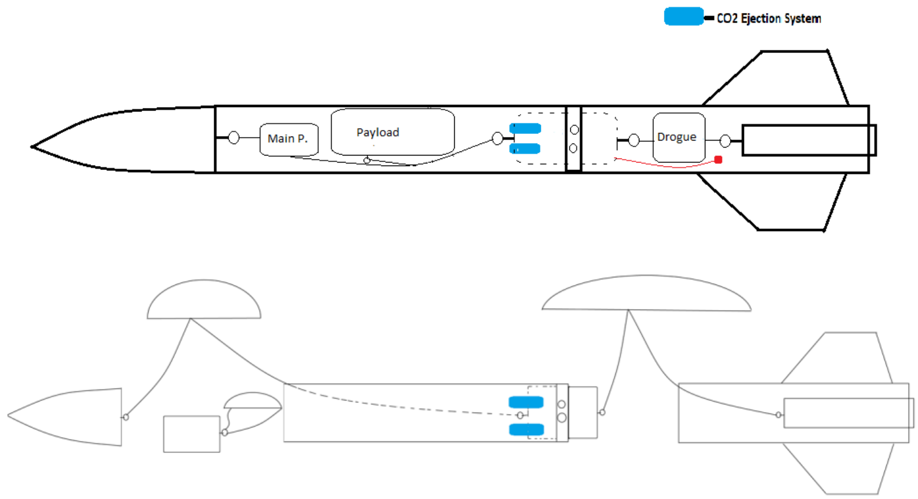

Figure 1 a, b Layout of a High-Powered Rocket before and after deployments

The Intercollegiate Rocket Engineering Competition (IREC) is an international competition challenging university students to design a high-powered rocket to reach a target altitude and develop an experimental payload to conduct an experiment during launch [2]. This year, Swamp Launch Rocket Team designed an autonomous folding quad-copter style drone for the competition payload. One major challenge encountered was collapsing the drone to fit within a six-inch diameter airframe and maintaining a sealed environment without the need for a complex release mechanism. However, leaving the drone unsealed meant exposing all the components, including sensitive electronics and lithium-ion batteries, to hot ejection gasses. Thus, the team sought out alternative ejection methods that would provide the necessary pressures without generating elevated temperatures or combustion byproducts.

Two major requirements of any selected system were: 1) pressurize the airframe to 15 psi within 2 seconds of "firing," and 2) all gasses must remain near or below ambient temperatures. A CO2-cartridge system was determined to meet both requirements while maintaining a compact and lightweight form-factor for ease of packaging into the airframe. The pressure inside CO2 cartridges at 70 °F is around 900 psi [3] and is easily released by puncturing the foil seal enclosing the throat of the cartridge. Herein, the design and analysis of a CO2 ejection system is discussed.

III. CO2 Ejection System Design

The CO2 ejection system had few preliminary requirements. It had to puncture the cartridges reliably under flight conditions and the puncturing method had to be integrated with COTS altimeters since they were used to trigger recovery events.

A. Determining the Puncturing Method

Possible methods of breaking the seal, all entailed applying pressure on the seal of the cartridge with a sharp tip. This could be done with a mechanical system involving servos and a control system. Another method was utilizing a pyro charge to create pressure to accelerate a piston with a sharp tip inside a chamber. The COTS altimeters trigger the recovery event by sending a current for 1 second through two wires to ignite an e-match. This made integrating any mechanical method of puncturing to COTS altimeters complicated and have a lot of possible modes of electronic or software failure. So, a small pyro charge triggered by an e-match was chosen as the method of puncturing. Even though black powder was not eliminated from the system, the amount used was as little as 5% of the amount necessary to eject a parachute. The black powder was also burned inside an enclosed combustion chamber and coupled with the cold CO2 releasing, the combustion byproducts and temperatures were virtually untraceable.

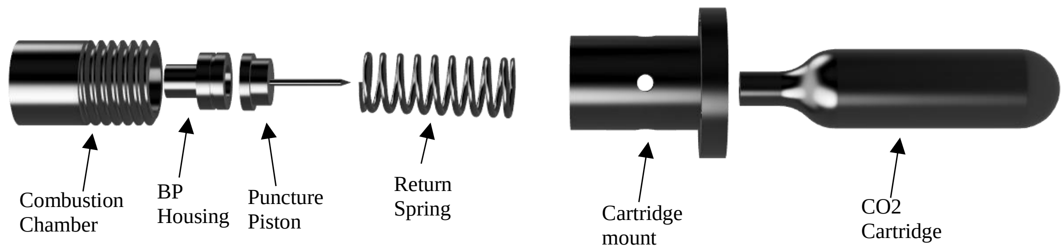

Figure 2 CO2 Ejection System Components

The system designed utilizes a pyro charge packed inside the black powder housing which sits inside the combustion chamber with the puncture piston. The volume behind the puncture piston gets pressurized when the pyro charge is set off. This applies a force on the puncture piston which causes it to compress the return spring and travel towards the cartridge seal.

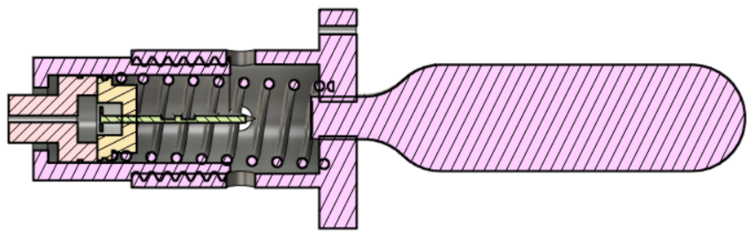

Figure 3 Section View of the Assembly

Aluminum 6061-T6 was selected as the material for constructing the components due to its low cost, density and high machinability when compared to other common materials used in aerospace applications. The CO2 Ejection system was designed to be modular to allow the components to be swapped out if necessary. All components other than the CO2 cartridge and the return spring were hand machined using a lathe and a mill. One notable design feature was the threads that were around the combustion chamber. This allowed the assembly to come together by screwing the combustion chamber into the cartridge mount which made arming the system a very simple process The puncture piston was constructed by placing a nail through a hole that is in the middle of the machined piston.

B. Choosing the Return Spring

The return spring's function is to keep the puncture piston and black powder housing from moving during flight and to spring back the puncture piston to prevent it from clogging the hole on the seal. The spring was chosen based on the diameter and height of the hollow section of the cartridge mount. To let the puncture piston sit flush and flat on the spring, inner diameter of the spring was chosen to be the same as the smaller shoulder diameter of puncture piston. A relatively high spring constant, k of 6 N/mm was chosen to prevent it from compressing under its own, puncture pistons and black powder housings weight while accelerating.

C. Arming the CO2 Ejection system

The system must be disassembled and laid out to start the arming process. An exploded view can be seen on Figure 1 which also show their order. The system is armed by first packing the pyro charge in the black powder housing. An e-match is placed inside the black powder hole and the wires connected to the e-match is brought out through the wire hole behind the black powder housing. A layer of cellulose insulation is packed inside the black powder hole and carefully weighted black powder is placed on top off the insulation layer. Another layer of cellulose insulation is packed on top of the black powder to fill up the volume completely and keep the black powder compressed. A piece of tape is used to close the top of the black powder housing to prevent is contents from spilling.

After the pyro charge is packed, black powder housing is placed on the opening of the combustion chamber followed up by the puncture piston and the return spring. These 3 components are pushed in place at the same time by applying pressure on the spring which prevents air gaps from forming. When the combustion chamber assembly is ready, it gets threaded inside the cartridge mount and a CO2 cartridge also gets threaded on the cartridge mount. Lastly, the e-match wires are connected to the charge terminals of the Altimeter.

IV. Performance Analysis of The CO2 Ejection System

The pressure created between the puncture piston and black powder housing depends on how much black powder is burnt. The mass of black powder necessary can be estimated by solving the Ideal Gas law for mass, *m.* But first unknown that needed to be determined was distance puncture piston had to travel which would be used to solve for a force value. Inspecting the CAD gave 15 mm between the tip of the nail and the seal of the CO2 Cartridge. Additional 5 mm was added to 15mm to account for reliable puncturing. Spring force formula (1) was used to determine the force required for 20mm of spring displacement, Δx. After, pressure was calculated using (3), force, *F* found on (2) and area of the puncture piston, *A* which was found to be 180mm^2 using the CAD model.

$$k * \Delta x = F \quad (1)$$

$$F = 20\ mm * 6\frac{N}{mm} = 120\ N \quad (2)$$

$$P = \frac{F}{A} \quad (3)$$

$$\frac{120N}{180mm\char`^2} = 0.66\ Mpa \quad (4)$$

Using ideal gas law (5), Pressure, *P* calculated in (4), volume of combustion chamber from the CAD model, *V*, burning temperature of Black powder, *T*. and gas constant, *R* mass, were used to calculate m.

$$PV = mRT \quad (5)$$

$$m = \frac{666{,}666\ Pa*1.0118*10^{-5}m^3}{8.3145(m^3*Pa*K^{-1}*mol^{-1})*1837\ K°} = 0.00044\text{ mol} \quad (6)$$

The sociometry of common black powder consists of 75% potassium Nitrate, 15% softwood charcoal, and 10% sulfur. Their molar masses in order are 101 g/mol, 12.01g/mol, and 32.1 g/mol [1]. Molar mass of black powder was found to be 80.8 g/mol by multiplying ingredients percentages with their molar mass and dividing the result by 100. The required amount of black powder was found to be 0.04 grams by multiplying its molar mass with number of moles, *m* found at (6). This number was rounded up to 0.05 grams and tested with the system armed. The test was successful, where the canister was punctured, and the gas was released.

The component experiencing the most stress throughout the ejection process was the combustion chamber. This component had to withstand the pressure that builds up when the black powder was burnt. The pressure was characterized during black powder size calculations to be 0.66 Mpa. Using Fusion 360’s simulation tool, the pressure was simulated on the part to analyze the stress concentrations and the location with lowest factor of safety.

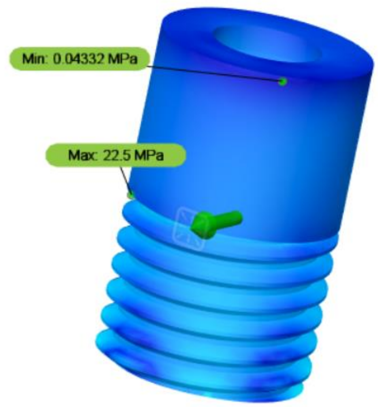

Figure 4 FEA analysis on the Combustion Chamber which shows 22.5 MPa as the highest stress experienced by the part.

The analysis showed that highest stress was experienced at the parts where threads were cut, which was expected since threads create a stress concentration. However, even the highest stress was well below the yield point of Aluminum 606.

A. Choosing the Cartridge size

The right size CO2 cartridges had to be chosen to reach the required pressure of 15 PSI inside the airframe. The ideal gas law (5) was used to solve for the moles of CO2 required to reach 15 PSI which is equivalent to 103421 Pa, *P*. The inner diameter of the forward airframe was 6 inches, and the height was 48 inches. This resulted in a volume, *V* of 1357 in^3 which is equivalent to 0.022 m^3. The volume occupied by the payload was accounted for by subtracting its volume, 0.005 m^3, from the total volume. The standard temperature at 1000 ft was used as the temperature, T in the equation. The mass of CO2 was found by multiplying the number of moles with molar mass of CO2 (8).

$$m = \frac{103421\ pa * 0.017m^3}{288K^\circ * 8.3145(m^3 * Pa * K^{-1} * mol^{-1})} = 0.73\ moles \tag{7}$$

$$w = 0.73\ moles * \frac{44g}{moles} = 32.3\ grams\ of\ CO_2 \tag{8}$$

The standard cartridge size that was closest to 32.3 grams was 34 grams which was chosen as the cartridge size. Next, the flow rate out of the punctured hole was calculated. Equation (9) was used to determine to find that flow out of the opening of the canister was choked [4].

$$\frac{p_{atm}}{p_{cartridge}} < \left(\frac{\gamma - 1}{2}\right)^{\frac{\gamma}{1-\gamma}} \tag{9}$$

$$\frac{101Kpa}{6205Kpa} < \left(\frac{1 - 1.3}{2}\right)^{\frac{1.3}{1-1.3}} \tag{10}$$

$$0.016 < 0.548 \tag{11}$$

Then using (12), the mass flow rate was calculated [4]. The exit area, A^* created by the nail which was found to be 0.071 cm^2 from averaging 5 punctured canisters.

$$m_{choked} = \left(1 + \frac{\gamma-1}{2}\right)^{\frac{1+\gamma}{2(1-\gamma)}} p_{cartridge} \sqrt{\frac{\gamma}{RT_{atm}}} \mathrm{A}^* \tag{12}$$

$$\dot{m_{choked}} = \left(1 + \frac{1.3-1}{2}\right)^{\frac{1+1.3}{2(1-1.3)}} 6.205\ Mpa \sqrt{\frac{1.3}{189\frac{j}{(kg*K)}293K}}\, 0.071cm^2 = 0.125\ kg/s \tag{13}$$

$$t = \frac{m_{cartridge}}{\dot{m_{choked}}} = \frac{34g}{125g/s} = 0.272\ seconds \tag{14}$$

The time it took for all the CO2 to vacate the canister was found to be 0.27 seconds, which was fast enough according to the requirements mentioned previously.

V. Conclusion

The CO2 system developed has proven to work through testing. It was able to puncture the cartridges that were put into test 100% of the time. Further tests will be conducted on getting real time pressure data inside a controlled volume using a pressure sensor. Some things that can be improved are comparing different puncture pistons to determine the effect it has on pressurizing time and looking into methods that can eliminate the use of black powder completely. It will be flown inside the IREC 2023 rocket at New Mexico which will prove its functionality during flight conditions.

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