Improving a Low-Cost Thermal-Vac Chamber for Testing Stratospheric Ballooning Payloads

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Abstract:

Building "near-space" payloads and lofting them into the stratosphere on weather balloon flights is far less expensive than launching payloads into outer space using rockets. However, even weather balloon flights can feel costly and be time-consuming, especially in educational contexts. Hence it is best for payloads to be ground-tested as rigorously as possible before flight, to identify (and remedy) potential failures.

One particularly useful device for simultaneously exposing payloads to the low temperatures and low pressures they will experience on a stratospheric balloon flight is a thermal-vacuum chamber (called a thermal-vac for short), such as the home-built "High Altitude Chamber" reported on by Howard Brooks of DePauw University. Using such a chamber, one can "bring the stratosphere (at least its low pressure and low temperature characteristics) into a lab or classroom" before deploying hardware and expending consumable resources on potentially-unsuccessful flight tests.

This paper discusses our experiences constructing, then making various modifications to, Brooks' thermal-vac chamber. While maintaining low cost, we were able to reach lower pressures and lower temperatures than Brooks reported, in part by using aluminum endplates (rather than Lexan) and by using dry-ice cooling (rather than deep-freezer cooling). We also used removable rubber gaskets for sealing the chamber and used simple metal feed-throughs to supply power to internal components from an external DC power supply to reduce the number of batteries depleted during thermal-vac testing. We also constructed a microcontroller-based sensor suite to monitor chamber conditions that is capable of communicating with the outside by short-range XBee radio. This provides real-time access to chamber environmental conditions and allows commanding of internal electric heaters and recirculation fans as desired without breaking the chamber's vacuum seal.

Introduction:

Building and flying payloads containing science experiments into the outer-space-like environment of the stratosphere using helium-filled or hydrogen-filled weather balloons can provide educationally valuable, and naturally-interesting, science training for students and adults alike. Such flights can also be used for conducting genuine research to study conditions up through stratospheric altitudes and/or for making measurements and remote observations from a "near-space" vantage point. The MN Space Grant Ballooning Team at the U of MN – Twin Cities, established in 2007, has conducted over 140 launches (many with more than one balloon), and helped train dozens of U of MN undergraduate students as well as helped faculty at multiple other higher education institutions (and a few pre-college schools) start ballooning programs of their own. We also regularly fly payloads built by pre-college schools (and sometimes colleges) that are interested in payload development but don't yet have a ballooning program of their own.

Unlike ballooning programs that are very research focused and tend to refine and fly the same payloads over and over again, hopefully eventually "getting them right," we tend to develop new payloads for almost every flight and generally expect that not everything tried will work in flight the first time. This is because of the harsh stratospheric environment, with temperatures dipping below -50 degrees Celsius, pressures down to less than 1% of atmospheric pressure, and dramatically increased levels of infrared light, ultraviolet light, and cosmic radiation from which we are generally protected at ground level by the full atmosphere. Most electronic components are surprisingly impervious to the harsh environmental conditions listed above but batteries, in particular, do poorly when they get cold and without battery power electronic systems will fail.

In addition to extreme environmental conditions, payloads can experience severe mechanical stresses due to occasional ascent turbulence, nearly-guaranteed post-burst descent turbulence (AKA post-burst “chaos”), at least on flights where payloads ascend to balloon burst or balloon release and fall from there, and shock associated with landing (sometimes in trees, from which payloads may need to be pulled to the ground, sometimes minus a parachute). Like actual spaceflight, the “recovery” phase of a near-space mission is often the hardest on the payloads (mechanically).

Careful payload construction, based on experience and past failures, plus pre-flight ground testing are critical to identify and mitigate potential failures. For example, to help ensure adequate strength we abide by maxims like “nothing sticks well to Styrofoam, including Velcro – always use zip-ties for final retention” and “avoid glues/epoxies since they get brittle in the extreme cold – use strapping tape (AKA filament tape) for instead.” Mechanical testing can involve “yank tests” on rigging and “drop/roll-down-a-flight-of-stairs tests” on payload shells, realistically weighted but perhaps without actual flight contents, lest something actually break. In general, if a payload shell does not survive aggressive yanking or dropping/rolling, or if such tests cause any components within the shell to come lose, additional strengthening needs to be implemented prior to flight.

Thermal challenges can be mitigated by placing electronic systems, especially their batteries, in Styrofoam containers (usually black in color, for a thermal boost from solar exposure). For stratospheric flights we use exclusively lithium batteries because they are more low-temperature tolerant than other types of battery chemistry. We sometimes use chemical hand-warmers for thermal inertia but these are mostly only useful on ascent (i.e. early in the flight) – they don’t continue to generate heat once in the stratosphere because the atmospheric chemistry is wrong. Heavier, but more effective, are electrical resistive heaters, especially when placed in the vicinity of batteries. Such heaters are sometimes coupled with microcontrollers and temperature sensors so the heaters only turn on when heating is required, thereby making heater batteries last longer.

An environmental testing (AKA “thermal-vac”) chamber is a valuable addition to a near-space-payload development program, though commercial chambers are too expensive for most amateur programs. Such chambers allow pre-flight testing at stratospheric-like low pressures and low temperatures, independently or at the same time (though not necessarily in exactly the order in which they are encountered in an actual stratospheric balloon flight, where pressure decreases continuously to burst but temperature only goes down till the payload enters the stratosphere, after which temperature starts to climb again). During a typical weather balloon flight which lasts only 2 or 3 hours and does not “float” at altitude in the stratosphere, payload overheating is generally not an issue so we rarely do elevated-temperature ground testing (at low pressures). However overheating can be a significant issue for outer-space craft and the thermal-vac chamber described below can be heated using external resistive mesh heaters, as well as cooled, both at low pressure.

Modifications to Brooks' Design and Operation:

Designs exist for at least two home-built, low-cost thermal-vac chambers, one by Brooks [Ref. 1] and one by L. Paul Verhage [Refs. 2 - 4]. We followed Brooks' design most closely, but made significant modifications to both construction and operation. Since details about the original Brooks' thermal-vac design are available [Ref. 1], we will focus our comments on the modifications we made to that design.

The body of our thermal-vac is made of 14 inch OD, 13 inch ID PVC pipe. Our original piece was 27 inches long but we elected to use a table saw to cut it into a 9 inch long section and a second 18 inch long section, in part for easier storage when not in use. Although this doubled the number of faces that needed to be sanded smooth for gaskets, having two sections of different lengths gave us significant added operational flexibility. A chamber using the short section can be pumped down and cooled more quickly than a larger chamber. A chamber using the longer section, on the other hand, can accommodate larger payloads. If need be, we can stack the two sections end to end with a rubber gasket between them and recover the original 27 inch length (Figure 1).

Fig. 1: The three different length-configurations of the thermal-vac chamber.

Brooks elected to permanently glue L-cross-section (garage-door) rubber gaskets to both ends of his PVC pipe. We elected to use removable flat rubber gaskets instead, covered on both sides with high-vacuum grease. We worried, perhaps more than necessary, that gluing on gaskets might make it harder to achieve a good pressure seal at all temperatures and also that "permanent" gaskets would make at least that aspect of the thermal-vac chamber much harder to service. We have found that flat relatively-soft neoprene-rubber gaskets [Ref. 5] make adequate seals if well-greased, despite the fact that they are only rated down to -20 degrees Fahrenheit. We also tried using much-harder (i.e. less squishy) gaskets rated down to -100 degrees Fahrenheit [Ref. 6] but were unsuccessful in getting them to seal well.

One of the most difficult things to accomplish with a thermal-vac chamber is to maintain a vacuum seal at all temperatures despite different thermal contraction coefficients of various parts of the device. Brooks used 3 threaded rods to pull down on transparent Lexan endplates, compressing rubber gaskets, to achieve such a seal. Although we started with Lexan endplates, in part because they allowed us to observe what was happening inside the chamber, we later switched to aluminum endplates because of greater thermal conductivity and to avoid potential cracking. We also decided to increase the number of threaded rods, in order to be able to pull down more uniformly around the perimeter on the rubber gaskets. Since we adopted Brooks' octagonal endplate shape we now use eight threaded rods, one in each corner of each endplate. Figure 2 shows photos of some steps of the construction process, following Brooks' design.

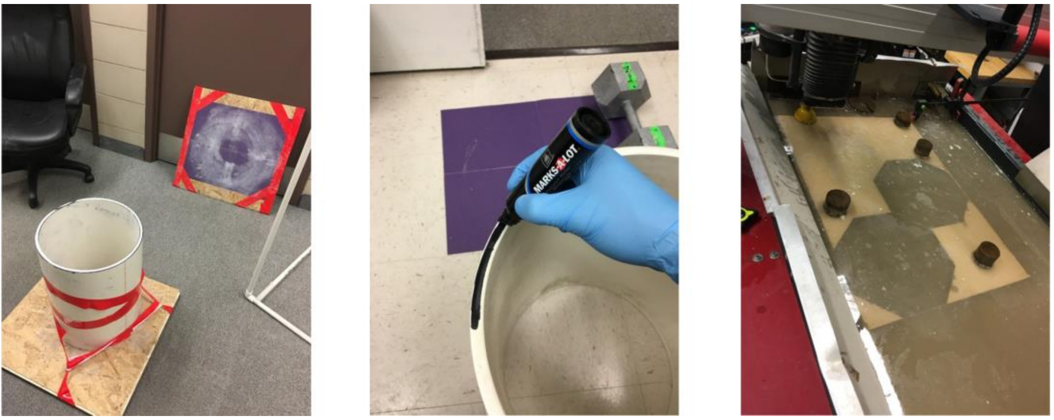

Fig. 2: Sanding the PVC pipe and cutting out Lexan endplates with a waterjet cutter, following Brooks' design [Ref. 1].

Like Brooks, we added a vacuum pump-out port on the curved side of each thermal-vac pipe section. We also threaded three pairs of short aluminum threaded rods through the pipe walls, to serve as electrical feedthroughs. All feedthroughs were covered with a filet of epoxy on both the inside and outside of the chamber to avoid potential vacuum leaks. Feedthroughs were placed close to one end of each pipe section and protected from direct contact with dry ice (see below) when cooling. These simple electrical feedthroughs allow us to power electronics inside the chamber using external power supplies, limiting the number of batteries we expend in testing and preventing the need to insulate/heat internal batteries to protect them from cold conditions. We also have the option of sending data out or in through the feedthroughs, but have not made use of that ability because of the XBee radio system described below.

During thermal-vac tests, it is useful to monitor internal pressure and temperature conditions, and possibly other sensor data as well, without breaking the vacuum seal. To monitor internal conditions in our thermal-vacuum chamber, we developed an Arduino Mega system with a pressure sensor and four thermocouple temperature sensors which can be placed at various locations in the chamber. There are also two fans in the chamber to help circulate residual air when desired. One way to get data out of the chamber without breaking the vacuum seal is to write it to a tiny OLED screen and view that from the outside through a transparent Lexan endplate. After originally implementing that, we later elected to add a short-range XBee radio to the internal Arduino system and send sensor data out by radio telemetry. This radio system can also be used reverse, letting us command internal electronics (such as turning on and off fans and/or internal electrical heaters (if any), from the outside by XBee radio. The system is currently in the process of being transferred to a more-powerful, more-compact Teensy 3.5 microcontroller, which boasts over ten times the microprocessor speed of the Arduino Mega at less than one quarter the size. Once completed and successfully tested, we intend to mount this new microcontroller/sensor suite on a custom printed circuit board for improved electrical connection reliability, ease of use, and compactness. The current Arduino-Mega-based system, as shown in Figure 3, has a lot of exposed wiring.

Fig. 3: The Arduino Mega microcontroller system in the bottom of the thermal-vac chamber for monitoring internal pressure plus temperature at four independent locations. Two fans are attached to the chamber walls. The Arduino Mega is powered through one pair of electrical feed-throughs (lower right). Additional electrical feed-throughs can be used to power items under test, if desired, to limit the number of batteries expended during testing (though payloads are often tested with batteries in place, if battery performance is one of the things being tested).

The most significant operational change from the Brooks' design is that we use dry ice, rather than a deep freezer, for cooling. This allows us to reach significantly lower temperatures than Brooks reported. We adopted this approach after talking to the ballooning team at St. Catherine University who followed Brooks' lead and built a thermal-vac which they have been using, cooled with dry ice, for several years. However, unlike the St. Catherine University team, we do not put dry ice directly inside the chamber when cooling it. To save space, we built a cylindrical enclosure out of Styrofoam to full-enclose the thermal-vac chamber. The Styrofoam was covered in aluminized tape. A one-inch wide gap between the chamber wall and the Styrofoam enclosure served as a volume in which to pack dry ice. We also apply dry ice on the top endplate, though we did not start doing that until after switching from Lexan to aluminum endplates. Enclosed in this way (see Figure 4) the thermal-vac chamber itself is no longer visible, meaning that having transparent Lexan endplates was no longer helpful. XBee radio transmissions are still able to penetrate the chamber, despite the aluminum endplates and the aluminized tape on the insulating enclosure.

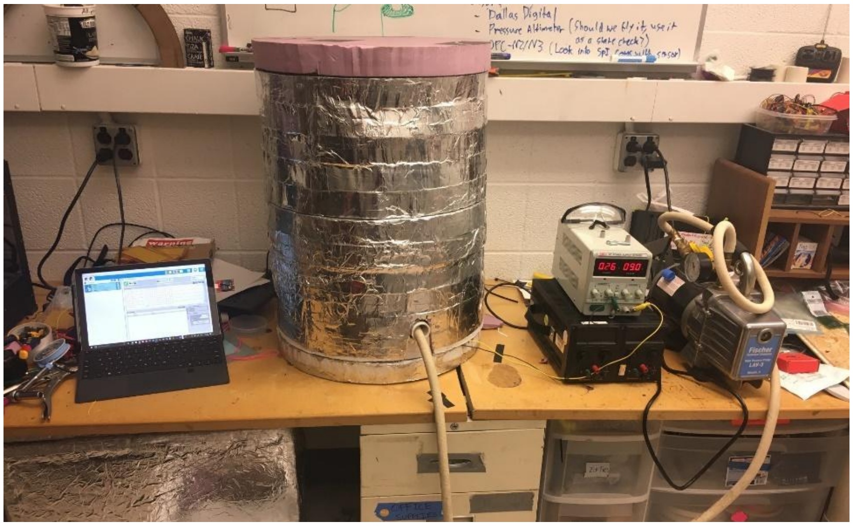

Fig. 4: Setup of a thermal-vac test with vacuum pump (far right – attached to the chamber by a rubber hose), power supply, Styrofoam insulation, and XBee radio (output on laptop screen).

Operation of the thermal-vac chamber and performance

Although we have not investigated all possible permutations of operations when pumping down and cooling the thermal-vac chamber, here are our current recommendations for best practices. Typically the bottom end-plate, bottom gasket, and chamber walls (PVC pipe) do not need to be moved between experiments. The top end-plate needs to be removed to insert and remove test articles (and, often, the chamber-monitoring electronics). High-vacuum grease may need to be reapplied to the upper rubber gasket and endplate between tests, especially if they were “cleaned off” when being stored. When the Styrofoam enclosure is added, paper towels and/or small pieces of Stryofoam are added above the vacuum feedthrough and electrical feedthroughs, all of which are low down near the bottom endplate, to prevent them from directly touching dry ice lest that lead to cracking of the rubber vacuum hose and/or the plastic covers on the clips on the electrical feedthroughs. The vacuum hose goes out through a notch in the Styrofoam enclosure – electrical feedthrough wires go down to the baseplate then out under the Styrofoam enclosure wall (connections visible in Fig. 4).

Chamber-monitoring electronics and test articles should be inserted and fully tested, including XBee radio connections, to ensure they are operating properly prior to closing the chamber. The chamber electronics sit at the vary bottom of the chamber, under a shelf, so test articles go in second. These too should be tested as thoroughly as possible prior to closing the chamber. The test article(s) are typically left on starting at this point and the chamber lid is closed. Nuts with washers on both the bottom and top end plates are screwed on each of the eight threaded rods in a pattern of two crosses, in order to compress the gaskets as uniformly as possible. The experiment is typically turned on at this point and the lid is closed. Nuts with washers underneath are screwed carefully on each of the eight threaded rods in a pattern of two crosses in order to tighten as uniformly as possible. All eight threaded rods are tightened as tightly as is practical under non-cooled, non-evacuated conditions, then re-tightened later as described below.

For cooling tests, dry ice is now applied to the outside of the PCV chamber (but inside the Styrofoam enclosure). Typically we use about 20 pounds of dry ice for the small thermal-vac configuration and 30-40 pounds for the large thermal-vac (and even more for the stacked configuration). All but 10 pounds of the dry is is finely crushed and spread around the sides of the thermal-vac in the ~1-inch-side gap between the PVC pipe and the Styrofoam enclosure. The final 10 pounds, in block form, is set on the top plate. A Styrofoam top is then added to the Styrofoam enclosure to minimize the dry ice sublimation rate.

The chamber is then pumped down, even before the chamber has fully cooled. Once vacuum is attained, which only takes a few minutes, the nuts on the threaded rods are re-tightened (in the "double cross" pattern). This requires removing the Styrofoam cover (at least). To speed cooling we sometimes intentionally vent the this chamber at this point, or at least turn the vacuum pump off so as not to combat possible (likely) small leaks that occur during cooling. On the other hand, if the test requires staying at low pressures as much as possible then the vacuum pump is left on during the cooling, which can take one or more hours, to keep ahead of possible leaks. The threaded rods are given a final retightening (quickly, to avoid too much heating) when the chamber interior reaches the desired lowest temperature and has been pumped back down again. Chamber conditions are monitored, and possibly test articles too, during the cooling phase. If any of the electronics stop working, the chamber may need to be opened for troubleshooting and the test restarted. That said, it is best (though admittedly not always practical) to be able to monitor data from test articles in real time during thermal-vac testing. Hint – adding XBee radios to test articles might be an option, even if data telemetry is not planned for use during flight.

Once fully cooled and pumped down, our modified thermal-vac can achieve temperatures down to -65 degrees Celsius and pressures down to 0.0005 atm, either independently or at the same time and hold these conditions for 3-4 hours and is sometime left overnight, by which point will have mostly sublimated and the chamber will have started to warm up. Such temperatures are similar to those experienced by stratospheric payloads as they pass through the tropopause, at the base of the stratosphere (which ranges from 30,000 to 40,000 feet above sea level). Such pressures are lower than those experienced by stratospheric payloads at 120,000 feet above sea level (according to the Standard Model of the Atmosphere), the practical altitude limit of our weather balloon flights. Thus our thermal-vac chamber can approximately reproduce the extreme temperature and pressure conditions up to 120,000 above sea level. This is adequate for testing our stratospheric ballooning payloads and is even similar to the conditions in which orbital spacecraft operate.

Payloads already tested in the thermal-vac:

Several interesting and unique payloads have already been tested in the thermal-vac chamber. They include optical particle counter calibration for MURI research, payloads being developed for local weather balloon flights, and a CubeSat being built for outer-space deployment.

One early motivation for building a thermal-vac was to create an apparatus capable of calibrating commercial optical particle counters for use in extreme stratospheric conditions. While it has since been decided that another, even more robust thermal-vac is needed to fully accomplish these experiments, preliminary tests have been conducted with optical particle counters in the current chamber. Qualitatively speaking the particle detectors do operate (but struggle somewhat) in extreme conditions with uncharacterized particulate content. Additional testing that includes cross-comparison between stratospheric-rated (but expensive) optical particle counters and low-cost particle counters is planned for the near-future, including flying a set of particle detectors on the late-summer 2019 HASP flight. Once completed, the HASP payload will be tested in our thermal-vac before taking it to CSBR in Texas for thermal-vac testing in July 2019.

Several local ballooning payloads have been tested in the thermal-vac, with valuable results. Examples of payloads include “SMART” balloon release units plus an “AeroBiology” payload. Thermally-related problems with the payloads have been uncovered and subsequent tests, after making changes, have shown improved performance and given us confidence in the value of doing pre-flight thermal-vac testing.

Perhaps most interesting of all, a genuine CubeSat called SOCRATES being built at the U of MN – Twin Cities, has started tested in the thermal-vac chamber. SOCRATES is scheduled to be delivered for launch by August 2019 and our new ability to do local thermal-vac testing should assist the SmallSat team in getting it ready for final integration and testing. In the first thermal-vac test SOCRATES did in fact experience a failure after a few hours, though it turned out to be a segmentation fault in the code rather than a thermal/pressure-induced failure. Our test provided invaluable insight into an issue that needed to be fixed prior to launch into outer space.

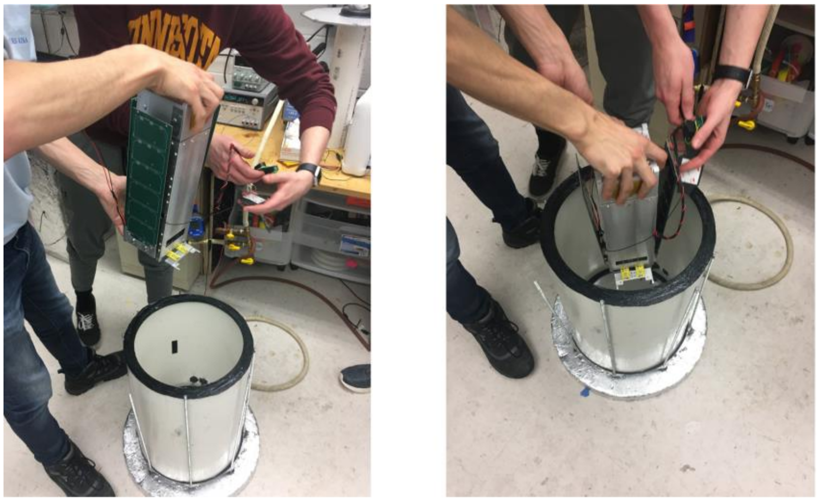

Fig. 5: The SOCRATES CubeSat (engineering model) being placed in the thermal-vac chamber for a low-temperature/low-pressure test on April 11, 2019.

Future Work:

The thermal-vac has already been used to ground-test several stratospheric payloads and one outer space payload, the SOCRATES CubeSat. However, the current design is not very well suited to accomplish one of our original goals – the calibration of optical particulate detectors in stratospheric conditions. This is because the current set-up does not allow the controlled introduction of specific concentrations of known-size particles. Thus, we intend to develop yet another thermal-vac system which will have an adjustable flow feature into which we can introduce and measure concentrations of known particulates in a wide variety of temperature and pressure conditions. That will be a custom installation, so we expect the current, more-generic thermal-vac chamber(s) will attract more users and probably get more use.

As stated above, we are working on replacing the current Arduino Mega microcontroller system with a Teensy microcontroller system. Most of the code will carry over and many of the same sensors will be recycled as well. The exception is that the analog Honeywell pressure sensors [Ref. 7] are being replaced by a potentially more-accurate Parallax MS5607 Altimiter/Pressure module [Ref. 8]. Other minor modifications need to be made since the Teensy is a 3.3-volt device whereas the Arduino Mega is a 5-volt device. The Teensy microcontroller and sensors will ultimately be placed on a printed circuit board for optimal performance, form-factor, compactness, and ruggedness (e.g. wires won't get snagged).

The ability to simulate a real balloon flight by changing pressure and temperature in the way they occur during an actual balloon flight is a potential future goal of this project. This could possibly be achieved by hooking up a throttling mechanism to the (constantly running) vacuum system and using resistive heaters to combat dry ice cooling. Ultimately data from actual (and proposed) balloon flights could be fed into a control mechanism that would attempt to replicate temperature/pressure conditions in the right order (though perhaps not for the right duration) for an actual balloon flight, not just the most extreme low pressure and low temperature conditions that the current thermal-vac aims for. Such a "programmable" thermal-vac might allow us to test performance in a wider variety of scenarios, including balloon flights with a "float at altitude" phases where overheating might in fact become an issue even in the stratosphere (such as has happened to some payloads flown on HASP flights which can float for multiple hours at stratospheric altitudes).

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