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Preliminary Thermal Validation Tests for Education-Class CubeSats and Weather-Balloon Payloads

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Abstract

Low development and launch costs of CubeSats, a type of small spacecraft typically one to three liters in volume, have made space science accessible to educational institutions, offering engaging opportunities for students in the science, technology, engineering, and mathematics (STEM) disciplines. Some university teams working on these education-class CubeSats conduct high-altitude flight experiments using balloons to test their instruments in the harsh environment at the edges of the troposphere and the stratosphere. Whether for the balloon experiment or for the actual spaceflight, temperatures of the operating environments are of concern. Instruments flown in space must be qualified for wide thermal ranges (e.g., −40°C to 70°C) in vacuum conditions. Likewise, instruments flown on the balloons must be able to operate in a similarly large range of temperatures (e.g., −50°C to 50°C) in the reduced pressure environment. Unfortunately, a thermal-vacuum chamber—standard testing equipment for spacecraft—is not accessible to many university teams. This paper presents incubator testing and cooling-bath testing methods as preliminary thermal validation tests that may be carried out easily, safely, and inexpensively, without any need for the expensive thermal-vacuum chamber. We also discuss an add-on demonstration in which a CubeSat prototype was flown on a weather balloon to an altitude of ~16 km. The two lab tests and the flight described in this paper may be adopted by university teams to conduct preliminary thermal validation tests for their education-class CubeSats and weather-balloon payloads.

1. Introduction

With the establishment of CubeSat development standards over two decades ago (Puig-Suari, Turner, and Ahlgren, 2001), these small satellites have been making space science accessible to a large number of educational institutions. One of the reasons CubeSats achieve low costs is their small size, being measured

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in the unit of "U", where 1 U has the dimensions of 10 cm × 10 cm × 10 cm. The most common sizes of CubeSats have been 1-3 U, although in recent years, one sees an increasing number of CubeSats with higher capabilities and larger sizes, e.g., 6 U or even 12 U (Skrobot and Coelho, 2012).

Among 400 CubeSats launched between 2002 and 2016, approximately half of them were built by universities (Zea et al., 2016). In addition, the number of university-built CubeSats launched in a given year has increased over time. During the 24-year period from January 1994 to December 2017, a total of 344 university-built spacecraft were launched into space; approximately two-thirds of them were CubeSats launched in the last eight years (i.e., January 2010 to December 2017) (Swartout, 2018). Recognizing the CubeSat's potential "to attract and retain students in the science, technology, engineering, and mathematics disciplines," NASA established Educational Launch of Nanosatellites (ELaNa), which allows university-built CubeSats to be launched by NASA rockets (Skrobot and Coelho, 2012). To ensure that their CubeSat is flyable for ELaNa, a team must conduct environmental testing, which can "include vibration, thermal vacuum bakeout, shock, and electromagnetic interference/electromagnetic compatibility (EMI/EMC) testing" (NASA CubeSat Launch Initiative, 2017). A team must also ensure that a ground station can locate, send commands to, and downlink data from the CubeSat in orbit. In addition to those tests conducted in the lab, some features of CubeSats may be tested from high-altitude balloon tests.

1.1. Balloon Flights for Preliminary Testing of CubeSats

According to the Standard Atmosphere model, the atmospheric pressures at altitudes of 15 km (nearly at the upper edge of the troposphere) and 30 km (in the stratosphere) are 12% and 2% of the values at sea level, respectively, and the temperatures at those altitudes are −57°C and −47°C, respectively (International Organization for Standardization, 1975). A balloon flight is useful for testing various features of small satellites, including long-range radio operated in harsh environments (Kimm et al., 2015; Tømmer et al., 2015). Seitzer et al. (2018) flew a balloon payload equipped with light-emitting diode (LED) panels, and demonstrated the feasibility of using an active illumination on spacecraft to track the spacecraft's position, attitude, and telemetry.

Balloon experiments also offer educational values to students working on small-satellite projects. For instance, the Missouri University of Science and Technology Satellite Research Team has developed a CubeSat prototype and flown it on a balloon for the University's aerospace engineering curriculum (Davis et al., 2019). Through the Air Force Office of Scientific Research (AFOSR) University Nanosatellite Program, 42 students in a two-semester senior design course at the New Mexico State University designed a nanosatellite prototype that collected photomultiplier data and measured intensities of the ultraviolet light (Horan, Hull, and Alvarez, 2012). More than 350 undergraduate student teams have participated in High Altitude Research Platform (HARP) balloon experiments. With support from NASA's ELaNa program, the AFOSR University Nanosatellite Program, and NSF's CubeSat program, these students were able to get involved in the development of many small satellites, two of which have been deployed into orbit (Voss et al., 2015).

During those balloon flights, the thermal state within the CubeSat prototype is affected by various factors, including the heat rejection to the cold outside air, the radiation from the sunlight, and the internal heat generated by electronic power consumption. Quantifying these effects is often challenging, as the material used in the outer casing of the payload alone could affect the temperatures at various locations on the payload. The thermal effects can be modeled using such methods as finite-element analysis. However, results from theoretical calculations are often unreliable, partially because many input parameters of student-built prototypes may be unknown, such as the effectiveness of thermal insulation provided by the structural skin. A CubeSat team faces the challenge of not knowing how, or whether, their instruments will perform when flown on balloons.

1.2. Thermal Validation Tests

Whether for balloon flights or spaceflights, there is a need for lab tests to validate the operational capabilities of the instruments. Among the validation tests CubeSats must pass to qualify for spaceflights, the thermal-vacuum test is perhaps the most important and expensive (Busch et al., 2013). Since thermal factors influence the success of any CubeSat missions, thermal-vacuum chamber tests will help ensure the spacecraft operates within the anticipated thermal range.

A CubeSat launched into low Earth orbit is subject to heat from various sources, including sunlight (both direct and albedo), infrared radiation from Earth, and internal heating due to electronic power consumption. With an inability to reject heat to the surrounding environment via conduction and convection (there is no air in space), the temperature may rise within the spacecraft. Overheating may cause such problems as damaged electronic components, melted battery packs, and broken solder joints (NASA CubeSat Launch Initiative, 2017).

Because sunlight is the largest heat source for the CubeSat body (Escobar, Diaz, and Zagal, 2016), the total heat flux on the orbiting CubeSat drops sharply as the spacecraft flies into the shadow side of the planet. Occupying an extremely low-thermal environment for too long is also a problem, because low temperatures degrade performance, if not halt the operation, of batteries and electronic components.

The thermal-vacuum tests validate the instruments' operational capabilities both at the high and the low ends of the anticipated thermal bounds. There are two types of thermal-vacuum tests: bakeout tests and cycling tests. Nearly all CubeSat missions require the thermal-vacuum bakeout tests, in which a spacecraft is placed into a heated vacuum chamber for long enough to outgas contaminants trapped within the instruments, thereby reducing the probability of malfunction during the actual spaceflight.

The thermal-vacuum cycling test, on the other hand, is not typically an official acceptance test, but an internal functionality test that teams perform for themselves. The thermal-vacuum cycling test simulates the anticipated thermal cycling experienced during space missions (NASA CubeSat Launch Initiative, 2017). To properly simulate the space environment, the pressure inside of the thermal-vacuum chamber needs to be very low, e.g., 10−5 torr (i.e., ~10−8 atm) (George C. Marshall Space Flight Center, 2020), because the presence of atmosphere introduces alternative paths for heat transfers via conduction and convection, both of which have diffusing effects on the concentration of heat within the instruments and structure. As a result, the presence of atmosphere can reduce the temperature of the components, both in the high- and low-temperature tests. The difference in the temperatures of the components tested under the two conditions could be 20°C or more (Gibbel, 1990).

Unfortunately, most teams working on the education-class CubeSats do not have thermal-vacuum chambers. Outsourcing this test may be costly—e.g., $4,000 per experiment (Space Dynamics Laboratory, 2019)—and require travel to a lab with such a facility. Although the final qualification tests (e.g., for NASA's missions) require an actual thermal-vacuum chamber, the teams may benefit greatly from conducting preliminary thermal tests with ease, safety, and low cost.

2. Objectives

In this paper, we consider simple thermal testing methods that may be used for preliminary validation of education-class CubeSats and balloon payloads. The thermal cycling test, which simulates the anticipated thermal cycling during the spaceflight, probes potential risks that may lead to failures of missions. A reasonable data output validates the survivability and the operational capabilities of the instruments in the target thermal environments. However, the cost or access to the test facility capable of such a test may be prohibitive for many teams working on education-class CubeSats.

As an easy and inexpensive substitute for the thermal vacuum cycling tests, we present lab tests that are conducted in non-vacuum conditions. Although conducted under standard atmospheric conditions, these lab tests allow the instruments to be tested at low and high temperature environments (e.g., −50°C and 50°C for two hours at each extreme), as done in the thermal-vacuum cycling tests. When these tests are conducted properly, we expect the interior temperature of a CubeSat prototype body (e.g., initially at a room temperature) to exhibit a warming or cooling effect, asymptotically approaching the ambient temperatures targeted in those lab tests.

For a high-temperature test, there are several possible candidates for experimental devices (e.g., an oven), so our version of the test was included primarily for completeness and as an example. We made use here of an incubator in a biology lab, which is normally used for cell culture growth and maintenance. The incubator can stably maintain a target temperature set by an experimenter. We used a representative temperature of 50°C.

While there are many methods to create a heated testing environment, testing at a low temperature is more challenging, because devices that produce desired temperatures are often unavailable. A freezer, for instance, may be too warm or too cold for the needed testing.

For a low-temperature lab test, there is a gap in the literature on methods available for use by a typical team working on education-class CubeSats and balloon payloads. In this paper, we present a technique of cooling bath for producing temperatures required for balloon flights or actual spaceflights. The low temperature of a cooling bath is maintained by a cooling agent (e.g., dry ice) that depresses the temperature of the solvent. We use a representative temperature of −50°C.

Our thermal range of −50 to +50°C is also representative of the thermal-vacuum cycling tests conducted prior to the high-altitude research balloon flights (Guzik et al., 2018). In those tests, the testing duration of two hours at each end of the temperature bounds is considered typical (LaSPACE HASP Team and NASA Balloon Program Office, 2020). Our incubator tests and cooling-bath tests are conducted in a standard atmospheric condition. Such a non-vacuum testing, which introduces alternative paths for heat transfers through atmospheric conduction and convection, is not a perfect substitute for vacuum testing. A non-vacuum, low-temperature test provides a more severe testing environment, because the presence of cold air can make the temperature of CubeSat components much lower than in the vacuum condition; non-vacuum high-temperature testing, on the other hand, provides a more moderate testing environment, because the presence of atmosphere could diffuse the high concentration of temperature within a hardware piece (Gibbel, 1991). That said, given the cost of the thermal vacuum tests, our non-vacuum tests are useful preliminary thermal tests.

This paper also discusses a weather balloon flight of a CubeSat prototype as an add-on demonstration, in which the instruments are subject to ranges of temperatures and pressures over varying altitudes. Such activity validates the functionality of the instruments, because the measured temperatures can be compared against the values predicted from the Standard Atmosphere model at corresponding altitudes.

The weather balloon used in our experiment is a latex sounding balloon, a few meters in diameter when inflated. The use of a weather balloon has the advantages of low cost and logistical simplicity, although when the payload exceeds certain sizes and weight, the flight within the US must comply with the Code of Federal Regulations (CFR) Title 14 Part 101. Our weather balloon is smaller and lighter than scientific research balloons flown, for example, by NASA’s Balloon Program Office and the Columbia Scientific Balloon Facility; their balloons have the payload capacity of several metric tons and flight duration exceeding 40 days. Scientific balloons such as this, i.e., zero-pressure polyethylene film balloons, were used in Louisiana State University’s High Altitude Student Platform (HASP), which allowed many student-built payloads to be tested in a near-space environment (Guzik et al., 2008).

In our demonstration, a relatively small weather balloon was used to fly the CubeSat prototype to the altitude of ~15 km, where the temperature is approximately −57°C and the pressure is approximately 12% of the sea-level value. This flight test serves as a proof-of-concept demonstration.

3. The CubeSat Prototype

We demonstrate the thermal test methods using a simple prototype of CubeSat. The 3D-printed prototype body (Figure 1) provides a mock-up structure of a 1 U CubeSat.

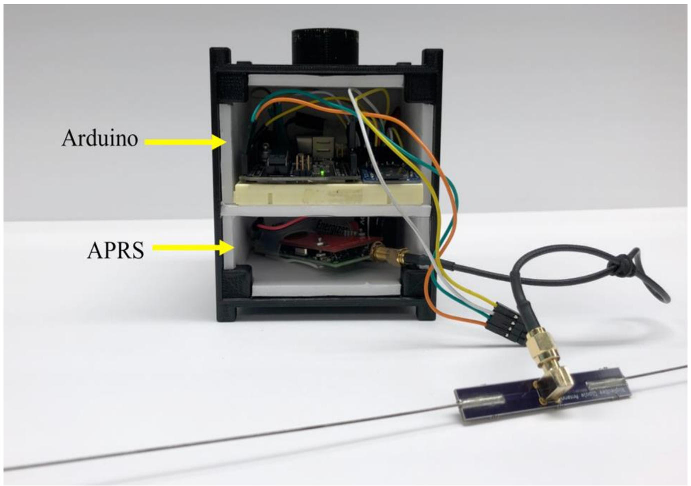

Figure 1. Internal view of the 1 U CubeSat prototype containing Arduino and APRS modules.

The prototype used in our demonstration is based on Arduino, a popular microcontroller which has also been considered for use in CubeSat applications (Peters, 2016). Thermal measurements are enabled by the Arduino Uno R3 microcontroller, the BME280 sensor (for the ambient air temperature), and the DHT22 sensor (for the internal air temperature).

We also make use of the Automatic Packet Reporting System (APRS), which is an amateur-radio-based synchronous communication system used by many users within a given geographical area, where received data are uploaded to the Internet to be shared globally (Bruninga, 2020; Bruninga et al., 2017). The APRS transmitter, which has a built-in GPS tracking unit, fits inside of the 1 U prototype body, but its antenna was attached on the outer surface of the prototype body. The power for the instruments was supplied by the 9V Energizer Ultimate Lithium Battery, which has an operational thermal range of −40°C to 60°C (Energizer, 2020). Most other components mentioned above were assumed to have typical thermal operational ranges, e.g., −40°C to 85°C.

4. Method

4.1. In-Lab Thermal Test at High Temperature

For the thermal test at a high temperature, we used an incubator (Lab-Line 4628 Incubator Shaker, shown in Figure 2), which is normally used for growing microbiological or cell cultures in a biology lab. Prior to the experiment, the incubator was preheated for a more than sufficient duration to ensure thermal stability at 50°C. During the testing duration of two hours, the temperature of the incubator was manually recorded every seven minutes (on average). The air temperature inside of the CubeSat prototype was measured using Arduino with the BME280 thermal sensor, which recorded data every 15 seconds. Because polylactic acid (PLA) used in 3D printing is a thermoplastic material that softens at the chosen testing temperature of 50°C, the CubeSat prototype's body for this test was replaced by acrylic plastic.

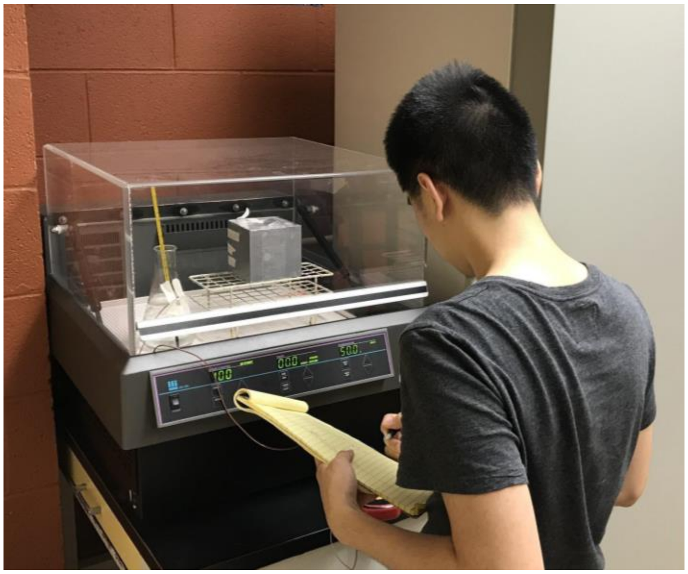

Figure 2. Prototype undergoing high-temperature tests.

4.2. In-Lab Thermal Test at Low Temperature

The in-lab thermal test at low temperature was the main challenge of our study. Teams working on education-class CubeSats and weather balloon payloads would need to know, for example, how their instruments (rated for > −40°C) would perform when placed in an enclosed casing (with partial thermal insulation) and subjected to < −50°C for some duration of time. Unlike the case of high-temperature experiments, choices of devices for producing low temperatures are limited. This is a problem, as there may not be any accessible devices that are able to produce the target temperature (e.g., a freezer being too warm or too cold).

We show how a technique of cooling baths could potentially serve as an easy, safe, and inexpensive preliminary thermal validation test. An example set-up is shown in Figure 3. In a cooling bath, a test specimen is submerged into the bath with a temperature that has been depressed by cooling agents, common choices being water ice and dry ice. With our target temperature of −50°C (lower than what is possible with water ice), an obvious cooling agent was dry ice, which has the sublimation point of −78.5°C. Dry ice is relatively inexpensive and easily obtained (e.g., from a local liquor store, in our case).

Figure 3. Cooling bath based on dry ice and the RV antifreeze was too warm (photo). Our target temperature (−50°C) required that a substantial portion of the solvents be replaced with ethanol.

Choosing a solvent required additional thinking, as there are numerous candidates. Empirical studies have shown that, when mixed with an excess of dry ice, different solvents equilibrate at different temperatures. For example, methanol, ethanol, acetone, and isopropanol were found to produce bath temperatures between −80°C to −70°C. (The melting points of those solvents are −114°C to −89°C; the temperatures of cooling baths are higher than the melting points of the solvents used.) We also preferred solvents that allowed our cooling-bath experiments to be carried out by students easily and safely. As such, the solvents were evaluated for their toxicity, ease of handling, and environmental impact.

According to Capello, Fischer, and Hungerbuhler (2007), there are many reputable studies on the environmental, health, and safety (EHS) impacts of substances; among over 100 substances included in their database, these researchers chose 26 commonly used pure organic solvents (e.g., alcohols, alkanes, dioxanes) for comprehensive EHS analysis, and ranked ethanol and methyl acetate as the least harmful. Methyl acetate is not as easily obtained as ethanol, so we chose ethanol as a solvent for the cooling bath. However, the cooling bath temperature using ethanol as the only solvent is −78°C (Lee and Jensen, 2000), which is a problem because we chose −50°C as our target temperature.

We faced a similar situation as Lee and Jensen (2000), who frequently needed to create cooling baths at temperatures between −80°C and −20°C, but found that methods reported in the literature proved impractical due to the unavailability of solvents or to the thermal instability of the bath. The researchers showed how mixing ethanol with ethylene glycol, which produces bath temperatures of −78°C and −12°C, respectively, would produce a cooling bath at temperatures between those two values. In fact, in the case of those two solvents, the relationship between the target temperature and volumetric mixture ratio was approximately linear: an experimenter can easily predict the bath's temperature by changing the mixture ratio of the two solvents.

Ethylene glycol, which is an active ingredient for automotive antifreeze, is unfortunately toxic to humans and animals, requiring extra care in handling and disposal. For this reason, we propose using an antifreeze solution based on propylene glycol as a second solvent to be mixed with ethanol. Commonly considered as a non-toxic substitution for ethylene glycol (Thomas, 2008), propylene glycol is used as an active ingredient for antifreeze for recreational vehicles (RVs). The pink-colored solution, which could be obtained from any automotive supply store, is non-toxic and can be disposed of into a drain. The particular brand of RV antifreeze used in our experiment was Super Tech RV & Marine Antifreeze (manufactured by Fox Packaging Co., St. Paul, Minnesota, US), which was rated for −46°C. The antifreeze contains 30% propylene glycol, with the remaining 70% being water and additives.

We used equal parts of ethanol and RV antifreeze, and found that the resulting cooling-bath temperature was approximately −50°C. To conduct the cooling-bath experiment, we filled a container with a mixture of ethanol and RV antifreeze, whose temperature was depressed by adding pellets of dry ice (Figure 4). The CubeSat prototype was placed in a sealed bag and submerged into the bath. Although not shown in the figure, a weight was placed on the top of the sealed bag to ensure that the bag submerged completely into the bath. Spacers were placed between the prototype body and the sealed plastic bag so the bag retained its shape and so contact was prevented between the prototype body and the bath. The air, which surrounds the prototype body, is what cooled to the target temperature.

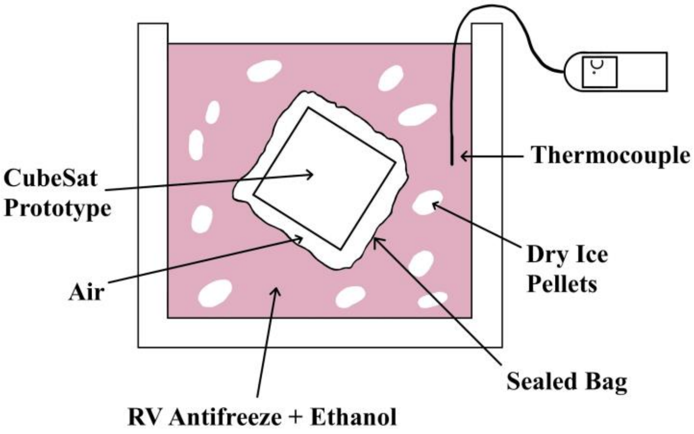

Figure 4. The CubeSat prototype was enclosed in a sealed plastic bag and fully submerged into a cooling bath at −50°C.

A thermocouple was used to measure the bath's temperature (Figure 4), which was manually recorded every 5–10 minutes. Dry ice pellets were added periodically to maintain the target temperature. During the testing duration of two hours, Arduino recorded the CubeSat's internal air temperature every 15 seconds.

5. Results

5.1. Incubator

Figure 5 shows the results from the high-temperature test, which lasted for two hours. Although the target temperature was set to 50°C, the actual temperature reported by the machine ranged from 49.0°C to 50.3°C. The slight variance is indicated by the "+" marker interspersed along the blue dashed line. The blue dashed line is the fitted data of those measurements, and the best estimate of the measured incubator temperature is 49.9°C.

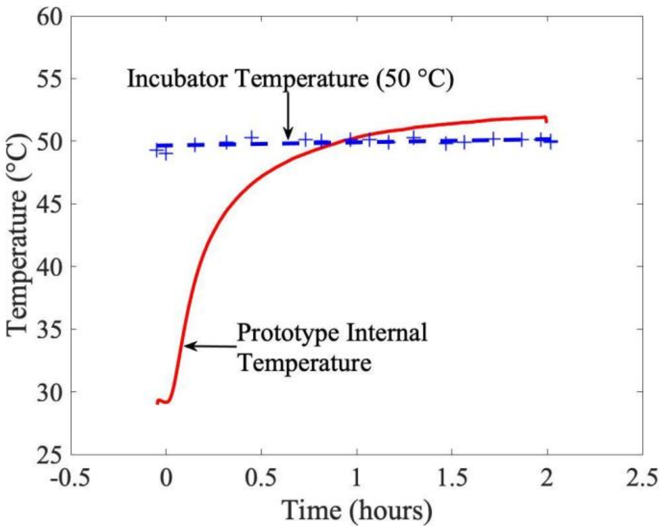

Figure 5. Results from the high-temperature testing using an incubator.

The red solid line shows the temperature of air inside the CubeSat prototype, as measured by the Arduino's BME280 sensor. In the beginning of the experiment, the prototype's internal temperature was 29°C—the temperature of the room in which the incubator machine was located. Once the prototype was placed in the incubator, the internal temperature started to rise, but the rate of increase in the temperature decreased over time. After the two-hour testing duration, the internal temperature was 51.9°C. The fact that the final temperature was 2°C higher than the incubator temperature could be (we believe it is likely) attributed to the electronic power consumption within the enclosed prototype structural casing.

5.2. Cooling Bath

The result from our cooling-bath experiment is shown in Figure 6. The measured temperature of the cooling bath ranged from −56°C to −41°C (shown as

"+" marker). The blue dashed line is a fitted line plotted on those data points, where the best estimate of the bath temperature is −50.1°C.

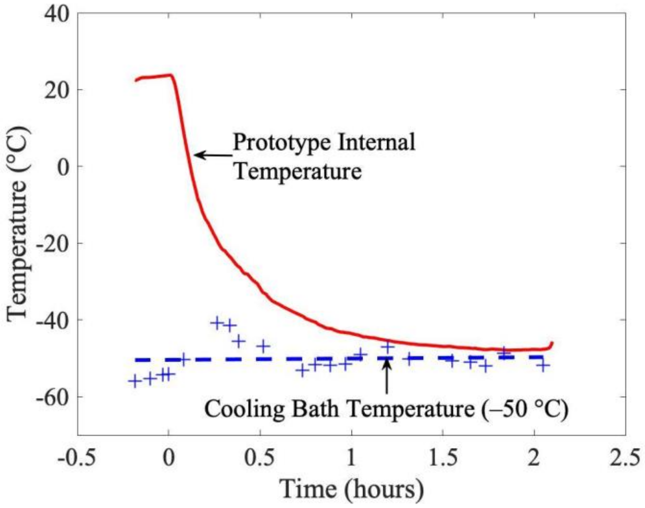

Figure 6. Temperature change of prototype internal temperature versus cooling bath temperature.

The red solid line shows the prototype's internal temperature recorded by the BME280 thermal sensor. The internal temperature was initially 23.7°C, which was the room temperature at the time of experiment. As soon as the prototype was submerged into the cooling bath, the temperature of the air inside the prototype started to decrease sharply, although the rate of decrease lessens over time. Figure 6 shows the exponential decay of the internal temperature with respect to time. At the end of the two-hour experiment, the internal temperature reached its lowest value −47.9°C, approaching the liquid's average temperature (i.e., −50.1°C). As in the case of the high-temperature incubator test, the final internal temperature was ~2°C higher than the temperature of the environment, likely due to the heat generated by power consumption. The experiment showed that the instruments placed in the flight configuration would be fully functional in an environment at −50°C for two hours.

6. Flight Demonstration via Weather Balloon

In addition to the two lab tests that simulate the thermal cycling test, we conducted a weather-balloon flight as an add-on demonstration. The CubeSat instruments (which were tested in the non-vacuum lab tests) are now subject to a range of thermal and reduced-pressure conditions corresponding to varying altitudes.

Figure 7 shows a photo image of our prototype near the maximum altitude. We see antennas for the APRS transmitter extending beyond the 1-U dimensions of the 3D-printed structure. Although not seen in the photo, the DHT22 sensor (placed inside of the body) and the BME280 sensor (placed outside) were used to measure the temperatures of the air inside the enclosed cubic structure and the outside ambient air, respectively.

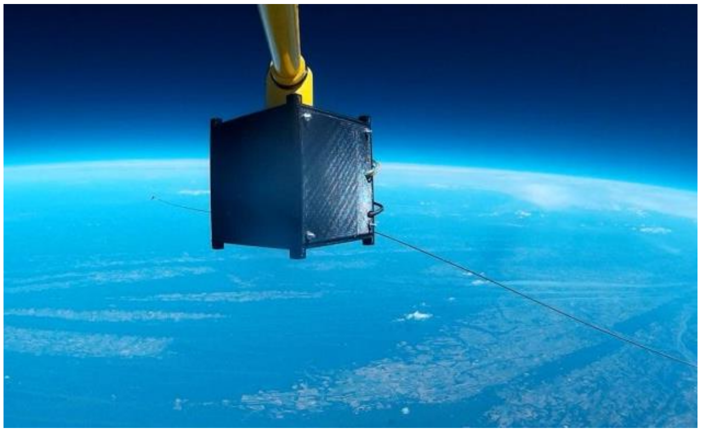

Figure 7. This image of the CubeSat prototype was captured at an altitude of 16 km. We note that the apparent curvature of the horizon is caused by the wide-angle lens of the camera.

The flight demonstration enables us to validate the functionality and accuracy of thermal sensors, as the measured temperature could be compared against the expectations, e.g., the values from the standard atmospheric model. A balloon demonstration is also important because GPS tracking and any features connected to the radio communications cannot be fully tested in lab testing.

If the CubeSat stayed on the ground, the internal temperature of the enclosed cubic body could rise due to the radiation from the sunlight, and, to a lesser extent, the heat generated by the power consumption of the instruments. The ambient air temperature during the flight, on the other hand, decreases as the balloon ascends to higher altitudes, resulting in an escape of heat to the outside air through conduction and convection. The net heat transfer was difficult to quantify, as the density of the air reduces dramatically as the altitude increases. We also did not know the effectiveness of the thermal insulation provided by the structural skin.

If our instruments failed due to the temperature, we conjectured (based on previous experience) that the more likely reason would be a cooling of the body's internal temperature, rather than in a rise in temperature. To ensure all instruments worked properly during the flights, we placed hand warmers in the prototype 15–20 minutes before the flight. The hand warmers, which served the purpose of preheating the structure, were likely ineffective soon after being placed in the enclosed body, as the hand warmers' heat generation requires oxygen to react. (After completing all experiments, we now think that the hand warmers were probably unnecessary.)

On June 27, 2019, at 9:45 AM, our balloon payload was released in central Pennsylvania. One hour and five minutes after launch, the balloon payload reached its maximum altitude of 16.3 km (~54 thousand feet). The balloon burst, and the payload descended via parachute. The payload eventually landed 68 km east of the launch site. Because APRS was set to transmit its coordinates in real-time, we could chase the balloon and locate it after landing. The total time of flight was 1 hour 35 minutes. The near-ground temperature reported by University Park Airport (FAA LID: SCE) at the time of the launch and landing were 28°C and 30°C, respectively.

Figure 8 shows the thermal-measurement results from the flight test. The blue dashed line and the red solid line show the external temperature measured by the BME280 sensor and the internal temperature measured by the DHT22 sensor, respectively. The horizontal axis shows the time since launch (so time zero is at 9:45 AM) to the moment of landing (11:20 AM).

The temperature of the air at the launch site was recorded as 30°C, initially. During the first half of the flight, when the balloon was ascending, the ambient air temperature decreased with respect to rising altitudes. Although a temperature-altitude plot was not included in this paper, the two variables exhibited an approximately linear relationship, as expected from the Standard Atmosphere model (International Standard Organization, 1975). The lowest recorded external temperature was −55°C, which was also close to −57°C, as expected in the Standard Atmosphere model. After the balloon burst, the CubeSat prototype descended via parachute. As the altitude decreased, the air temperature increased. At the moment of landing, the measured ambient air temperature was 30°C, which was consistent with the temperature reported by the local airport.

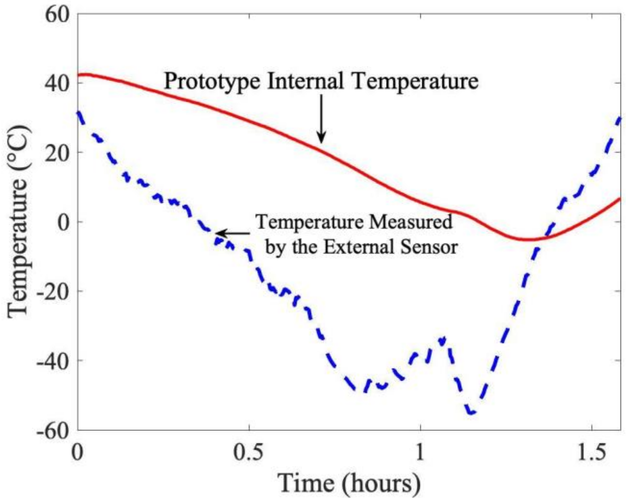

Figure 8. Recorded internal and external temperature during the weather-balloon flight. The time axis indicates the flight duration from launch to landing.

The red solid line shows the internal temperature recorded by the DHT22 sensor. We can see in Figure 8 that the internal air temperature (42°C) was initially higher than the ambient temperature (30°C) due to the use of the aforementioned hand warmers. As the payload ascended into the sky, the heat was escaping into the ambient air, which continued to cool. Even so, the air inside the prototype never went below −5°C, presumably due to the hand warmers, the partial thermal insulation provided by the walls of the prototype body, and the warming effects from the sunlight. A similar lag between the external and internal temperatures was observed during the parachute-descent phase. The internal temperature at the time of landing was 6°C, significantly lower than the ground air temperature of 30°C.

7. Conclusion

High-altitude testing using a weather balloon has been considered an effective demonstration of some features of CubeSats. Whether for high-altitude balloon flights or actual missions in outer space, the hardware must be prepared for harsh thermal environments. Unfortunately, thermal-vacuum chambers—standard testing equipment for spacecraft—are not accessible to many university teams. To those working on education-class CubeSats, there is a need for easy preliminary testing methods. For many teams, conducting high-temperature testing may not be a serious obstacle, since there are choices of heating devices. In our experiment, an incubator in a biology lab was used to produce a testing environment at 50°C. Conducting a similar test at the low-temperature bound is more challenging, due to the lack of readily available and adjustable devices (e.g., a freezer that is too warm or too cold). We propose a cooling bath as a testing method for preliminary thermal testing at low temperatures. In our experiment, the target temperature of −50°C was produced by adjusting the volume ratio (50:50) of ethanol and RV antifreeze (containing 30% propylene glycol), which were selected for their nontoxicity, low cost, and availability. Finally, a high-altitude demonstration was conducted by flying our CubeSat prototype on a weather balloon. The activities described in this paper serve as easy, safe, and inexpensive preliminary thermal tests, as well as a compelling flight demonstration for teams working on education-class CubeSats and weather-balloon payloads.

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