COB-2023-0445
ANALYSIS OF A THERMAL VACUUM CHAMBER PROJECT FOR TESTS IN NANOSATELLITES

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Abstract. *To guarantee that a nanosatellite complies with operating requirements, taking into account the launch, commissioning, and operation phases, it must undergo a series of qualification tests, whether requested by the launch vehicle supplier or the project team. Thermal tests are critical to the design of a nanosatellite, and some are part of the launch qualification list. Among such tests, the bake-out and thermal cycling tests stand out, which simulate the sudden increase in temperature and the life cycle of the satellite in the orbit of interest, sometimes receiving direct radiation from the sun, sometimes in contact with deep space. However, tests in vacuum chambers, a device that simulates extreme temperatures and vacuum conditions, are considerably expensive, making it impossible for project teams with low budgets to carry out such tests before the qualification phase, which causes insecurity regarding the integrity of the product, as there may not be enough time for changes in the event of a breakdown. To overcome this situation, this study presents the design characteristics of a low-cost vacuum-thermal chamber used for testing during the development phases of a nanosatellite. Its conceptual design, structural and insulation characteristics, and thermodynamic behavior are presented. The chamber can reach 1x10*$^{-5}$ *mbar of internal pressure, a maximum temperature of 120°C and a minimum temperature of -10°C for isopropyl alcohol as a refrigerant. To ensure the effectiveness of the simulation of the problem, this study presents an isothermal analysis of the chamber developed through the acquisition of temperature data in a cage that models the standardized dimensions for CubeSats. Two configurations are compared: the chamber with a glass window and a reflective metal door, releasing radiation to the external environment and applying two hatches in the shroud for isolation. Both configurations were tested in two situations: cooling and heating. In the cooling test, the configuration with hatches presented lower heat loss and more significant temperature uniformity. Meanwhile, the configuration without the hatches presented a sudden temperature drop along the length of the cage, with minimum values in the central points. The variation of the central point among configurations was approximately 6°C. However, both configurations showed similar behaviors in the heating test, with more significant heating near the door in the configuration without hatches. The results indicate that the chamber performs well in testing objects with small dimensions, such as CubeSats 1U, picosatellites, and CanSats. For the CubeSats 6U analysis, modifications regarding the heat source uniformity and thermal insulation must be made.*

Keywords: *Vacuum Chamber, Thermal Tests, CubeSat, Thermal Control.*

1. INTRODUCTION

Nanosatellites are small orbital platforms capable of performing missions with various objectives. They are affordable and have considerably shorter production times than larger satellites. As central elements of the New Space initiative, nanosatellites can vary in size and configuration, and they can also be standardized to facilitate production and assembly, as is the case with CubeSats. CubeSat is a term that refers to nanosatellites formed by units (denominated "U") of 10cm x

10cm x 10cm, weighing no more than 1kg each. One of the problematic issues related to CubeSat projects is the need of more of opportunities to conduct environmental tests in the early stages of the project before the definition and assembly of the Flight Model. This limitation results from the lack of resources available to perform such tests, which are usually conducted in certified laboratories and have high costs. A common effect of this limitation is the occurrence of component failures during vibration and impact tests due to inadequate verification of connections and fixtures.

Furthermore, failures can occur in in-house tests due to overheating electronic components. One solution to this problem is the creation of in-house testing setups, which involve the development of test benches like those available in certified laboratories but with reduced costs and suitability for the required tests. There are several studies in the literature on thermal validation tests in satellites, each with its experimental parameters, as presented by Kubicka *et al.* (2020), Dunwoody *et al.* (2022) and Jensen *et al.* (2022) in their specific CubeSat missions. Chisabas *et al.* (2017) provide an overview of the thermal cycling of CubeSats in thermal vacuum chambers, including standards and specifications for other types of thermal tests. Before the concept of nanosatellites, previous works also developed experiments in controlled temperature and vacuum environments for larger satellites, as described by Parker (1987). With this scenario in mind, the team from the Laboratory of Applications and Research in Space (LARS) at the Federal University of Santa Catarina - Technological Center of Joinville (UFSC-CTJ) has developed a small-scale vacuum-thermal chamber for thermal and vacuum environmental testing of nanosatellites and other smaller equipment. Therefore, the main objective of this work is to present the analysis of the chamber's isothermal behavior, aiming to ensure that its construction can satisfactorily represent the required tests for the project team and other collaborators. As secondary objectives, improvements in the configuration will be applied to mitigate the immediate effects of non-isothermality and identify future adaptations to enhance the efficiency and effectiveness of the equipment.

2. METHODOLOGY

The present work relies on a chamber with vacuum application and thermal cycling that can accommodate nanosatellites up to 6U. Figure 1 shows pictures (above) of the closed (left) and open chamber (right) - with an instrumented CanSat for the visualization of the test section scales - and indicates the chamber's primary connections with the peripheral equipment needed for its operation (below). Table 1 lists the leading equipment that is part of the experimental setup, covering the operation part and the data acquisition. The chamber's nominal length and diameter are 58.1cm e 88.0cm, respectively, and its interior can be accessed through a door with sealing and a glass window for the experiment visualization, each in one edge of the chamber. The test section has a diameter of 36.0cm and a length of 59.0cm and is surrounded by a cylindrical sheet painted with black matted paint named shroud.

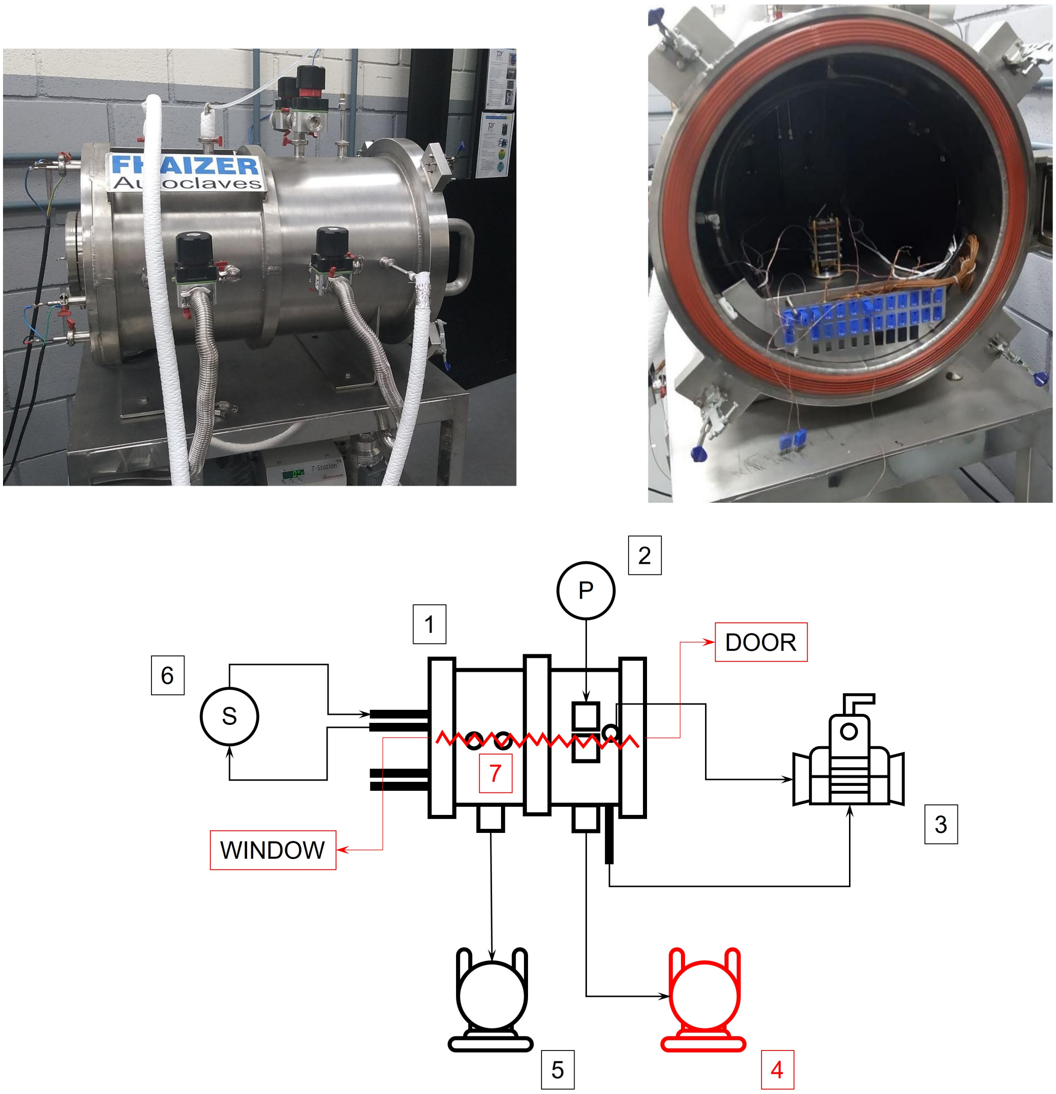
Table 1. Equipments

Name	Model	Manufacturer	Quant.
Pump 1 - Dry Scroll Vacuum Pump	nXDS10iC	Edwards Vacuum	1
Pump 2 - Turbo molecular Pumping Station	T-Station 75	Edwards Vacuum	1
Cooling System - Refrigerated Circulating Thermostatic Bath	RP 1845	Lauda	1
Pressure Sensor - Active Digital Controller	D39591500	Edwards Vacuum	1
Source - Programmable Power Supplier	GEN-300-5	TDK-Lambda	1
Resistances	-	-	2
Thermocouple	Type T	-	18

The temperature measurements are made on the shroud surrounding the test section and on the points of interest of the tested object. In this research, the study object is the cage identified in Fig. 2. Such a cage is made of steel edges and aluminum blocks in the joints, simulating the neighborhood and the center of a CubeSat 3U. The purpose of this contraption is to verify the chamber's isothermality during the tests, ensuring its reliability.

The thermocouples are allocated on the blocks to obtain the local temperatures during each test, and these aluminum blocks are painted black to guarantee the reliability of the measurements regarding their emissivity. The connections number configuration is shown in Fig. 2, considering that the side with blocks 10, 11, 12, and 13 is in the region of the chamber's door.

In addition, four more thermocouples were used to evaluate the cage surroundings: two connected to the shroud (above block 6, named point 14 - Shroud) e two kept loose (below block 7, named point 15 - Center). Using these redundant thermocouples was a safety measure, so if one pair failed, the other could continue the data acquisition of the same point. There are two constructive conditions compared in this study: the initial condition, with a glass window at the opposite end of the chamber door for the visualization during the test, and the condition with the addition of two metal hatches painted with black matted paint, placed over the window and on the inside of the door. This investigation intends to define the influence of the window and door on the tests' section isothermality quantitatively since they could behave as heat sinks.



1	Thermal Vacuum Chamber	**4**	Turbo Molecular Pumping Station	**7**	Thermal Resistance
2	Pressure Sensor	**5**	Vacuum Pump		
3	LAUDA Chiller	**6**	Power Source		

Figure 1. LARS's Vacuum-Thermal Chamber. Above: chamber photographs; Below: schematic of the chamber and peripheral equipment.

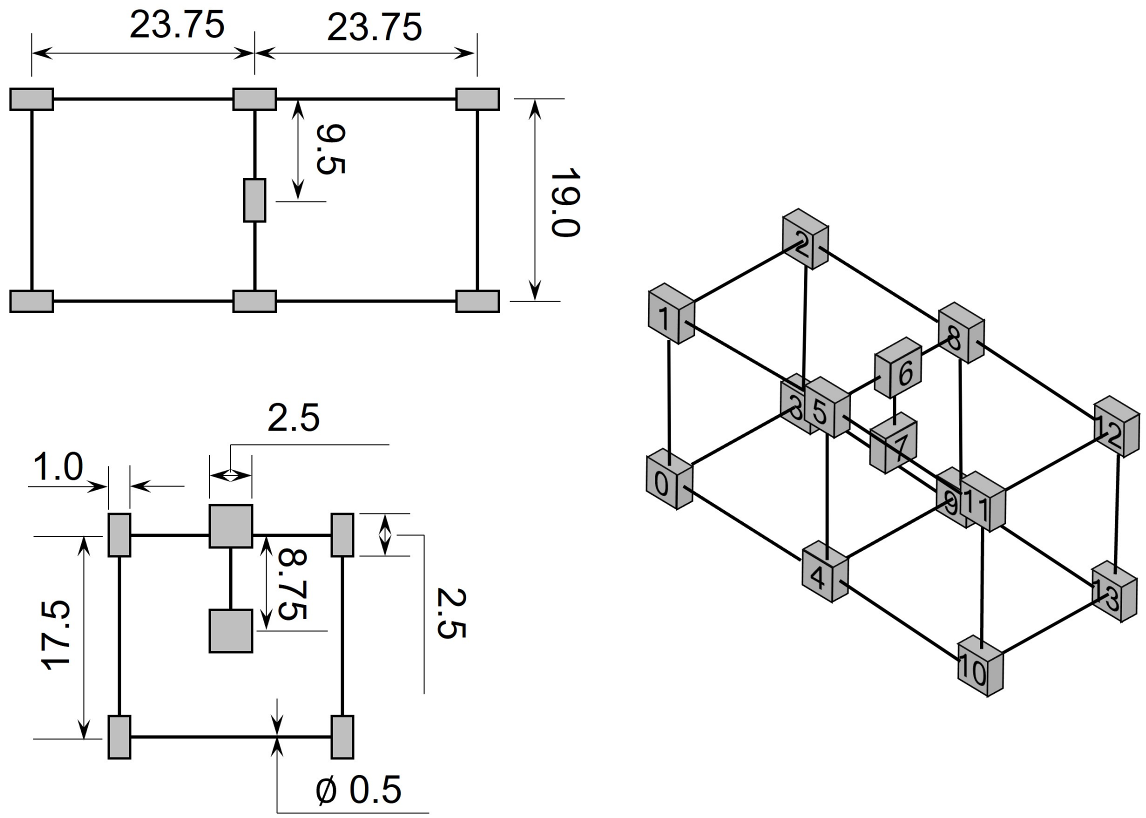


Figure 2. Cage main dimensions for the isothermality tests. Measures in centimeters.

2.1 Analyzed cases

Four tests were performed: hot and cold with insulation hatches, and hot and cold without insulation hatches. In all cases, the cage is placed inside the chamber following the connections configuration of the thermocouples, of which the data is read and recorded through the software LabVIEW. The initial procedure of the vacuum is done the same way for all the tests. Thus, the chamber's door is sealed, and the pumping system is turned on in the following way: 1) Pump 1 is switched on to promote a pre-vacuum up to $1 \cdot 10^{-2}$ mbar and then turned off; 2) Pump 2 is activated and kept operating until the end of the test. After the pressure level reaches $1 \cdot 10^{-2}$ mbar, the desired thermal test is launched following the steps bellow.

Test 1 Cooling Test: initially the cooling system Lauda is activated and set to -30°C with alcohol as a refrigerant. The pipeline transports the fluid through the serpentine, cooling the shroud. The data acquired by the thermocouples are recorded from the point when the Lauda reaches the set temperature.

Test 2 Heating Test: the internal resistances are activated through LabVIEW, and the data acquired starts to be recorded at that moment. The heating rate is controlled by the PID controller from LabVIEW, such that the parameters are: $K_c = 0,7$; $T_i = 0,3$; and $T_d = 0,2$. The maximum voltage and current applied on the resistances are 1 V and 5 A, respectively.

In both cases, the data acquisition is interrupted and the test is concluded when changes in the temperature distribution are insignificant, being that moment considered a steady state.

3. RESULTS AND DISCUSSIONS

Figures 3 and 4 present a temperature color mapping during the steady state condition of the cold and hot tests, respectively. A low-temperature gradient region was observed near thermocouple number 7; for this reason, this was one of the points for further analysis. As so, Fig. 5 presents the temperature variations of the shroud point 14 and thermocouple number 7 for the cold and hot tests.

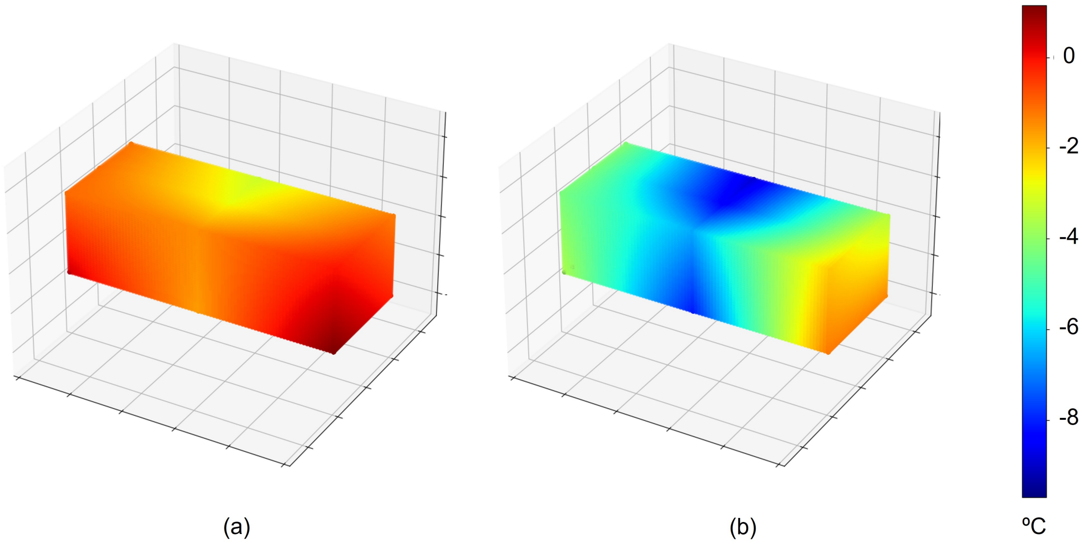


Figure 3. Temperature distribution during the cold test. Left: with hatches; Right: without hatches.

The cold test without hatches presented temperature divergences, indicating a high-temperature gradient between the shroud and thermocouple 7. Discontinuity and temperature peaks are observed along the test due to the data processing. With hatches, the said divergence and gradient are smaller. The radiation isolation promoted by the hatches between the ambient inside and outside of the chamber makes energy loss difficult, creating an isothermal condition.

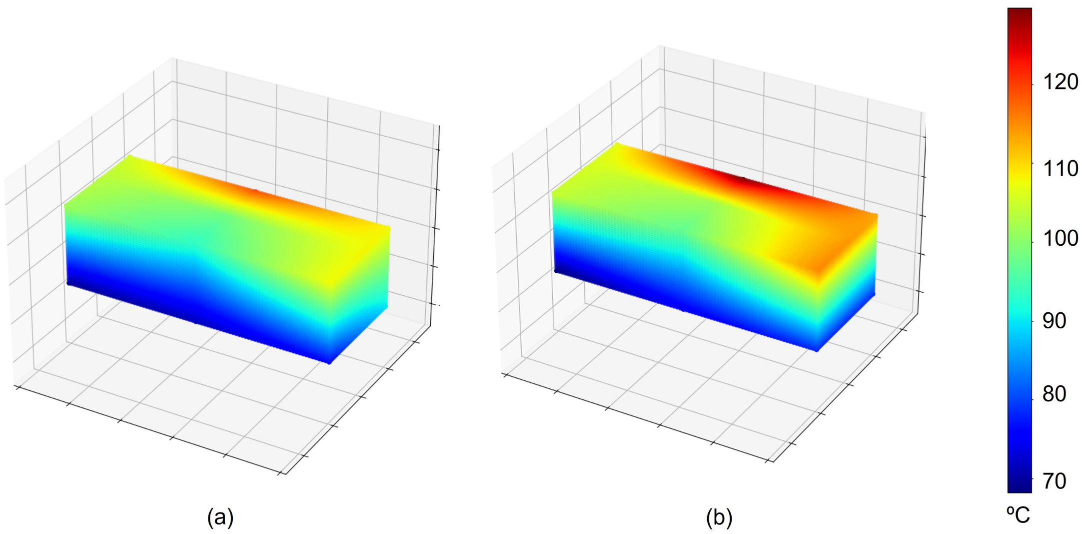


Figure 4. Temperature distribution during the hot test. Left: with hatches; Right: without hatches.

The hot test with hatches presents close temperatures for the shroud and thermocouple 7. Meanwhile, without the hatches, besides the more time-consuming heating, there are minor temperature variations between the points, indicating that the shroud tends to heat more in comparison to point 7 because it is closer to the resistances. Also, it is observed that the hatches have little influence over the temperature gradient during the steady state, because as observed in Fig. 4, the gradient tends to have the same distribution in both cases.

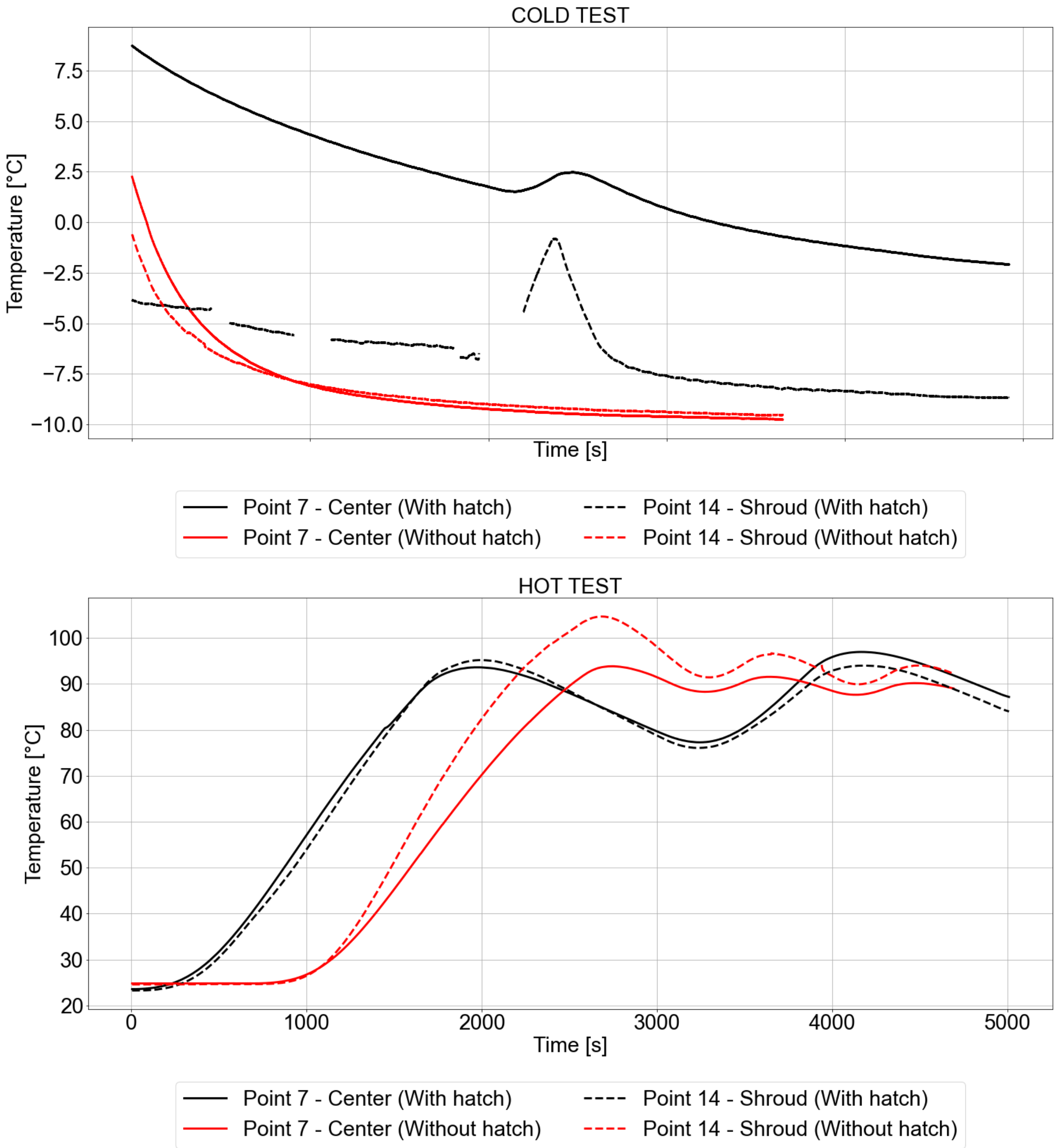


Figure 5. Temperature Monitoring during the cold test (above) and the hot test (below) in points 7 and 14.

The curves for the thermocouples 7 and 14 in the configuration with hatches, shown in Fig. 5, present a decrease in the decay rate and an increase in the oscillation period (cooling and heating test, respectively) regarding the configuration without hatches. This behavior indicates a more significant temperature uniformity, and it is estimated that by adding the hatches, the test will reach the steady state later; however, there are more significant chances of presenting isothermally.

4. CONCLUSIONS

The thermal vacuum chamber studied can accommodate nanosatellites as big as CubeSats 6U in its test section. To ensure the existence of isothermality along the test section, heating and cooling tests were conducted with two configurations: with and without isolation hatches on the edges of such section. According to the results, for cold tests, the chamber without hatches does not present isothermality along the points of the cage. The results confirmed more considerable temperature uniformity in the configuration with hatches during the cooling test and little influence during the heating test.

There is a region of low-temperature gradient nearby point 7 that increases as the points move away from that region, indicating that smaller satellites such as 1U and Picosats will get better results during thermal tests; however, for hot tests, bigger satellites will experience appoximately 25°C temperature gradients due to heater location.

Monitoring the points on the edge of the shroud - test section fairing - and on the center of the cage indicate temperature oscillations with a more significant period on the configuration with hatches, although with improved smoothness. It is concluded that adding the hatches even out the test section, increasing the internal temperature and delaying the steady state, in which it is reached bigger isothermally.

As recommendations for enhancement, it is advisable to enhance the distribution of electrical resistance throughout the shroud, particularly in its lower section. Additionally, employing forced convection within the serpentine structure that encompasses the shroud could be considered to heat the chamber.

5. REFERENCES

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