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Peltier-based Thermal Testing (PeTT) Vacuum Chamber: Affordable Testing Facility for Lean Satellites

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SUMMARY

Satellite thermal vacuum test (TVC) is very necessary to check the functional performance of its internal subsystems within appropriate limits, subject to a given range of environmental conditions and operating modes. However, the cost of conventional TVC facilities is expensive and complex to operate and therefore is owned by a few institutions, especially in developing countries. The objective of this paper is to provide a straightforward and affordable Peltier-based Thermal Testing (PeTT) Vacuum Chamber facility for lean satellite testing. The PeTT device consists of 4 multi-stage Peltier elements sandwiched in-between a copper surface plate and water-cooled heat sink to achieve a cold temperature limit of -77 ^{o}C. The PeTT device has a mass of 3.4kg and a size 152mm length x 127mm width x 40 mm height having a maximum heat exchange capability of 400W. This paper presents the design and development, components details and cost and the demonstration of the PeTT vacuum chamber using a replica 1U CubeSat.

KEYWORDS: Peltier; Thermal vacuum chamber; Lean satellites;

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NOMENCLATURE

AIT	=	Assembly Integration and Testing
CeNT	=	Center for Nanosatellite Testing
COTS	=	Commercial off the Shelf
LN2	=	Liquid Nitrogen
DP	=	Diffusion Pump
PeTT	=	Peltier-based Thermal Testing
TVC	=	Thermal Vacuum Chamber
SSO	=	Sun-Synchronous Orbit
ISS	=	International Space Station Orbit
J-SSOD	=	Japanese Small Satellite Orbital Deployer
UHF-TX	=	Ultra-high frequency Transmitter
VHF-RX	=	Very-high frequency Receiver
MLI	=	Multi-Layer Insulator
FAB	=	Front Access Board
dT	=	Temperature difference
A	=	Area of the surface material
s	=	Stefan –Boltzmann constant
e	=	Emissivity of the material
k	=	Thermal conductivity of the material
QT	=	Qualification Test
DAQ	=	Data Acquisition
Q_c	=	Heat dissipation power for CubeSat
Q_{rad}	=	Radiation exchange
T_c	=	Cold surface Temperature
T_h	=	Heatsink Temperature
T_w	=	Water Chiller Temperature
T	=	Temperature

1. INTRODUCTION

The space activities in developing countries have greatly increased due to the utilization of a lean satellite concept. Lean satellite concept utilizes non-traditional risk-taking development and small team management approaches with the aim to provide a value of some kind to the customer at low-cost and without taking much time to realize the satellite mission [1].

In 2015~2018, countries including Ghana, Bhutan, Mongolia, and Bangladesh, have successfully launched their first country satellite (1U CubeSat) into the International Space Station (ISS) orbit through the JAXA/Kibo ISS Deployment Program and these projects took less than 2 years to realize their satellite missions [2][3].

Satellite thermal vacuum chamber (TVC) test is very necessary to check the functional performance of its internal subsystems within appropriate limits, subject to a given range of environmental conditions and operating modes. The ISO 19683: Design Qualification and Acceptance Test of Spacecraft and Units: provides the minimum thermal vacuum test requirement (-15ºC to +50ºC) [11] and test methods to qualify the design and manufacturing methods of commercial lean satellites and their unit. The ISO 19683 places emphasis on achieving reliability while maintaining low cost and fast delivery and is applied to lean satellites such as CubeSat whose development methods are different from the ones used for traditional satellites. This calls for an affordable and straightforward thermal vacuum testing facility that can somehow meet ISO 19683 thermal vacuum testing requirements without necessary using the traditional TVCs for lean satellite testing.

Initially, TVCs were designed for conventional satellites. Since the advent of lean satellites, however, TVCs have been re-designed to fit lean satellite-needs. Stevenson et al. [4] presented the broad overview on technical evolution of space simulation chambers from conception (at the beginning of the 1960s) to the present moments of 2016 and identified conventional operational requirement and functions of the various state of the art commercial chambers which consist of the structure of the chamber, the vacuum system, the thermal regulation system, controls and instrumentation, and the supply system. To simulate the vacuum environment, the structure of the chamber and pumping systems monitored by control and instrumentation systems are used to generate high vacuum (10^{-1} Pa to 10^{-7} Pa) to ultra-high vacuum (10^{-7} Pa to 10^{-10} Pa) environment [4] and to simulate the cold and hot environment, the thermal regulation system mostly equipped with thermal radiative shroud system and supply systems(example: liquid/gas Nitrogen, silicon oil, Infra-red emitters/heaters) are used to generate as close as the cold and hot temperature environment in outer space.

Conventional TVC is expensive and complex to operate without an expert and therefore is owned by a few institutions, especially in emerging space economies. To investigate further we conducted a research survey with the purpose to create an inventory of AIT facilities in Africa regions to provide easy access to AIT facilities in Africa for satellite and space systems development during the 7th African Space Leadership Conference (ALC) held in Abuja, Nigeria on the 5th to 7th November 2018.

Space experts and researchers from 18 different countries in the African Region contributed to this research survey which includes Southern Africa (South Africa and Namibia), North Africa (Egypt, Tunisia, and Algeria), Central Africa (Cameroon), East Africa (Kenya, Ethiopia, Rwanda, and South Sudan) and West Africa (Ghana, Nigeria, Senegal, Burkina-Faso, Cote D'Ivoire, Benin, Togo and Mali).

From the survey outcome, South Africa is the only country in Africa equipped with an operational thermal vacuum chamber facility. Some of the main challenges facing Africa are TVC facility is expensive especially for universities, lack of experts to develop, operate and maintain TVC facility, and the use of LN2 in some parts of Africa is not common. Therefore the question of investigation is what is the affordable and easy access thermal vacuum testing facility that can be suitable for university space activities in developing countries?

One common type of TVC is mechanical refrigeration systems with a silicon fluid-based thermal vacuum chamber. This type of thermal configuration system utilizes silicon fluid due to its low vapor pressure, low surface tension, and magnificent thermal stability. The silicon fluid is combined with a closed-loop cascaded refrigeration system capable of cooling down temperatures as low as around -80ºC and +150 ºC using heater cartridges. Figure

1 shows an example of a mechanical refrigeration system with intermediate fluids based thermal vacuum chamber manufactured by Abbess Systems and the facility cost is around 52,000 USD or more depending on consumer application [5] and this chamber can accommodate up to 3U Cubesat.

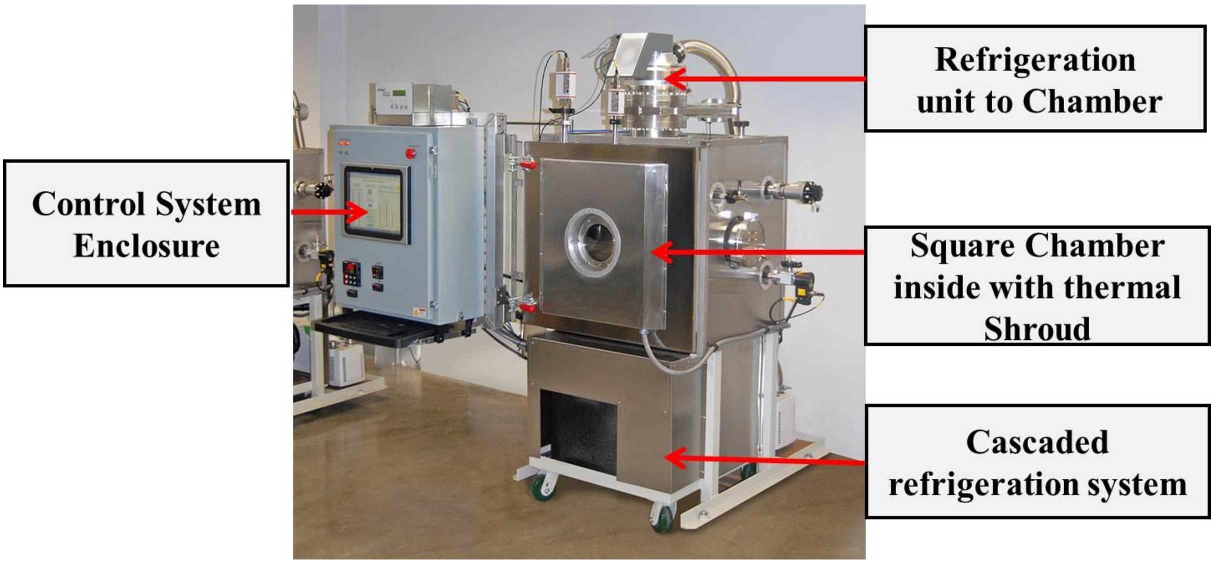

Figure 1 Mechanical refrigeration with silicon fluid (Picture credit: ABBESS Instruments http://abbessonline.com/index.aspx)

However, a research study has shown that using this type of configuration in academic laboratories poses challenges, especially for satellite testing if proper care is not considered. Refrigeration ability to remove heat from the test object decreases with decreasing temperature. Additionally, recirculating heat transfer fluids exhibit a rapidly increasing viscosity with decreasing temperature. Concern over possible test article contamination may be a major deterrent for satellite testing in mechanical refrigeration based thermal vacuum system [6].

Liquid Nitrogen (LN2) based thermal vacuum chambers are widely used by space agencies and other states of the art testing laboratories because LN2 has an extremely low temperature in its liquid state with a boiling point below -195.79 ^{o}C [4] and can be able to simulate as closely the heat cold sink of outer space.

For example, the Center for Nanosatellite Testing (CeNT) at Kyushu Institute of Technology (Kyutech) has eight years' experience in space environment testing and is equipped with state of the art thermal vacuum chambers suitable for testing from 1U CubeSat to a 50cm sized satellite. Figure 2 is an example of a state of the art thermal vacuum chamber at CeNT which can test up to 3U Cubesat. On the left in Figure 2 is a 4900-liter tank facility filled with LN2 and on the right is a vacuum chamber the which has inner diameter of 30cm equipped with thermal radiative shroud system installed in the wall of the chamber that has a passage to be filled with LN2 for generating low temperature around -150^{o}C and utilizes infra-red heaters for generating hot temperature around +150^{o}C during operation and facility cost is around 260,000 USD. Nevertheless, it is very expensive and complex to operate without an expert, and once LN2 is injected during operation it cannot be stopped quickly in case there is an anomaly accident in a satellite system.

Peltier effect concept was discovered in the early 19th century [7]. The Peltier effect occurs whenever electrical current flows through two dissimilar conductors; depending on the direction of current flow, the junction of the two conductors will either absorb or release heat. Nowadays, the Peltier-effect concept is applied in thermoelectric coolers mostly made up of bismuth telluride semiconductors. It is developed using two thin ceramic wafers with a series of P-type and N-type (one P and one N make up a couple) doped bismuth-telluride semiconductor material sandwiched between them. The thermoelectric couples are electrically in series and thermally in parallel and can contain one to several hundred couples as shown in Figure 3 [7].

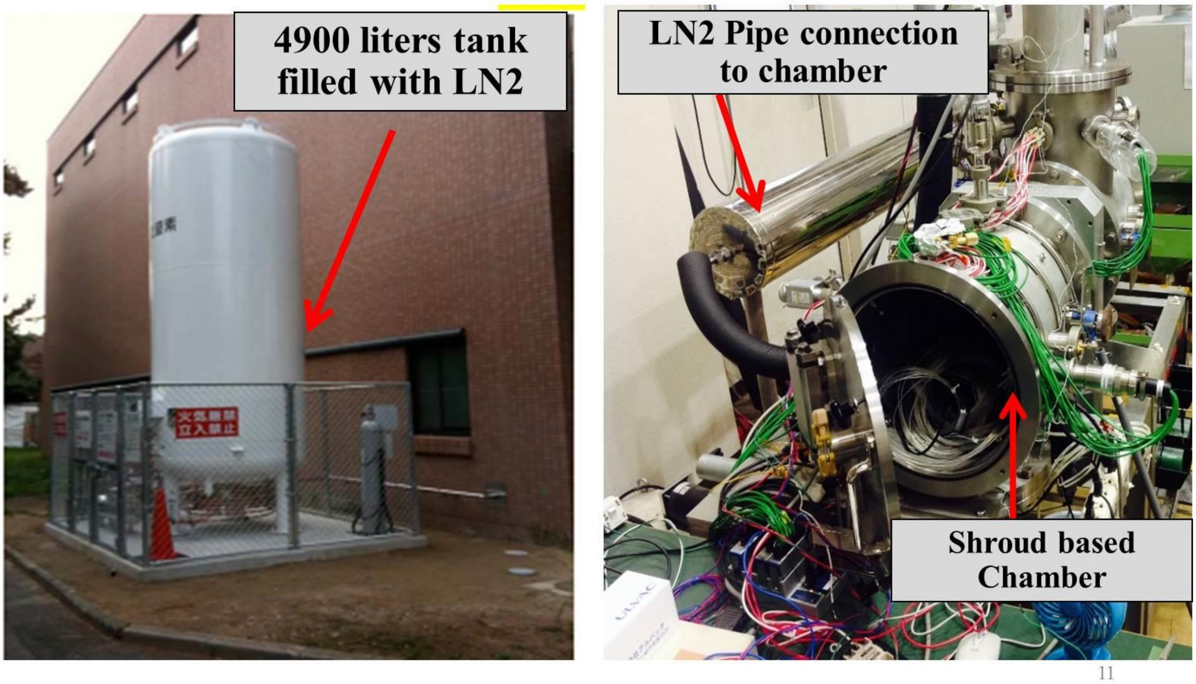

Figure 2 CeNT Thermal vacuum chamber using LN2 and Infra-red Heaters configuration system. (Source: CeNT at Kyushu Institute of Technology)

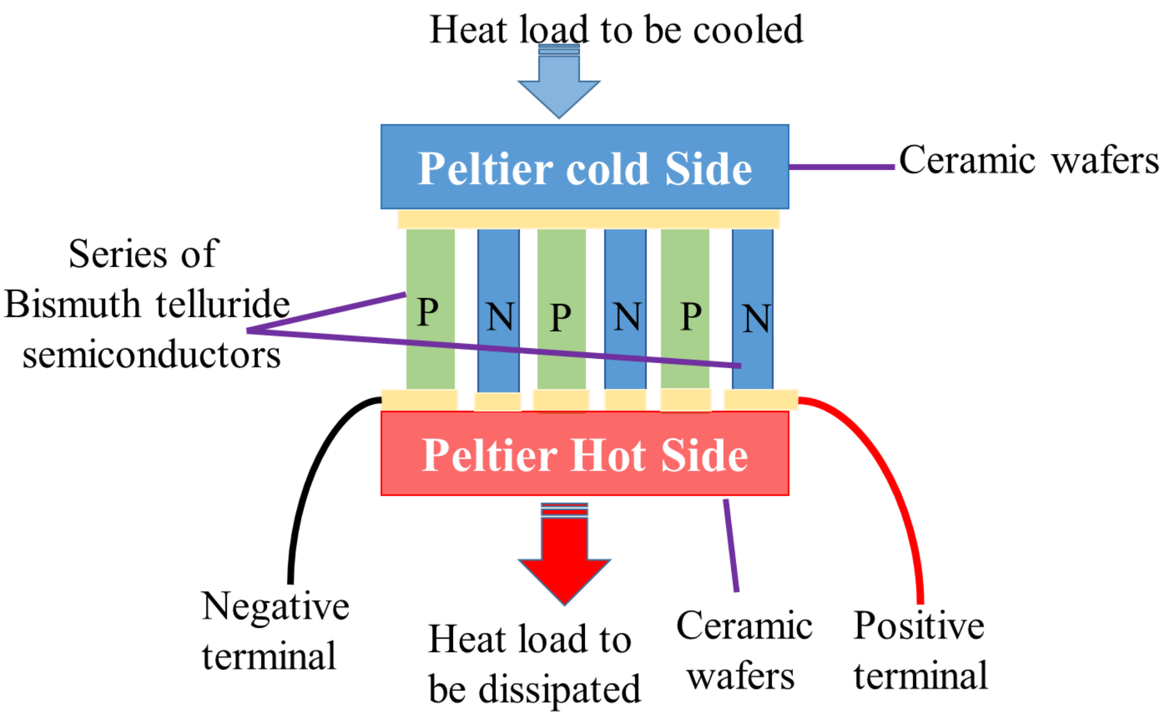

Figure 3 The architecture of the Peltier element

Applications of thermoelectric (Peltier) modules cover a wide spectrum for cooling down devices such as computer processor units, analytical instrumentation, food and beverage cooling, air conditioners, Imaging systems, and many more [8].

Previous studies [9] compared the use of a Peltier cooling unit and LN2 for cooling a cold finger on an electron probe microanalysis of carbon inside a vacuum chamber. From the outcome results, the temperature at which minimal amounts of contamination is achieved is -27 °C for the Peltier cooling unit and -75 °C for LN2 cooling at a chamber pressure of 3.6 x 10^{-4} Pa.

The author further observed that the Peltier cooling unit does not affect the analytical stability whilst the Peltier unit was operating. In his conclusion, the author suggested that Peltier cooled cold fingers are thus demonstrated viable and will provide a good alternative to LN2 cooling and they have the potential to run for extended periods of time and save cost (could not give the cost of the Peltier Unit) as compared to LN2 cooling configuration system inside vacuum chamber

Another study [10] developed a thermal vacuum testing system of a supercapacitor using a Peltier device. The test system was demonstrated to work in a range of -15ºC to +50ºC with the total maximum heat exchange capacity of 700W. From the investigation results, the author could demonstrate that it is feasible to implement a Peltier cooling device inside a vacuum chamber for different test needs. However, exploring the capabilities of a Peltier-based thermal vacuum testing system for CubeSat testing is not common.

The purpose of the present paper is to demonstrate the 1U CubeSat thermal vacuum testing using Peltier thermal testing (PeTT) device in a vacuum chamber known as PeTT Vacuum Chamber. We aim to provide easy access and affordable thermal vacuum testing facility for emerging space economies. The present paper has been separated into four chapters. In the first chapter, we introduced the lean satellite concept and its applications, the challenges facing emerging space economies when it comes to TVC facility, highlight on the two types of commercially available TVCs and their prices. The second chapter presents the design and development of the PeTT vacuum chamber and the cost of components. The third chapter presents the phases of the experiment and the results of the demonstration of the PeTT vacuum chamber using a replica of 1U CubeSat. Finally, the fourth chapter presents the conclusion and future works

2. DESIGN AND DEVELOPMENT OF PeTT VACUUM CHAMBER

PeTT vacuum chamber is defined as a Peltier based Thermal Testing (PeTT) device which utilizes the Peltier effect phenomenon to generate cold and hot temperature inside a simulated vacuum chamber environment.

In this section, we present the design process criteria, numerical and simulation analysis for selecting the desired Peltier element and its additional components (heat sink, thermal interface, and cold surface plate) and cost of developing the PeTT device and the installation of diffusion pump vacuum chamber.

2.1 Design and Development of the PeTT Device

Design process criteria

The appropriate design of a Peltier thermal testing (PeTT) device depends on at least four parameters. These parameters are the dissipation power (Q_C) of the test object and its temperature range, the environment condition, and the selection of the Peltier module (Peltier element, heatsink, cold surface plate, thermal interface material, mechanical fasteners,).

Firstly, we considered BIRDS-2 1U Cubesat as the test object. The total heat dissipation power (Q_C) of 9W was considered with an active power dissipation of 2W and passive power dissipation of 7W. The active power corresponds to the heat released when electric current flows through electronic device (Joule heating effect) of the CubeSat internal electronic components, whiles the passive power dissipation corresponds to the heat loss in contacts such as the mechanical fasteners, bolt, and nuts, cables, and thermal insulators and others [2] [14].

Secondly, we determined the temperature range design requirement of the PeTT device. The first parameter was based on ISO-19683 Design Qualification and Acceptance Test of Spacecraft and Units which specifies the -15 to

+50 ºC as the minimum requirement of internal unit thermal vacuum test [11]. And for the second parameter, we considered an on-orbit temperature profile of 100 lean satellites (1U CubeSat) launched into ISS orbit and SSO orbit. We targeted for active lean satellites less than 6 months in orbit. The minimum and maximum temperature cycles (night and day) of the CubeSat internal subsystems which include but not limited to the Electric Power subsystem, EPS (Battery and power control board), Onboard Computer (OBC), Payload and Communication Subsystem (radio transceivers) were recorded. The sources of housekeeping data were collected from amateur radio communities [12] and the primary ground station of the satellite developers.

In the case of ISS orbit, 38 number of 1U CubeSats housekeeping data for minimum and maximum temperature for each internal subsystem were recorded. We calculated the mean value for both minimum and maximum temperatures of each internal subsystem. The typical temperature ranges of the internal subsystems were as follows: EPS (-8 to +50 ºC), OBC (-10 to +49 ºC), Payload (-14 to +44 ºC) and Communication (-12 to +53 ºC). From the results of the analyzed data, we again find the mean value of all the minimum temperature value to be -11 ºC and maximum temperature value to be +49 ºC. From the result, we could say the typical temperature range of the ISS orbit satellites were around -11 ºC to +49 ºC.

Also in the case of SSO orbit, 62 number of 1U Cubesats satellites housekeeping data for minimum and maximum temperature for each internal subsystems were recorded. We calculated the mean value for both minimum and maximum temperatures of each internal subsystem. The typical temperature ranges of the internal subsystems were as follows: EPS (-16 to +59 ºC), OBC (-10 to +51 ºC), Payload (-20 to +49 ºC) and Communication (-18 to +57 ºC). From the results of the analyzed data, we again find the mean value of all the minimum temperature value to be -16 ºC and maximum temperature value to be +54 ºC. From the result, we could say the typical temperature range of the SSO orbit satellites were around -16 ºC to +54 ºC.

In summary of the analyzed results (for both ISS and SSO orbit lean satellites), we calculated the mean value minimum temperature value to be -13.5 and maximum temperature value to be +51.5 ºC.

After all, we set -20 to +50 ºC as the temperature range design requirement because from the gathered data (-13 to +51.5 ºC) is close to the ISO-19683 Design Qualification and Acceptance Test of Spacecraft and Units which specifies the -15 to +50 ºC for CubeSat internal unit. So we added an acceptable margin of 6.5 ºC to the minimum temperature value to achieve -20 ºC and on the other hand, we reduced the maximum temperature by 1.5 ºC to achieve 50 ºC as an approximate value with reference to the ISO 19683 standard.

Thirdly, we employed thermal analysis guideline simulation software developed by Kryotherm [13]. The Kryotherm software is a free online software which enables us to select the desired Peltier module which includes but not limited to the optimum power input, configuration mechanism, choice of material, type of heat sink and most significantly the expected cold surface temperature and the hot surface temperature to be dissipated by the heat sink based on the known parameters of the test object (temperature range and Qc).

From the results of the analysis including margins, we selected a 4 multi-stage Peltier element, with 2 series and 2 parallel configurations, power input (P_{in}) around 388W, a water-cooled heat sink type made up of copper, average thermal resistance (R) around 0.02 ºC/W to achieve a cold surface temperature around (T_C)-80 ºC by controlling the water-cooled heat sink temperature (T_h) range around 2 ºC to 10 ºC using a water chiller temperature (T_w) around 0 ºC. The total maximum heat exchange capacity of 400W was achieved for the simulation analysis.

From the given parameters of the power input of the selected Peltier element (P_{in} =388W) and the heat load power to be dissipated by the Cubesat (Qc = 9W).we could calculate for the total heat load power to be dissipated by the heat sink (Qh =397W) as expressed in equation 1.

$$Q_h = Q_c + P_{in} \tag{1}$$

We calculated for the total thermal resistance (RT =0.025 ºC/W) network given as the sum of thermal resistance of thermal gel interface (Rgel=0.00208 ºC/W), surface plate (Rplate =0.000025 ºC/W), Heatsink (Rsink=0.022 ºC/W), Peltier module (Rpeltier=0.0008 ºC/W) and Cubesat (Rcubesat=0.00045 ºC/W). Apart from the Rcubesat which was derived using equation 2, where K is represented as thermal conductivity (K =222W/m/K), of the CubeSat considering the structure to be an aluminum and L is the thickness of the CubeSat (L = 0.1m), the rest of the thermal resistance was derived from the datasheet of the selected components provided by online vendors as listed in Table 1.

$$R_{cubesat} = \frac{L}{K} \tag{2}$$

The heat sink temperature (T_h) of 9.9 ^oC was derived from the total thermal resistance network (R_T = 0.025$^oC/W$), the total heat load power to be dissipated by the heat sink (Qh =397W), and the water chiller temperature(T_w=0^oC) which represents the controlled temperature of the heat sink as expressed in equation 3.

$$T_h = T_w + \left(R_T \times Q_h\right) \tag{3}$$

The cold surface temperature (T_C) of -80 ^oC was derived using equation 4 from the heat sink temperature (T_h) of 9.9 ^oC and the temperature difference (dT) of 90^oC using equation 4.The temperature difference of 90 ^oC was considered because it corresponds to the selected input power (Pin) of the Peltier element employed using thermal analysis guideline simulation software developed by Kryothem [13] which has the datasheet of the selected Peltier element. To derive the dT we find the parameters from the graph performance curve of the selected Peltier element which contains dT versus current (Amperes), dT versus Voltage (Volts), dT versus input power (P). We considered 80 percent of the maximum Power of the Peltier module (the reason was to avoid burning the module as instructed on the datasheet by manufacturer) and its corresponding dT on the graph performance curve provided on the datasheet [13] and the temperature difference (dT) of 90 ^oC was selected.

$$T_c = T_h - dT \tag{4}$$

We also considered the vacuum environment losses by radiation heat exchange (Q_{rad1}) between the PeTT device plus and the chamber wall using equation 5. We selected the following parameters which include the emissivity of the vacuum chamber wall to be stainless steel ($e_2 = 0.59$), the emissivity of the PeTT device to be copper ($e_1 = 0.78$),.chamber wall temperature (T_2= 303K) and temperature of the PeTT device (T_1= 193K), and Stefan Boltzmann constant (s = 5.67 x10^{-8} W/m^{2}K^4). We assume a steady-state condition and Qc to be negligible. We simplified the area of both the PeTT device and the chamber wall to be two concentric spheres. The two spheres considered do not need to be concentric. However, the radiation analysis will be most accurate for the case of concentric spheres, since the radiation is most likely to be uniform on the surfaces in that case. We assumed the diameter of both the PeTT device and chamber wall to be 100mm and 170mm. Therefore, using the formula of the area of a sphere, we calculated for the area of the PeTT device (A_1= 0.03 m^2) and the area of the chamber wall (A_2 = 0.08 m^2). From the results calculated, Q_{rad} of 10W was the radiation exchange loss between the vacuum chamber wall and the PeTT device. The PeTT device is supposed to remove 10W in addition to the dissipation power of the satellite, Qc.

$$Q_{\mathrm{rad}} = \frac{A_1}{\frac{1}{\varepsilon_1} + \frac{A_1}{A_2}\left(\frac{1}{\varepsilon_2}\right)} \sigma\left(T^4{}_2 - T^4{}_1\right) \tag{5}$$

To improve the design, we considered an MLI copper shroud around the surface plate of the PeTT device to cut away the radiation exchange losses. We could calculate for the Q_{rad1} between the MLI copper shroud and the chamber wall using equation 5. The parameters set for the chamber wall is the same values in the previous calculation and the parameters for the MLI copper shroud includes: emissivity of the MLI copper shroud to be gold foil ($e_1 = 0.03$), Area of the MLI copper shroud assuming a spherical shape (A_1= 0.045 m^2) and MLI copper shroud temperature (T_1= 193K) and we could obtain Q_{rad2} of approximately 0.5W, which means MLI can able to cut the radiation heat exchange loss to the vacuum chamber wall. Figure 4 shows an overview of the thermal system design of the PeTT device inside a vacuum chamber.

As listed in Table 1 shows the components and specifications selected for the PeTT device. These COTS components include four multi-stage Peltier elements, power supply, water circulating cooling system, thermal interface gel sheet, cold surface plate, and water-cooled heat sink. The total cost for developing the PeTT device only is 2000 USD and including the water cooling system and varying DC power supply adds up to a total cost of 4,900 USD.

Table 1 Components and Specification of the PeTT device

Items	Specification
Peltier Module	Qmax =16.9 W, Delta T = 111 ºC , Imax =6.7 A , Vmax =23.6 V Model:TB-4-(199-97-49-17)-1.5 Stage 1 (Hot side): 62 mm x40 mm x 3.63 mm Stage 2 : 44mm x 44mm x 3.63 mm Stage 3: 31mm x 31mm x 3.63mm Stage 4 (cold side) : 20mm x 20mm x3.63mm Thermal resistance: 0.0008 ºC/W Material: Aluminum Nitride Thermal conductivity: 180W/m/K Operating Temperature: 80 ºC Soldering Temperature Limit:95 ºC Manufacturer: Kryotherm
Surface Plate	Material Type: Copper Thermal Conductivity :388 W/m/K Dimension: 152 mm length x 127 mm width x 10 mm height Thermal reistance:0.000025 ºC/W
Heat Sink	Size: 152 mm x127 mm x 15 mm Type: Heat sink water cooler Flow rate :6.8 liter/min Heat sink pipes: Copper Heat sink surface: Aluminum Tube: Copper Thermal resistance: 0.022 ºC/W
Power Supply	I = 13.5 A V = 80 W Model: PSW 80-13.5
Thermal Gel Sheet	Thermal conductivity :1.9 W/m/K Temperature Range :-80 ~ +200 ºC Thickness :2.2 mm Thermal resistance: 0.00206 ºC/W

Water Chiller	Temperature range: : -20ºC ~ +30ºC Cooling Capacity:650W Max flow rate:12.9 L/min Liquid Tank : 16 Liters Model:LTC-2000A

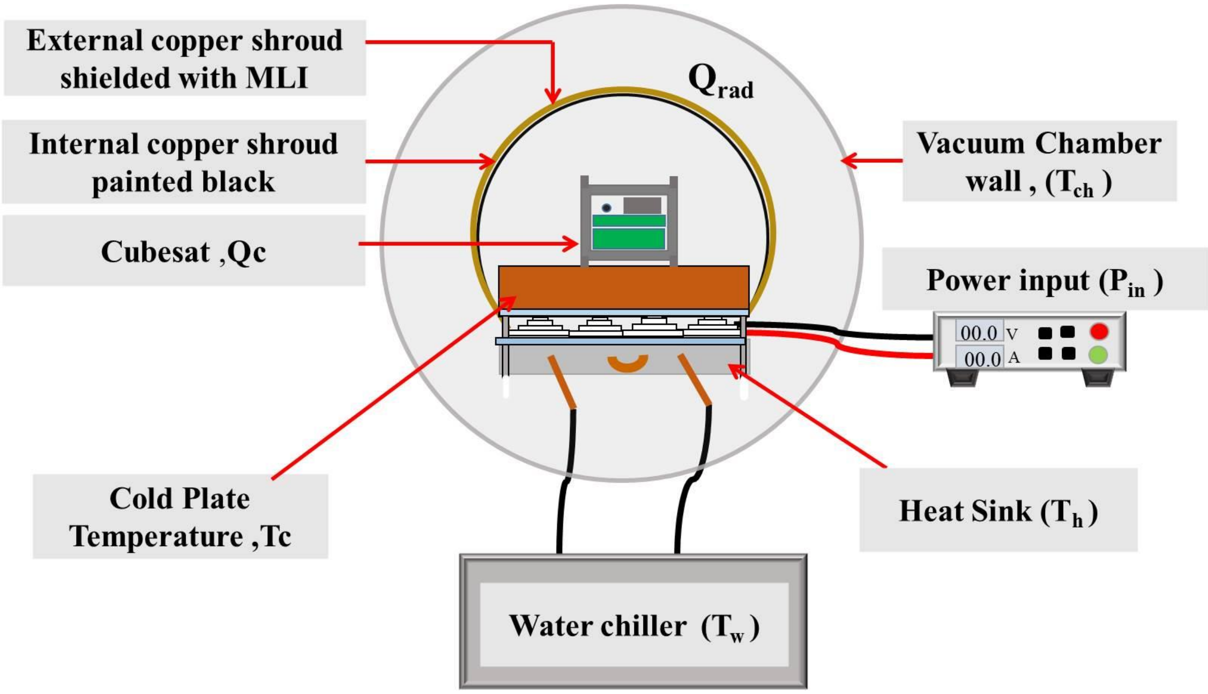

Figure 4 Overview of the thermal system design of the PeTT device inside a Vacuum Chamber

2.2. Assembly Procedure of the PeTT device

Four cascaded arrays of 4 multi-stage Peltier elements are connected in series and parallel (2 series and 2 parallel). We applied the thermal gel sheet on the heatsink where the hot side of the Peltier elements is attached and the same for the cold side where the copper surface plate is attached as shown in phase 1 and phase 2 of Figure 5. A thermal copper shroud with 0.3mm thickness is attached to the copper surface plate and outer surface insulated with a Multi-Layer Insulator (MLI) to reduce heat loss by thermal radiation inside the vacuum chamber. The inner surface of the copper cylinder is painted with black paint (TASCO THI-1B) surface with high values of emissivity, to produce consistent radiant heat fluxes under very good control as shown in phase 3 and Phase 4 of Figure 5. We bolted the heat sink to the copper surface plate and carefully apply torque in small increments using a torque-limiting screwdriver and bolted the thermal copper shroud on the copper surface plate for maximum conduction exchange energy transfer. The total mass of the assembled PeTT device is 3.4kg and has a size of 152mm length x 127mm width x 40 mm height suitable for Cubesat.

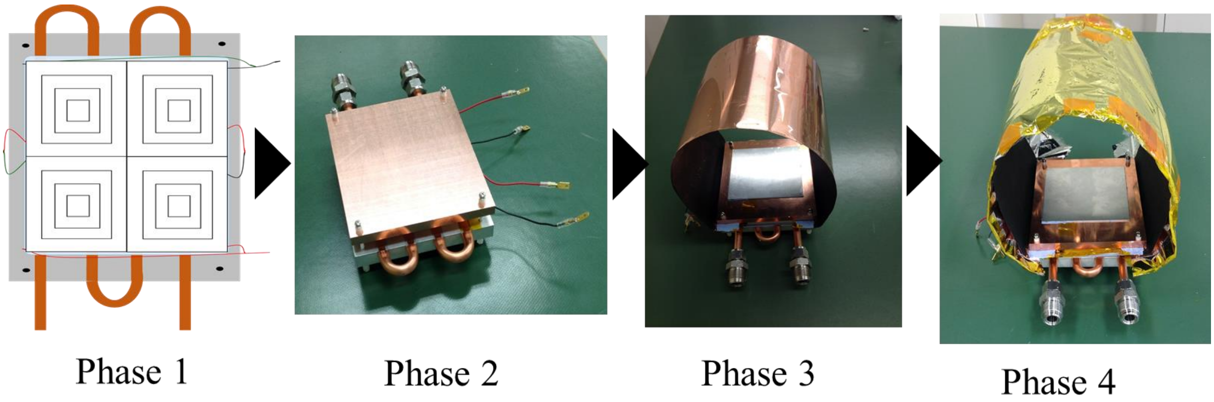

Figure 5 The Assembly phases of the PeTT device

2.3. Installation of the Vacuum Chamber

Figure 6 shows the schematic diagram of the overall system of the vacuum chamber which includes the chamber structure, vacuum system, and the control and instrumentation system. The total facility cost of the TVC is 26,000USD. As listed in Table 2 are the components and specifications of the vacuum chamber and Figure 7 to Figure 9 are the pictorial diagram of the configuration of the vacuum chamber.

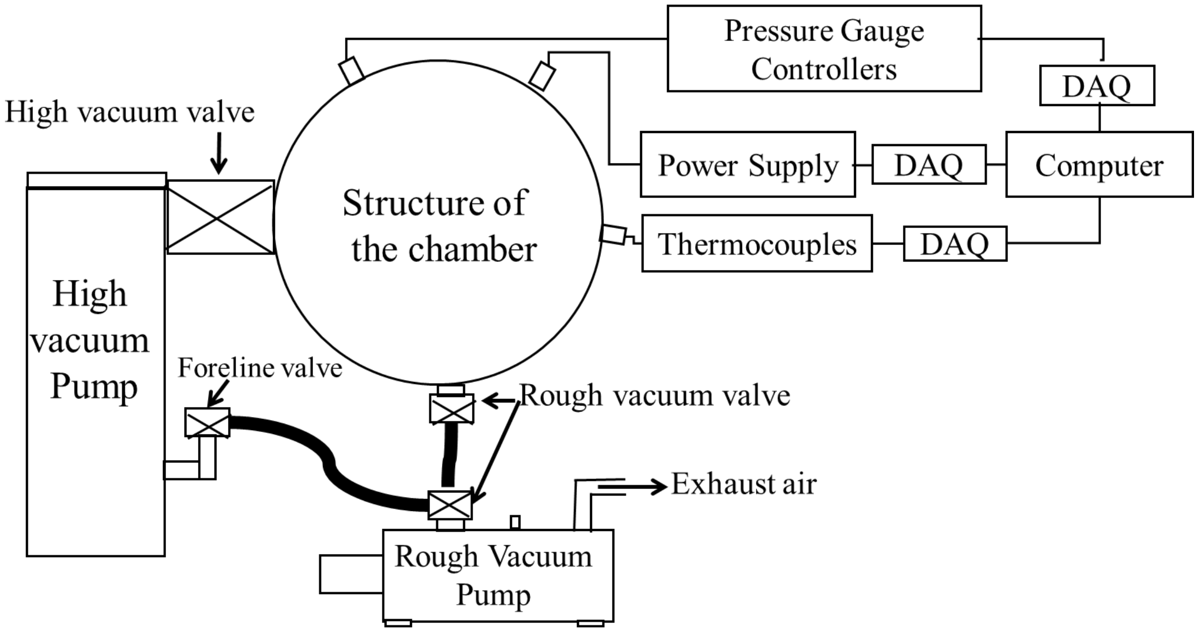

Figure 6 The overall system of the TVC

Table 2 Components and Specification of the TVC

Components	Specifications
Diffusion Pump	Ultimate Pressure: 10^{-5}Pa Pumping Speed: 1950l/sec, Power Supply @200V 1φ :1800W Oil Capacity: 500mL Water Flow: 4L/min Model: S-80149

	Manufacturer: SAN-EI RIKEN
Oil Seal Rotary Pump	Dispalcement:750/900 Displacement : 750 /900 L/min Revolution: 1430 /1715 rpm 1430 (200v , 6.4A@60Hz) 1715 (200v, 6A @ 60Hz) Power : 3-phase @1500kW Oil Capacity : 3.3 Liters
Chamber Structure	Shape: Cylinder with flat ends Material: Stainless steel Inner Diameter: 550mm Axial Length: 470mm
Ionization gauge	Controller: G1-TL3RY Filament: WIT 1801MG Manufacturer: ULVAC
Pirani gauge	Controller:GP-1S Pressure:0.4Pa Manufacturer: ULVAC Model: NI9213
DAQ	For thermocouples 16channels, 75 S/s aggregate, 78mV Model: N1USB-6009 For power supply Control: 14-Bits, 48 kS/s

Figure 7 shows the detailed descriptions of the chamber structure and feedthroughs. The structure of the chamber has a shape of a cylinder with flat ends with an inner diameter of 550mm and 470mm height which can test up to 3U Cubesat. The chamber structure is produced from a high- quality stainless steel able to withstand the pressure differences between both internal and external environment and treated to minimize leak rates and contaminants such as outgassing, capable to achieve high vacuum. The chamber structure has 27 feedthroughs adequate to interface it with control and instrumentation unit interfaces such as thermocouples, pressure ionization, and Pirani gauges, power, pressure pumps, and water cooling system. The chamber structure does not have an inbuilt shroud system for thermal regulation as in the case of LN2 or mechanical refrigeration based TVC.

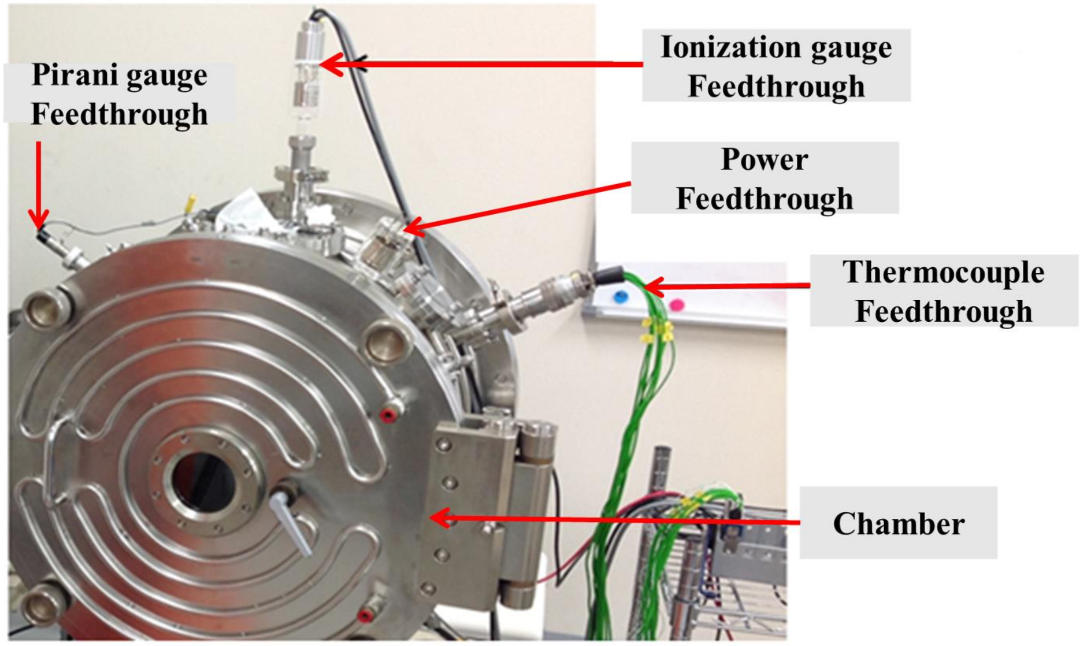

Figure 7 The Chamber structure and feedthrough

Figure 8 shows the detailed description and configuration of the pumping system. The vacuum system is equipped with a combination of two pumps to achieve different levels of vacuum. The first phase is the Oil sealed rotary pump used to decrease pressure inside the chamber from atmospheric pressure (101.3k Pa) to rough vacuum (less than 5Pa) and the second phase is a diffusion pump used to reduce the pressure from rough vacuum to high vacuum (less than 10^{-5} Pa). One advantage of using the diffusion pump is because it has no moving part and uses the vapor of boiling fluid to capture gas molecules. It has cooling fins that cool down and releases the air molecules to the fore line via the rotary pump to the atmosphere.

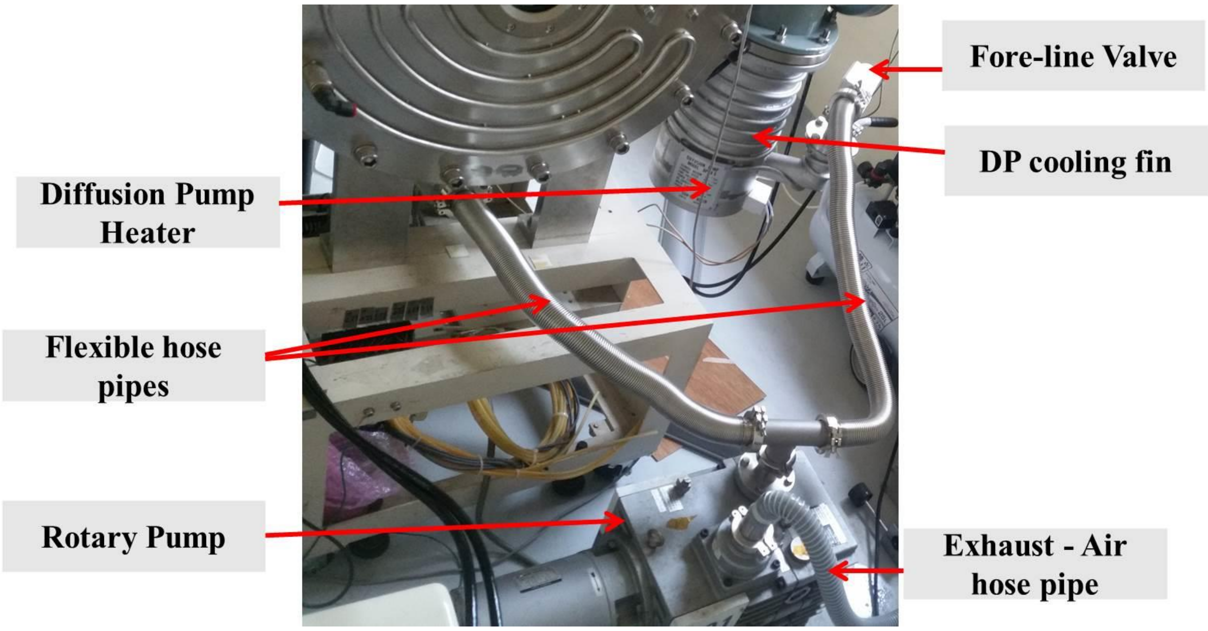

Figure 8 The configuration of the Pumping Systems

Figure 9 shows the detailed configuration of the water chiller interface to the chamber. The connecting hosepipe between the water feedthrough interface and the water chiller is 1 meter long. A valve is connected to the water feedthrough to control the cool water leakages inside the chamber in case of an emergency. The water chiller feedthrough is connected to the water-cooled heat sink to remove heat. The measured flow rate is 9.2 L/min which is adequate to remove heat from the heat sink to achieve the desired temperature as simulated with Kryotherm thermal analysis software.

The control and instrumentation system consists of the pressure gauge controllers, power switch control, temperature control systems, and LabVIEW software-controlled computer. The computer LABVIEW software Interface monitors the temperature and pressure activities inside and outside the chamber by recording it on the PC via a Data Acquisition (DAQ) system. The LabVIEW has a polarity control switch to control the PeTT device heating and cooling mechanism. The power supply systems have an interface connected via DAQ to the PC to control the current and voltage supply to the PeTT device. The chamber pressure is measured by the ionization gauge which is connected via DAQ to the PC for data storage.

After assembly and integration of the vacuum chamber, we perform a test to measure the ultimate chamber pressure levels under no-load condition (which means empty chamber) and also measured the stable temperature for both the DP heater and DP cooling fins. Figure 10 shows the results of the ultimate chamber pressure and stable temperature for both DP cooling fin and DP heater for a period of 27 hours. From the results, we could achieve a chamber pressure of 2.7 x10^{-4} Pa, DP cooling fin stable temperature of 20 ^{o}C and DP heater stable temperature of 166 ^{o}C.

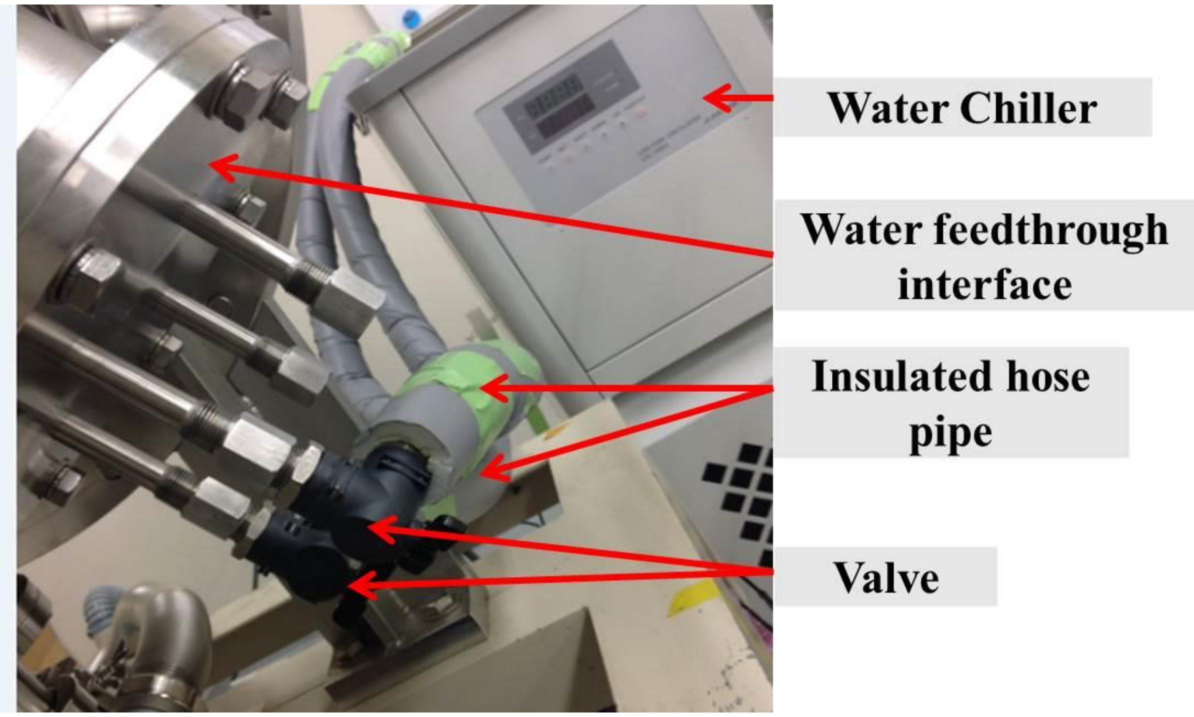

Figure 9 Shows the water chiller system integration with the Chamber

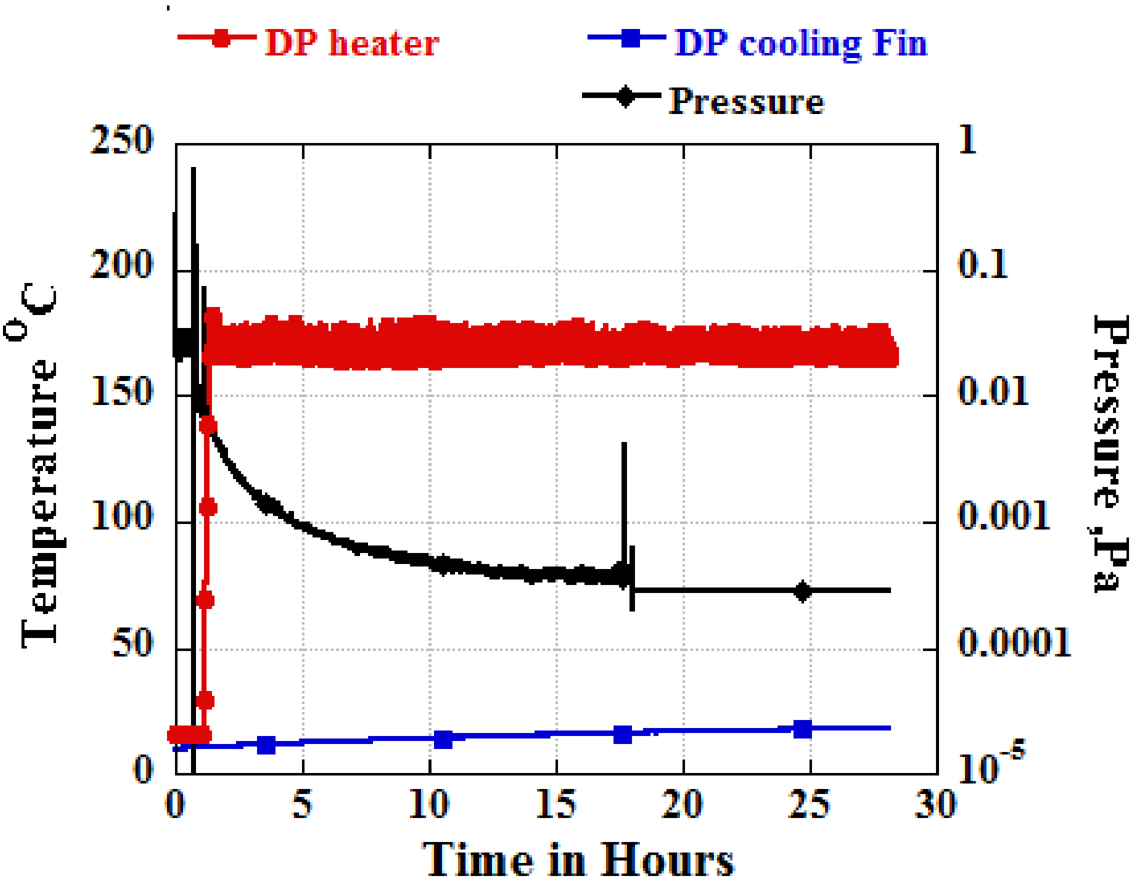

Figure 10 Results shows chamber pressure and stable temperature for DP heater and DP cooling fin

3. EXPERIMENT AND RESULTS

Experiment 1: The PeTT device no Load condition inside the Vacuum Chamber

The first experiment is to measure the maximum cold temperature limit of the PeTT copper surface plate under the no-load condition and monitor time duration it achieved a steady-state temperature condition. In this set up we focused on the PeTT copper surface plate without attaching a thermal copper shroud. Figure 11 shows the set up inside the chamber. We attached thermocouples on the PeTT copper surface plate to monitor the uniform temperature distribution on the surface plate. The PeTT was supplied with an optimized input power of 387.2W. From the software simulation analysis results the expected cold temperature targeted was -80ºC in ideal condition. Multi-Layer Insulator was applied on the copper surface plate to prevent radiation heat exchange loss to the vacuum chamber wall. Inside the chamber, the PeTT device is connected to the water chiller via the R½ stainless flexible tubes. Swagelok connectors are used for leak-tight fittings to prevent water leakages in the chamber. We measured the mass flow rate to be 9.2 L/min which is enough to dissipate heat from the water-cooled heat sink. The water cooling system set point was 0ºC. The generated vacuum pressure and temperature data of thermocouples are acquired via DAQ and are stored in a monitoring PC.

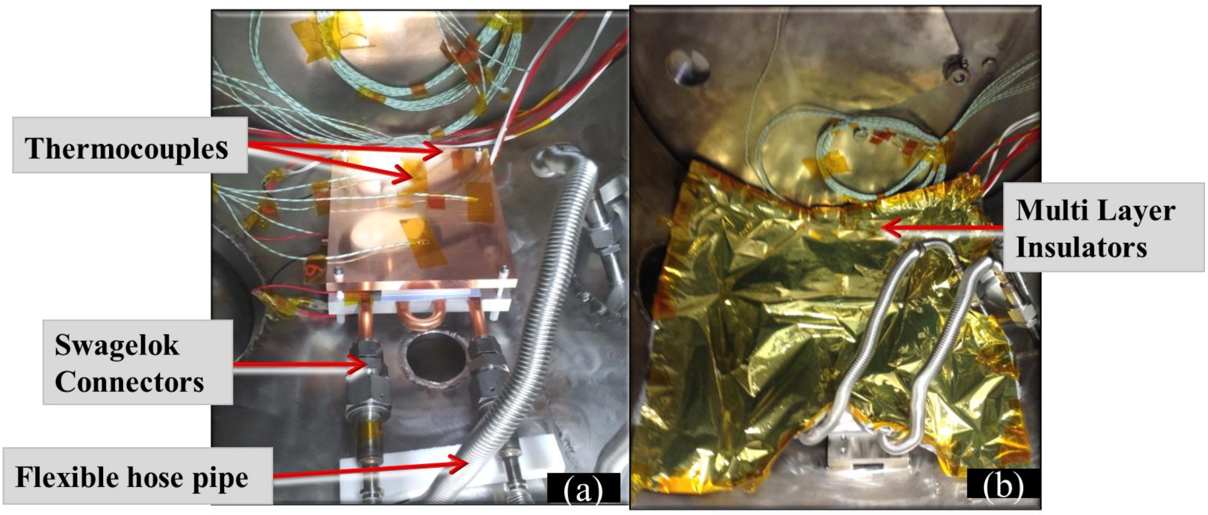

Figure 11 (a) Setup of the PeTT device inside the TVC, (b) PeTT device surface shielded with a multi-layer insulator to cut away heat loss from the chamber wall

Results of Experiment 1

Figure 12 shows the results recorded during the total time duration of 22 hours for the PeTT copper surface plate. The chamber pressure recorded was 3.6 x 10 $^{-4}$ Pa. The output power recorded was 323.84 W which is quite acceptable due to the increase in temperature differential between the cold and hot sides of 4 multi-stage Peltier elements, as a result, leads to voltage drop. We could achieve an average ramp rate of -1.2°C/min and a steady-state temperature between the periods of 5 hours to 22 hours for the PeTT copper surface plate. Table 3 summarizes the test results.

Table 3 Summary of the temperature range for the PeTT device no-load condition

Name	Low Temperature, °C	High Temperature, °C
Surface Plate_1	-77	17
Surface Plate_2	-77	17

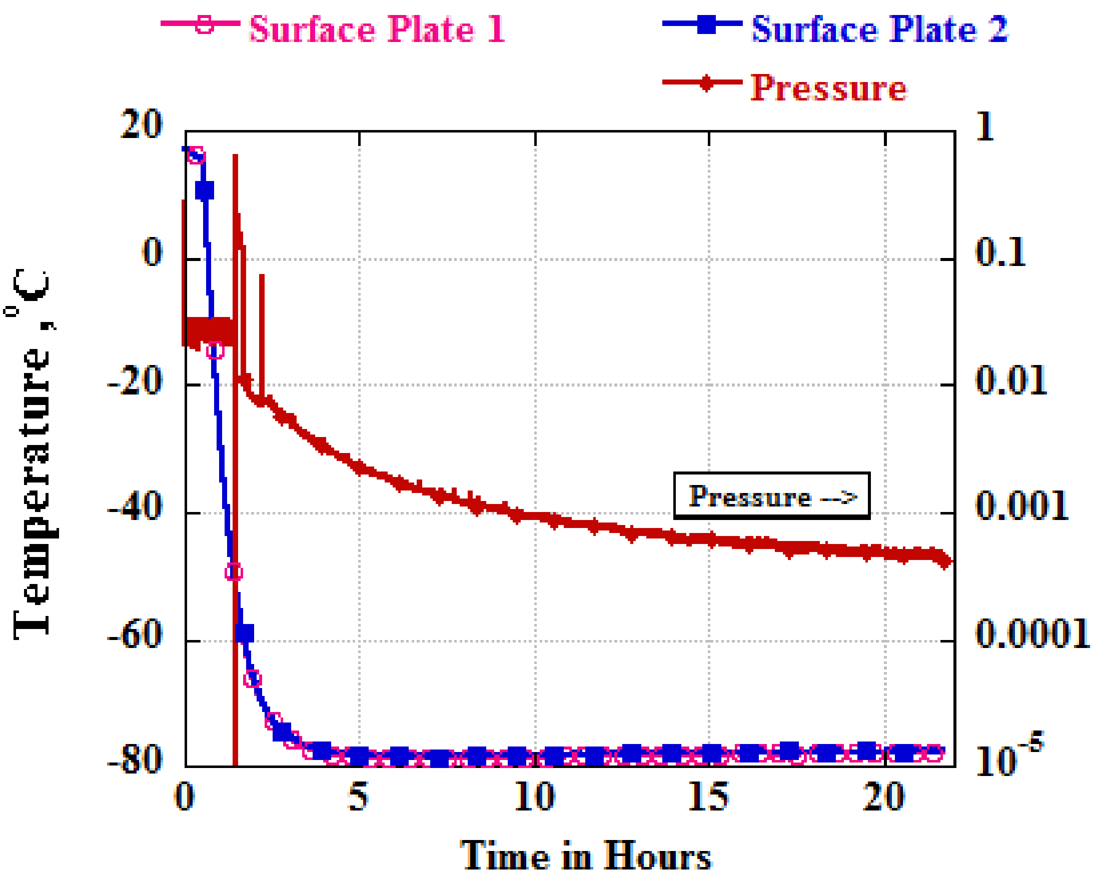

Figure 12 Results of the PeTT device no Load condition showing the chamber pressure and steady-state cold temperature limit inside the TVC

Experiment 2: The PeTT device Copper Shroud no Load condition inside the Vacuum Chamber

The aim of the second experiment is to measure the maximum low-temperature limit of the PeTT copper surface plate and the attached thermal copper shroud under no-load condition. Another secondary test purpose was to remove contaminants from the inner surface of the copper shroud by performing a bake out test to produce consistent radiant heat fluxes under very good control. We applied heater (34.5W) at the copper shroud to perform a bakeout test before cooling down to a stable temperature over several hours. Multi-Layer Insulator was applied on the copper surface plate to prevent radiation heat exchange loss to the vacuum chamber wall as shown on the right side of Figure 13 and the left side of figure 13, thermocouples were attached to five different positions to measure uniform temperature levels.

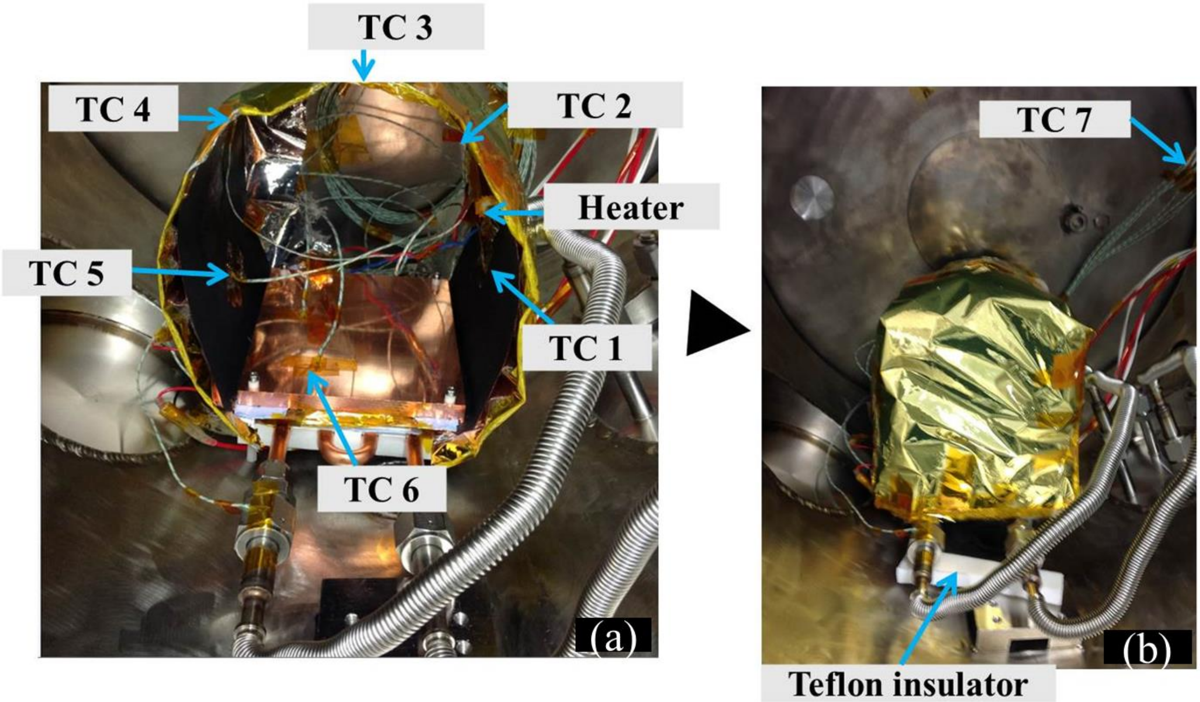

Figure 13 (a) Shows setup of the PeTT device with copper shroud attached with thermocouples inside the TVC, (b) Shows PeTT device with copper shroud shielded with a multi-layer insulator to cut away heat loss from the chamber wall

Results of Experiment 2

Figure 14 shows the results recorded during the total time duration of 26 hours. PeTT device cooling was activated 1.7 hours after the heater was turned off. The chamber pressure was recorded to be 3.2 x 10^{-4} Pa. The output power recorded was 323.84W. We could achieve an average ramp rate of -1.5ºC/min and a steady-state temperature between the periods of 5 hours to 22.5 hours. The chamber wall has a temperature difference of -1ºC (24 to 23 ºC), which means the MLI was able to cut the radiation heat exchange losses. In the summary of the analyzed results, the average low temperatures of the copper shroud achieved were -62 ºC and the PeTT copper surface plate achieved was -67 ºC under no-load condition. Table 4 summarizes the test results.

Table 4 Summary of the temperature range for the thermal copper shroud, PeTT device, and Chamber wall

Thermocouples (TC)	Description	Low Temperature, **ºC**	High Temperature, **ºC**
TC 1	Copper shroud_1	-62	130
TC 2	Copper shroud_2	-60	127
TC 3	Copper shroud_3	-61	126
TC 4	Copper shroud_4	-62	127
TC 5	Copper shroud_4	-65	113
TC 6	PeTT copper surface plate	-67	122
TC 7	Chamber Wall	23	24

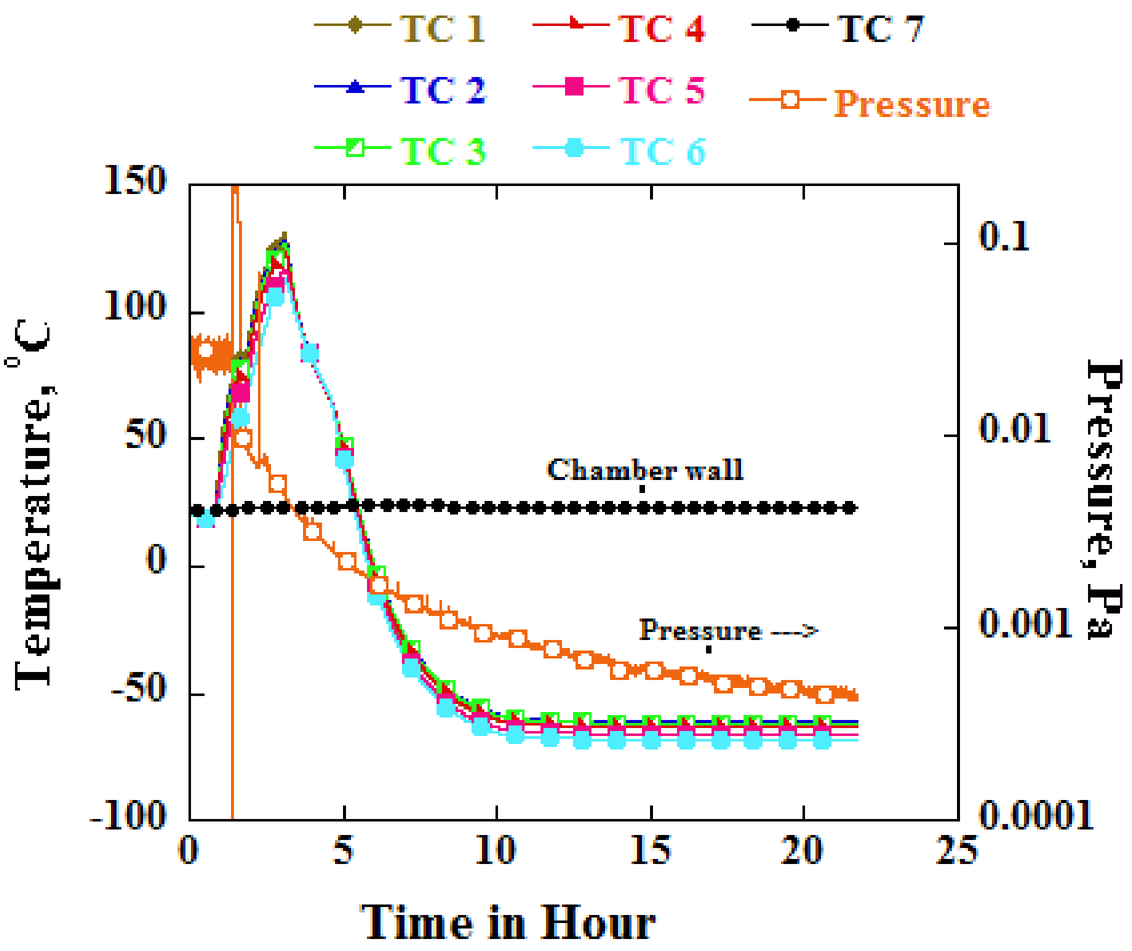

Figure 14 Results of the PeTT device thermal radiative copper shroud no Load condition inside the TVC

Experiment 3: Replica BIRDS-2 Cubesat using PeTT Vacuum chamber

The primary objectives of this test are; (1) to generate the internal heat dissipation of the internal subsystem (UHF-TX and VHF-RX) by using heaters under extreme cold and hot condition and (2) Measure temperatures at different points of the internal subsystem (UHF-TX and VHF-RX) under extreme cold and high condition. The secondary objectives are to measure temperatures at different points which include FAB, Battery Box, Backplane and external panels.

We considered a replica of a Birds-2 1U CubeSat structure model (STM), with some of its internal subsystems which include UHF-TX, VHF-RX, Battery Box, FAB, Backplane and external panels used for engineering model phase. The Bird-2 STM is designed to fit into the J-SSOD and has four rails that can accommodate the internal subsystems. To generate the internal heat dissipation, we attached 2 heaters to the UHF-TX board and VHF-RX. We decided on a heater input power of 4.2W based on the Birds -2 power requirement for UHF-TX [2]. Figure 15 shows the assembled replica of Birds-2 CubeSat (on the left) and the selected internal subsystem arrangement (on the right) as shown in red arrow with a defined axis same as the satellite install case for J-SSOD. The total mass of the assembled CubeSat was 0.95kg. The external panel was attached to the rails via a thermal gel sheet except for +Z axis side which was open due to many harnesses such as internal heater cables and thermocouples and Figure 16 shows some the internal subsystem of the Birds-2 Cubesat and thermocouples are attached to different points for temperature measurement as listed in Table 5.

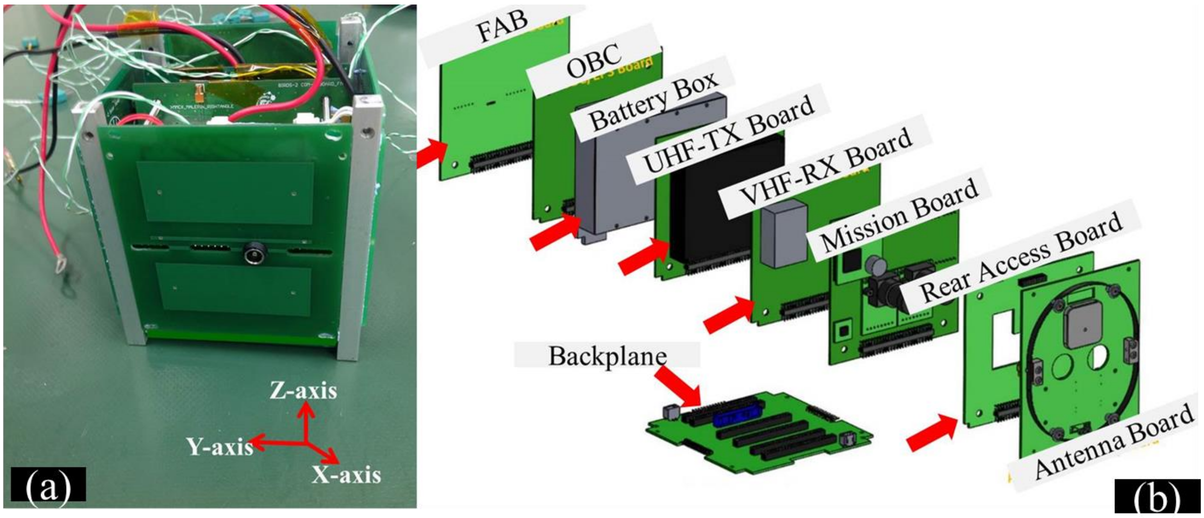

Figure 15 (a) Shows the Assembled prototype Birds-2 Cubesat, (b) Shows the internal subsystem (red mark) arrangement employed in the assembly and integration of the Birds-2 Cubesat,

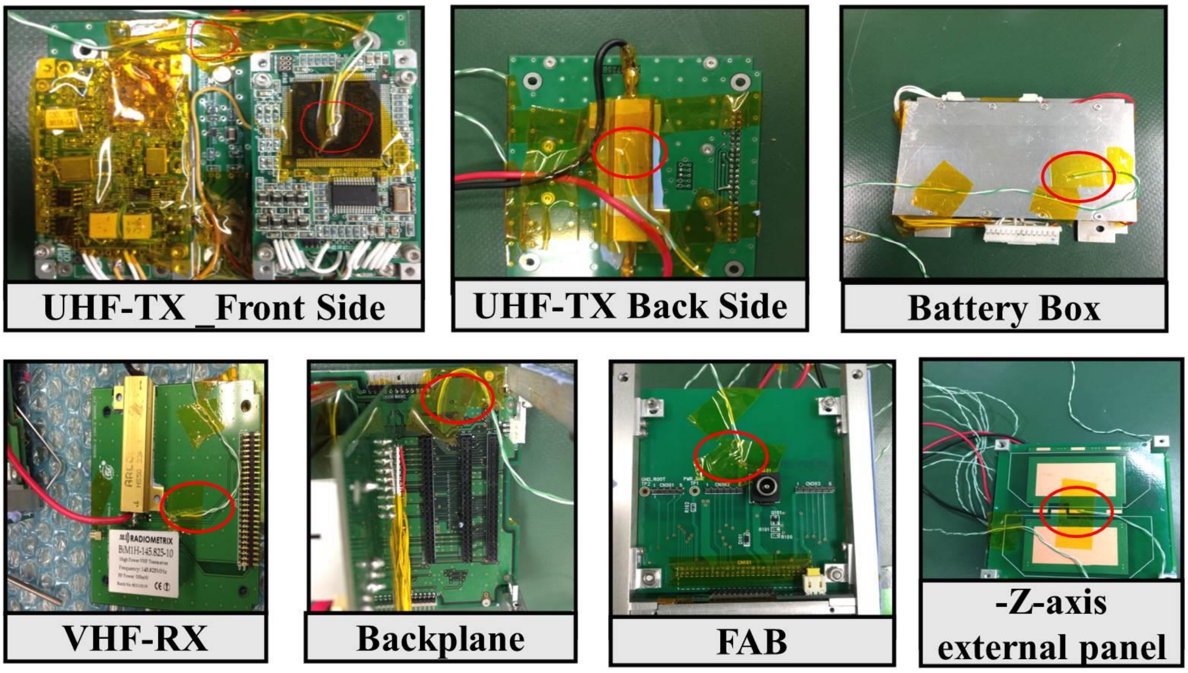

Figure 16 Thermocouple attachments of Birds-2 internal Subsystems

Table 5 Selected Internal Subsystems Thermocouple attachment

Internal Subsystems	Thermocouple Measurement Point
UHF-TX	UHF-TRX Processor
	UHF-TX Board
VHF-RX	VHF-RX Board
Battery Box	Battery Box

FAB	FAB Board
-Z axis External	-Z axis External Board
Backplane	Backplane Board

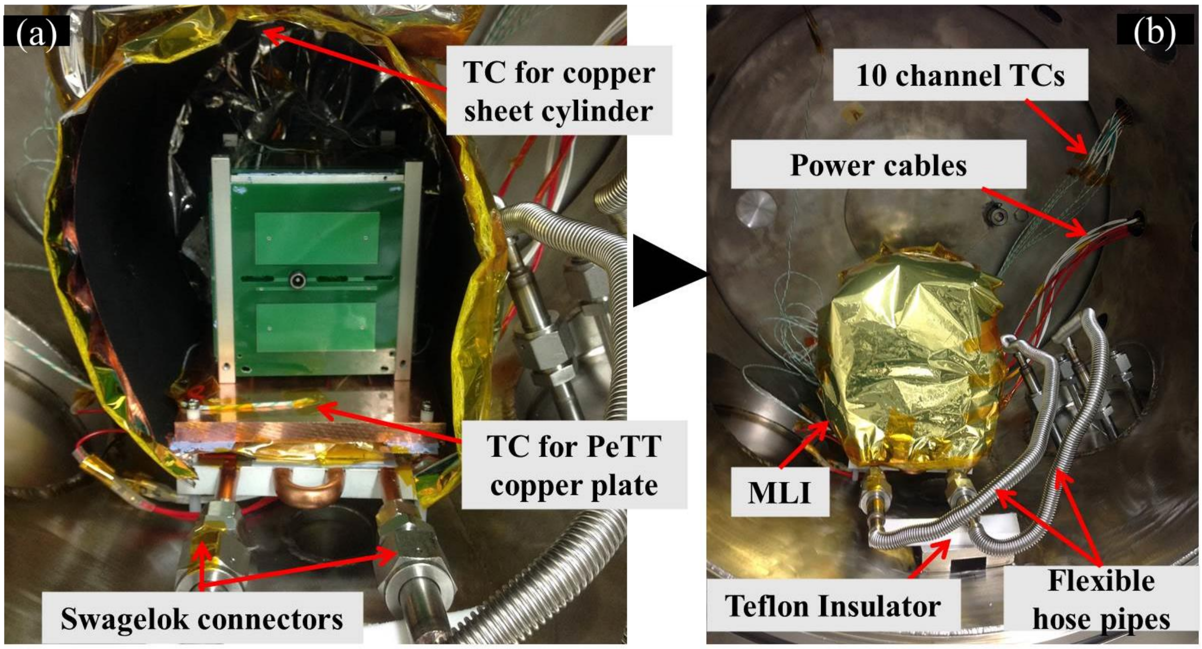

Figure 17 (a) Shows the prototype Birds-2 Cubesat placed by direct contact on the surface of PeTT device, (b) Shows PeTT device and prototype Birds-2 Cubesat shielded with a multi-layer insulator to cut away heat loss from the chamber wall

Table 6 ISO 19683 Test level requirement for Lean satellite class internal unit

Test Levels	Parameters
Low-temperature limit	-15 °C or lower
High-temperature limit	50 °C or higher
Temperature ramp rate	± 1 °C/min
Chamber Pressure	1 x 10 $^{-3}$ Pa or lower

Results of Experiment 3

Figure 18 shows the temperature measurement results obtained from the PeTT device including the –Z-axis external of the CubeSat throughout the operation cycles. The total time duration for the test was 21 hours. The stable chamber pressure recorded for the test was 4.9 x 10 $^{-4}$ Pa. The total thermal cycle was one and a half cycles. We turned on internal heaters to generate internal heat dissipation during cold stable temperature (second half cycle) and hot stable temperature (third half cycle). The chamber wall temperature decreased from 25 to 24 °C with a temperature difference of -1°C, which explains the MLI was able to cut the radiation heat exchange losses from the chamber wall.

The differential temperature between –Z-axis external board and the CubeSat internal subsystems was from 5 to 10 ºC which means the thermal copper shroud was able to transfer energy by radiation to the external panel of the Cubesat.

During the first half cycle, the internal heaters of the subsystems were turned off except the PeTT device which was in heating control mode. In less than an hour, the PeTT device could achieve a maximum high temperature of 65 ºC at an average temperature ramp rate of 2.2 ºC/min. Whiles the CubeSat internal subsystem temperatures were increased to an average temperature of 34 ºC.

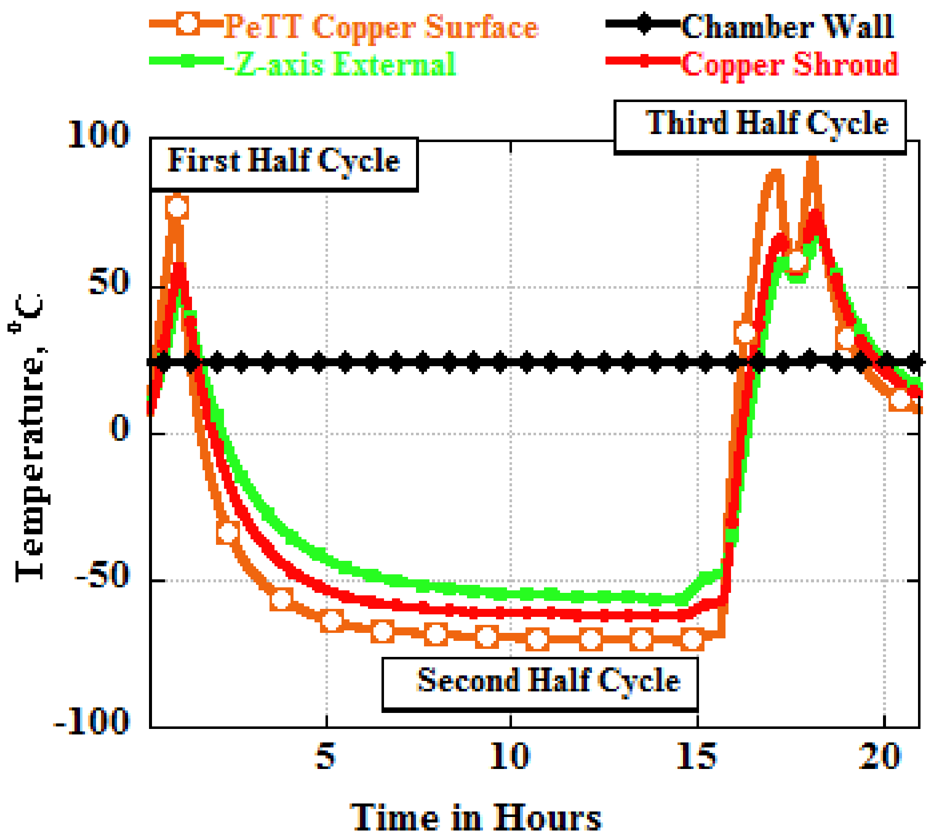

Figure 18 Overall results of the replica 1U Cubesat inside the PeTT Vacuum Chamber

Figure 19 shows the details of the CubeSat internal unit temperatures during the second half cycle. The PeTT device cooling control mode was activated to achieve a cold stable temperature of -70 ºC between the periods of 5 hours to 14.5 hours. The average temperature ramp rate recorded before the cold stable temperature was -1.5 ºC/min. The internal heaters of the CubeSat subsystem were turned off during this phase of the operation. Table 7 summarizes the results of the internal subsystems during the cold stable temperature period of 5 hours to 14.5 hours.

Table 7 Summary of cold stable temperatures of the CubeSat internal subsystem under internal heaters OFF condition

PeTT device cooling control mode	Temperature of Internal Subsystems					
Cold stable Temperature	UHF-TX processor	UHF –TX Board	VHF-RX Board	Battery Box	Backplane Board	FAB Board
-70 ºC	-49 ºC	-50 ºC	-50 ºC	-52 ºC	-52 ºC	-50 ºC

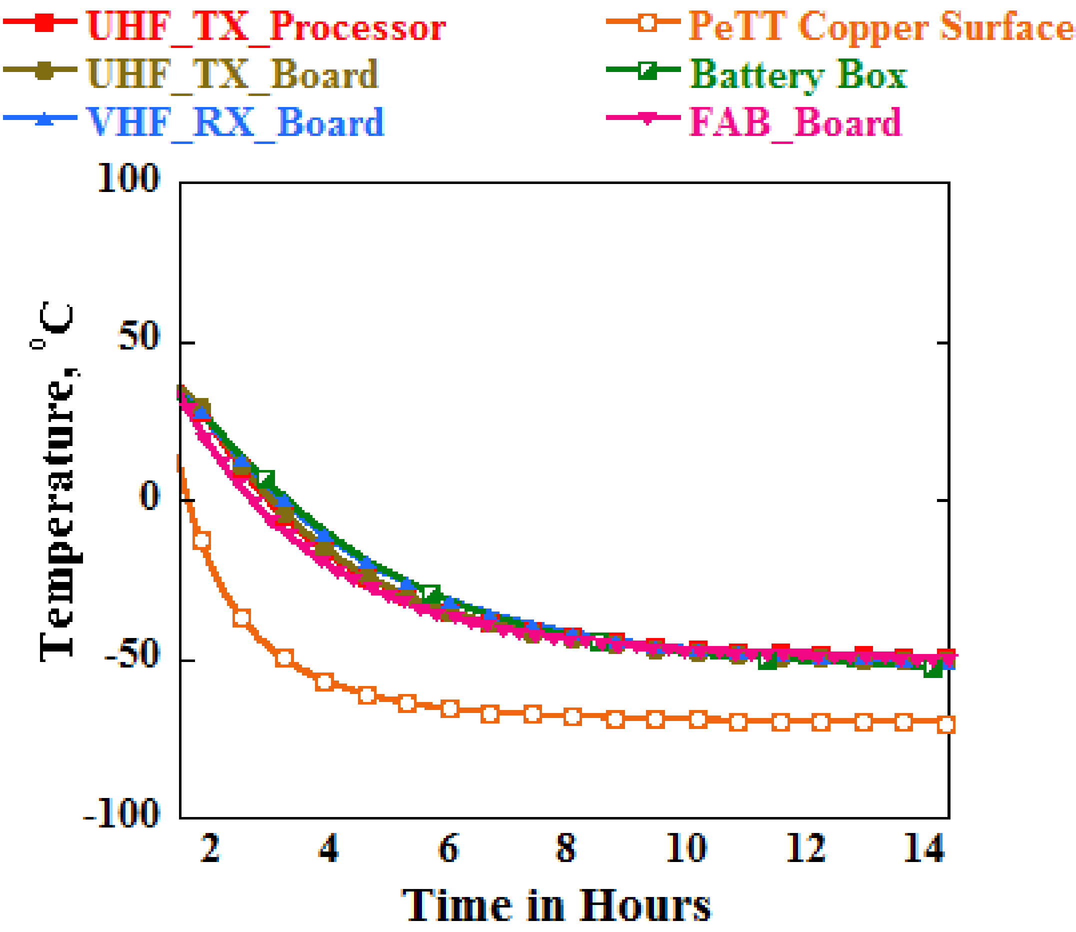

Figure 19 Cold stable temperature of CubeSat internal subsystems under internal heaters OFF condition

We turned on the internal heaters attached to UHF-TX and VHF-RX to generate the internal heat dissipation for a time duration of 1.1hours. Figure 20 shows details of the internal heat dissipation period of 14.5 hours to 15.6 hours under cold stable temperature conditions. This result was to also check standard ISO 19683 test requirement for internal unit qualification (QT) which defines lean satellite internal unit test requirement in a thermal vacuum chamber. From the below results, we can say, the cold condition meets the ISO 19683 test requirement for internal unit qualification (QT) which defines lean satellite internal unit test requirement under cold stable temperatures and moreover, we can say the PeTT device cooling control mode was successful. Table 8 summarized the results of the internal subsystems during the internal heat dissipation under cold stable temperatures. The VHF–RX was 9 °C lower than the UHF-TRX. The FAB board was 8 °C to 16 °C lower than both VHF-RX and UHF-TX

Table 8 Summary of cold stable temperatures of the CubeSat internal subsystem under internal heaters ON condition

PeTT device cooling control mode	Temperature of Internal Subsystems					
Cold stable Temperature	UHF-TX processor	UHF –TX Board	VHF-RX Board	Battery Box	Backplane Board	FAB Board
-70 °C	-21 °C	-22 °C	-29 °C	-31 °C	-35 °C	-37 °C

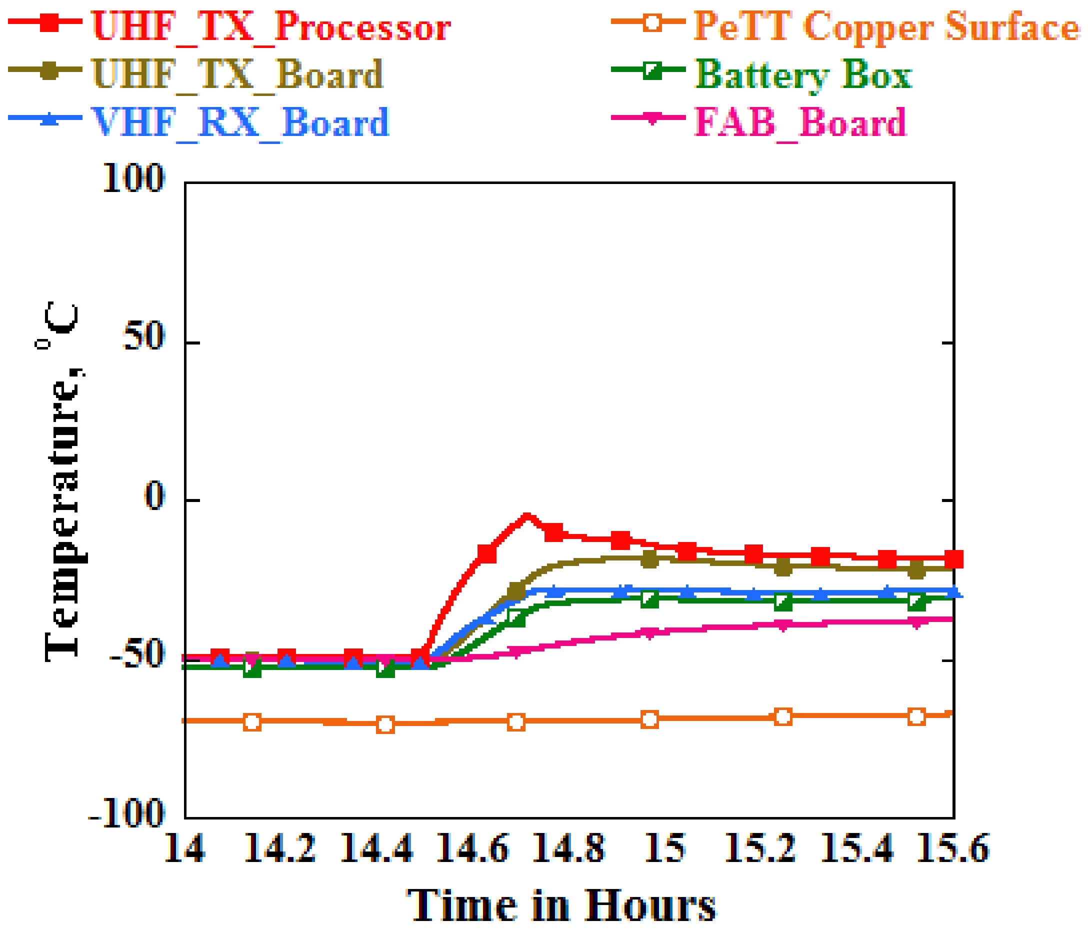

Figure 20 Cold stable temperature of CubeSat internal subsystems under internal heaters ON condition

Figure 21 shows the details of the third half-cycle. PeTT device cooling control mode was switched to heating control mode to raise the temperature of the internal subsystems to an expected high-temperature that meets the ISO 19683 test level requirements for high-temperature limit condition equal to above 50 °C as listed in Table 6 When the PeTT device heating control mode temperature was controlled to 88 °C, the internal subsystem average temperature of 50 °C was achieved which means Before we turned on the internal heaters of the subsystems (UHF-TX and VHF-RX), the PeTT device heating control mode was decreased below 88 °C to safe mode due to the limitation of the PeTT device high-temperature limit especially the soldering temperature point should not be higher than 95 °C. We turned on the internal heaters for an hour and we observed a rise in PeTT control temperature up to 93 °C. Table 9 summarized the results of the internal subsystems under a hot stable temperature limit of the PeTT device heating control mode

Table 9 Summary of hot stable temperatures of the CubeSat internal subsystem under internal heaters ON condition

PeTT device heating control mode	Temperature of Internal Subsystems					
Hot stable Temperature	UHF-TX processor	UHF –TX Board	VHF-RX Board	Battery Box	Backplane Board	FAB Board

88 ~ 93 ºC	54 ºC	52 ºC	50 ºC	48ºC	55 ºC	56 ºC

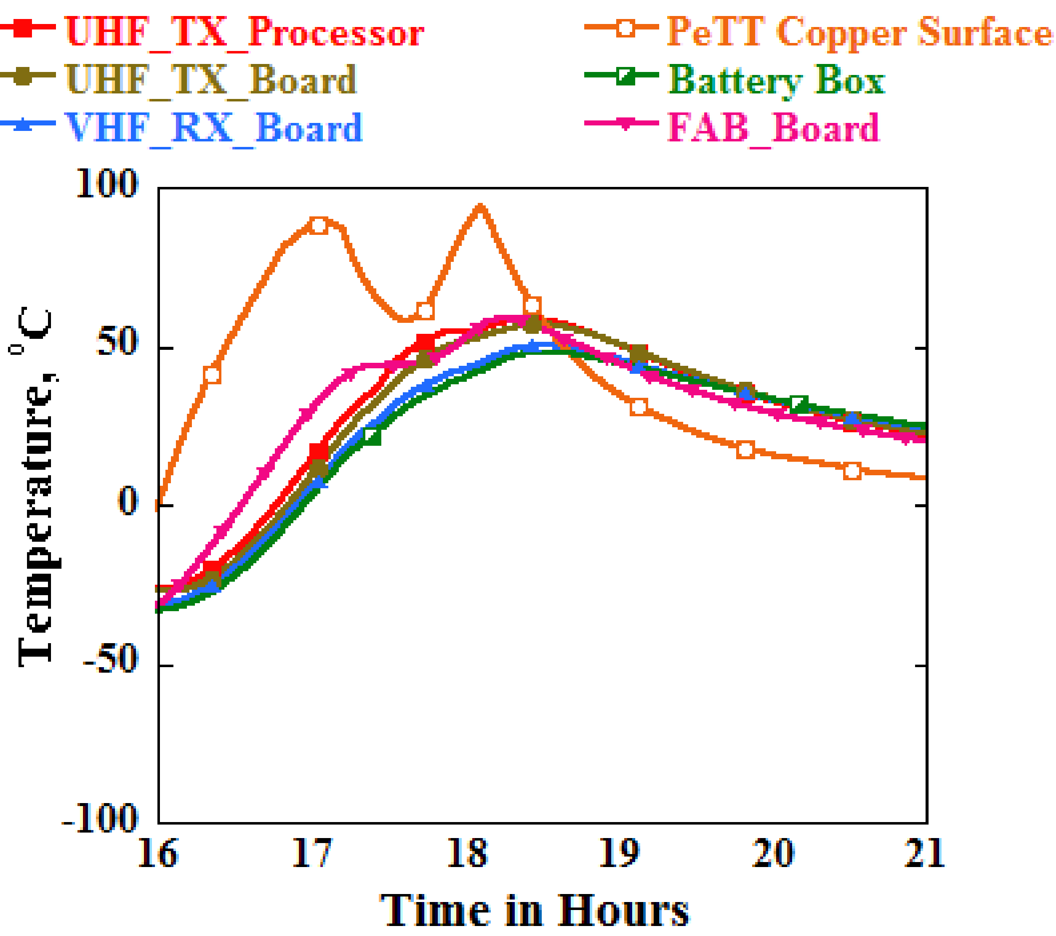

Figure 21 Hot stable temperature of CubeSat internal subsystems under internal heaters ON condition

From the lesson learned in the third half-cycle test, we recommend PeTT heating control mode should not be above the operating temperature of 80 ºC to prevent destroying the Peltier elements. The reason is that 4 multi-stage Peltier elements overheat very fast when you change polarities, therefore, we advise you try to monitor both the temperature of the Peltier element and the cold surface plate during operation.

We conducted another test to demonstrate the PeTT device can control the Hot soak levels of the external panel of the replica Cubesat for half -cycle using the same set up as shown in experiment 3, We attached thermocouples to some selected part of the external panels which includes –X/+X panel and -Z-axis panel. This test was significant to enhance workmanship in testing the operator's skills and also correct the challenges faced in our lesson learned in experiment 3. As shown in Figure 22 represented a half cycle of the hot soak levels of the external panels of Cubesat. The steady-state for hot soak temperature level was achieved 9 hours after the PeTT Device hot mod was turned ON. Table 10 summarizes temperature for PeTT surface plate, shroud and external panels at the steady-state. From the results, the differential temperature (dT) between the PeTT surface plate and the shroud was 5 ºC, the dT for the shroud and the external panels (Z panel and ±X panel) was from 3 to 7 ˚C.

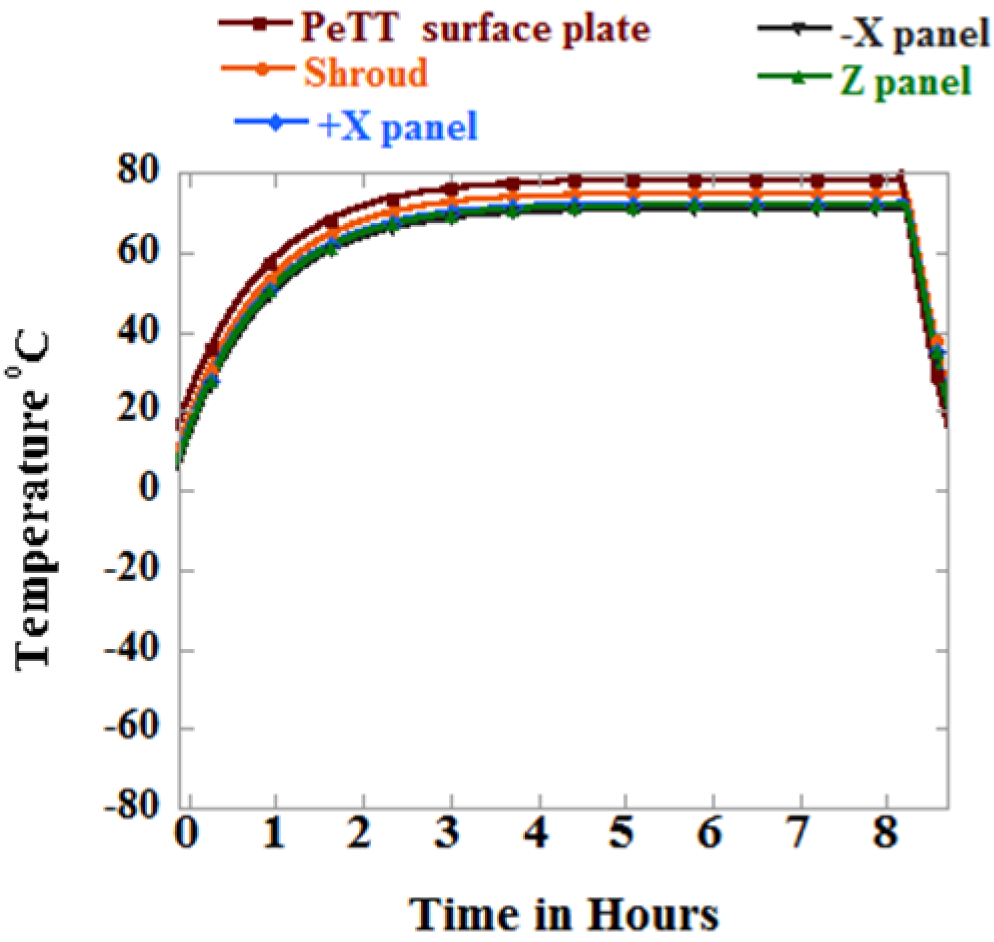

Figure 22 Hot stable temperature for PeTT surface plate, shroud and external panels of a replica CubeSat

Table 10 Summary of hot soak temperature levels of the PeTT device, Shroud and external panels of a replica Cubesat

Name	Maximum High Steady State Temperature, °C
PeTT Surface Plate	78
Shroud	73
-X panel	70
+X panel	68
-Z panel	66

4. CONCLUSION AND FUTURE WORK

The recent proliferation of lean satellite activities worldwide demands proper testing infrastructure. A thermal vacuum test requires special equipment especially to simulate the cold condition in space. The use of liquid nitrogen to generate cryogenic temperature is difficult for emerging space countries. In the present paper, we have demonstrated an affordable way of conducting the thermal vacuum test even in resource-limited countries by using PeTT technology.

We demonstrated the capabilities of the PeTT vacuum chamber using a replica 1U Cubesat by generating the internal heat dissipation using internal heaters (4.2W) to achieve an average temperature range of -29 ^{o}C to 52 ^{o}C at a chamber pressure of 4.6 x 10^{-4} Pa. The summary of the test results meets the ISO 19683 test requirement for internal unit qualification (QT) which defines lean satellite internal units. The PeTT device components are available from online vendors, which make it possible to have access to replicate the design of the PeTT device in any area of the world. The cost of the PeTT vacuum chamber developed was 31,000USD.

The operation of the PeTT vacuum chamber is not complex and does not require more labor, and longtime set up preparation as compared to LN2-based thermal vacuum chamber.

Moreover, the PeTT vacuum chamber operation can stop anytime, when there is an accident in the test article by turning off the power supply of the PeTT device. PeTT vacuum chamber can serve as a TVC facility for space activities in developing countries to build human capacity in thermal vacuum testing. We propose this idea should be supported by the global space communities not limited to University Space Engineering Consortium (UNISEC), Africa Union Space Programme, in contributing to the sustainable space activities in developing countries and also towards achieving the United Nations Office for Outer Space (UNOOSA) Space 2030 Agenda for the Sustainable Development Goals.

Due to time and lack of Onboard Computer (OBC) we could not have a real CubeSat to perform the real functional test. In future work, we will perform a functional unit test of a real 1U CubeSat under the cold and hot temperature condition using the PeTT vacuum chamber for at least 3 cycles. Furthermore, we will upgrade the PeTT device design to able to test 1U to 3U CubeSats.

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