Enabling Critically Cooled Instrumentation via Active Thermal Management for CubeSats: The Active CryoCubeSat Project

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ABSTRACT

We explore the development and testing of an active thermal management system for CubeSats to enable electro optical and subcooled instrumentation targeted at advanced aerospace missions. The Active CryoCubeSat utilizes a two-stage thermal control architecture. The first stage consists of a mechanically pumped fluid loop with an additively manufactured heat exchanger and a deployable radiator. The second stage is a Ricor K508N cryocooler which enables the generation and maintenance of a cryogenic environment. This project focuses on the design and testing of a ground-based prototype in a relevant thermal vacuum environment as well as a review of the preliminary results. Ultimately, the ACCS project will further enable the capabilities of CubeSat-based platforms for advanced Earth observing, deep space, and helioscience missions through the use of miniature cryocoolers and active thermal management for small satellites.

INTRODUCTION

The Active CryoCubeSat (ACCS) project is a joint research effort between the Center for Space Engineering at Utah State University (CSE, USU) and the Jet Propulsion Laboratory (JPL). Under a NASA Small Spacecraft Technology Partnership, the team has developed an active thermal management and control subsystem for CubeSats. It relies upon a two-stage thermal control architecture. The first stage is composed of a single-phase mechanically pumped fluid loop (MPFL)[1] that circulates coolant from a cold plate rejection Heat Exchanger (HX) internal to the satellite, to an external deployed and tracking radiator. The second stage relies upon a micro tactical cryocooler to provide cold tip cryogenic thermal management. The ACCS system is capable of managing and rejecting thermal loads greater than 60 W from onboard electronics, instrumentation, avionics, and power generation systems as well as its own generated thermal load. It can also maintain environmental temperatures throughout a mission of <35°C to thermally stabilize and enable onboard cryogenic optical instrumentation. The integrated miniature tactical cryocooler provides cold tip temperatures in the range of 70-110 K with cold-tip thermal loads up to 500 mW.

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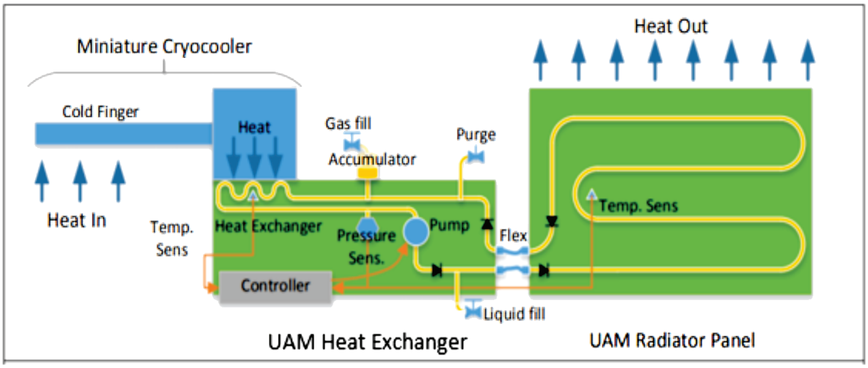

Figure 1. Concept of operations for the active thermal control of the ACCS system

The system utilizes Novec-7000[2], a low viscosity coolant, as well as a commercially available micro pump and cryocooler to form the two stages of the system. The system also relies heavily upon additive manufacturing and the technique of ultrasonic foil welding (UAM) to integrate the fluid coolant channels directly into the chassis of the CubeSat. This helps to miniaturize, simplify, and integrate the system into standard commercially available CubeSat platforms. The ACCS system is designed to fit within a 1U standard volume and specifically targets 6U CubeSat buses. Figure 1 outlines the operational concept of the ACCS system. Further details on the basic design of the ACCS system can be found in References 3 and 4.

The primary objectives of the ACCS project are summarized in Table 1 along with the required performance benchmarks. At this time, the ACCS project has successfully developed a ground-based prototype active thermal management system appropriate for CubeSats and demonstrated it in a relevant environment. In addition, the project has advanced the TRL of the ACCS subsystem to 5 (TBR) and furthered the development of CubeSat missions capable of cryogenic instrumentation for future NASA Science Mission Directorate programs.[5]

Table 1. ACCS grant objectives and requirements[3]

ACCS Project Objectives	
1)	Develop a miniature mechanically pumped fluid loop thermal control system for a CubeSat
2)	Develop advanced manufacturing techniques using Ultrasonic Additive Manufacturing (UAM) and Direct Metal Laser Sintering (DMLS) with aluminum to construct multifunctional structural-thermal components of a CubeSat
3)	Demonstrate thermal accommodation of a miniature cryocooler suitable for a cryogenic instrument

Required Performance	Performance Goal
MPFL	
Thermal Load: > 30 W Interface: 20-30°C Power: < 4 W Mass: < 2 kg Volume: < 1U Pointing: < .005°/s	Thermal Load: > 60 W Interface: 10-30°C Power: < 0.3 W Mass: < 0.5 kg Volume: < 0.3U Pointing: < .0005°/s
Additive Manufacturing	
10 cm x 10 cm HX Panel	10 cm x 10 cm HX Panel 20 cm x 30 cm Radiator
Cryocooler	
Temperature: < 100 K Thermal Load: > 50 mW Power: < 15 W Mass: < 1 kg Volume: < 1U	Temperature: < 75 K Thermal Load: > 250 mW Power: < 5 W Mass: < 0.2 kg Volume: < 0.3U

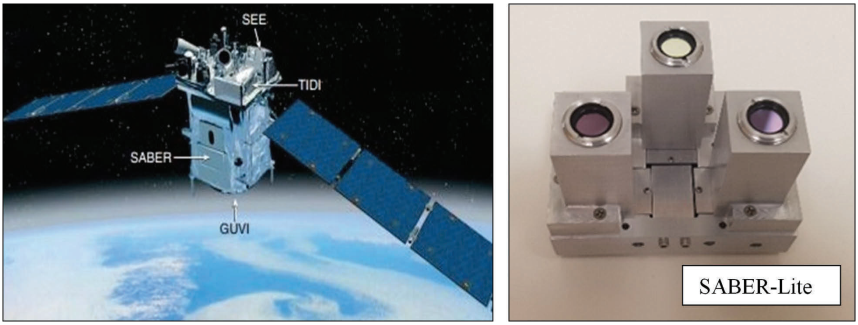

Figure 2. (Left) Original SABER Instrument on the TIMED Spacecraft[4,5] and (Right) prototype SABER-Lite instrument

REFERENCE MISSIONS

The ACCS project aims to enable advanced CubeSat missions, specifically, electro-optical instrumentation requiring the use of cryocoolers and subcooled optics/detectors. An example of this is the Sounding of the Atmosphere using Broadband Emission Radiometery (SABER) instrument on the TIMED spacecraft[6-7] (Fig. 2). SABER measured the atmosphere using broadband limb-scanning infrared radiometry. This instrument is now aging and could be replaced by a series of miniaturized instruments and CubeSats. The ACCS project along with the CSE is currently developing a miniature SABER-Lite (Fig. 2) radiometer for CubeSat architectures and plans to propose a future CubeSat mission based on the ACCS system and the SABER-Lite instrument. Another potential mission would be as the integrated thermal control subsystem for the National Oceanic and Atmospheric Administration's EON-IR missions.[8]

EXPERIMENTAL DESIGN

The ACCS testbed is designed to operate within the USU/CSE TVAC chamber. To this end all the system components are built into a sized-to-fit test cube shown in Fig. 3. The entire system is standalone and includes the HX, radiator, recirculating flow path for the MPFL, and support structures for each. The bottom layer of the test cube houses the radiator sandwiched between LN2 shrouds and wrapped in a dedicated MLI blanket. The upper layer contains the HX, flow meter, accumulator, pressure transducers, instrumentation, and internal electronics. The entire test cube is wrapped in a second MLI blanket. Figure 3 shows the standalone test cube and the test cube integrated into the TVAC chamber. The Ricor K508N cryocooler was chosen for this project due to its wide operating temperature range, cold tip performance, comparatively low power requirements, size, weight, and availability.[9]

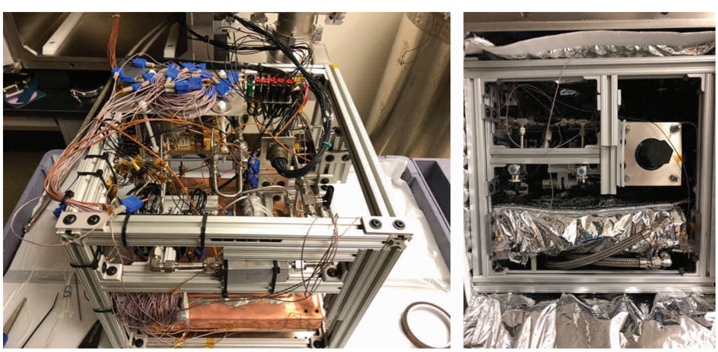

Figure 3. (Left) ACCS Test Cube fully assembled (Right) Test Cube integrated with the TVAC

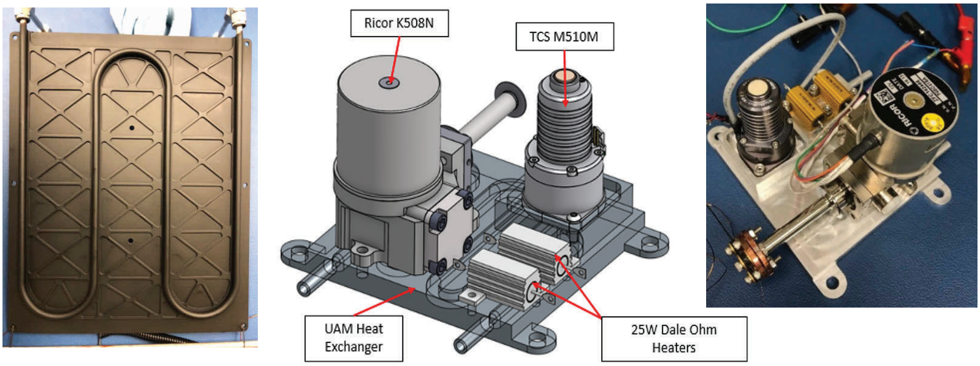

Figure 4. (Left) UAM radiator with light weight design. (Right) HX CAD model and prototype

The ACCS radiator is a UAM[10-11] double sided 6U design manufactured by Fabrisonics.[12] The radiator was painted with Z306 Aeroglaze black paint for high emissivity. The HX is also fabricated via UAM and is used as a thermal rejection cold plate for the surface-mounted Ricor K508N cryocooler and the manifold-mounted TCS M510 micro pump.[13] Dale ohm and patch heaters are mounted on the HX, radiator, and cryocooler cold tip to simulate additional thermal loading. Figure 4 shows the UAM radiator as well as a preliminary CAD model of the HX platform next to the fabricated prototype.

Instrumentation

The ACCS test cube is instrumented with temperature sensors, voltage monitors, pressure transducers, and IR cameras. Temperature is monitored by 30 type T surface mount temperature sensors and two Lakeshore RTD DT 670 diodes. The thermocouples are divided between the various major components with six measuring the thermal distribution across the radiator and five doing the same for the HX. Four emersion type thermocouples monitor the inlet and outlet fluid temperatures of the coolant for the HX and radiator. In addition, the Ricor K508N cryocooler and TCS M510 micro pump are also monitored with surface thermocouples as well as the various structural components at select locations. The two RTD sensors are bolted to the copper rejection plate on the tip of the cryocooler and provide a redundant and isolated measurement of the cryogenic temperature of the cold tip.

The flow rate of the coolant is monitored by a venturi meter while the pump differential pressure and the overall static pressure of the system are measured by separate Honeywell pressure transducers. The power to each component and the RPM's of the pump are also recorded. Two FLIR[14] Lepton IR camera cores are used to study the temperature distribution across the bottom of the HX plate as well as the cryocooler and micro pump mounted on top of the HX.

Electrical and Software

The ACCS system required a custom electronics support package. This included a National Instruments (NI) data acquisition module with boards for voltage and temperature measurements. The system also included voltage dividers and current sensors for each powered device within the system. A dedicated controller for the pump and cryocooler as well as current converters for the MPFL's pressure transducers. Ultimately, the data is connected to a PC running LabVIEW and post processed data values such as flow rate, power, and pressure are calculated and stored, along with the raw data, to doubly redundant data backups. Remote system monitoring is also used for longer test runs. Figure 5 shows the in-house built E-box for the ACCS system.

TESTING PROCEDURE

The ACCS system was tested in a relevant environment by performing a series of TVAC thermal tests. The test cube was placed into the CSE TVAC chamber and a vacuum of at least 10^{-5}

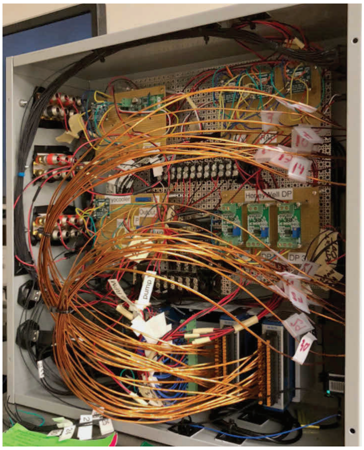

Figure 5. Custom electronics box for the control and processing of the ACCS system

Table 2. Typical ACCS testing procedure

ACCS Preliminary Testing Procedure				
1	Pull a vacuum of at least 5x10^{-5} mbar: To prevent convective heat transfer			
2	Cool the LN2 shrouds to below 90 K			
Test				
3	HX Power: 20 W	Pump Power: ~10 W	Cold Tip Power: 0.25 W	Flow: Turbulent
4	HX Power: 30 W	Pump Power: ~1.5 W	Cold Tip Power: 0.25 W	Flow: Laminar
5	HX Power: 35 W	Pump Power: ~10 W	Cold Tip Power: 0.25 W	Flow: Turbulent
6	HX Power: 45 W	Pump Power: ~1.5 W	Cold Tip Power: 0.25 W	Flow: Laminar
7	HX Power: 20 W Rad. Power 30 W	Pump Power: ~10 W	Cold Tip Power: 0.25 W	Flow: Turbulent
8	HX Power: 30 W Rad. Power: 30 W	Pump Power: ~1.5 W	Cold Tip Power: 0.25 W	Flow: Laminar
9	HX Power: 55 W	Pump Power: ~10 W	Cold Tip Power: 0.25 W	Flow: Turbulent
10	HX Power: 20 W	Pump Power: ~10 W	Cold Tip Power: 0.5 W	Flow: Turbulent

mbar was pulled. Once a stable vacuum was achieved, liquid nitrogen (LN2) was pumped into the cooling shrouds surrounding the radiator plate. The flow of LN2 and the temperature of the shrouds was controlled by an Omega I series PID process controller down to cryogenic levels. Once a stable vacuum and thermal rejection environment was reached, a preliminary testing procedure that defined the maximum and minimum performance boundaries of the system was executed. Table 2 details the first preliminary tests of the system. It should be noted that the Ricor K508N cryocooler was set to 12 V while the internal controller dynamically varied the power to an average of about 6 W.

PRELIMINARY RESULTS

The following results were collected during a series of early test runs and are preliminary. A total of four consecutive and complimentary test runs are represented below. The variation in total power throughout a given test run is shown in Fig. 6, while Figs. 7-10 show various parameters for a single test run for clarity. These power values in Fig. 6 correspond to the steady state temperature values of the cold plate rejection heat exchanger and the radiator in Fig. 7. The flow rate of Novec-7000 coolant was varied from the laminar to turbulent regime for each steady state temperature and power level (Fig 8). The temperatures of the Ricor K508N motor & piston casing and the cold finger mounting joint are given in Fig. 9. The cold tip of the cryocooler was set to ~110 K and was maintained throughout the entire test run and is shown in Fig. 10.

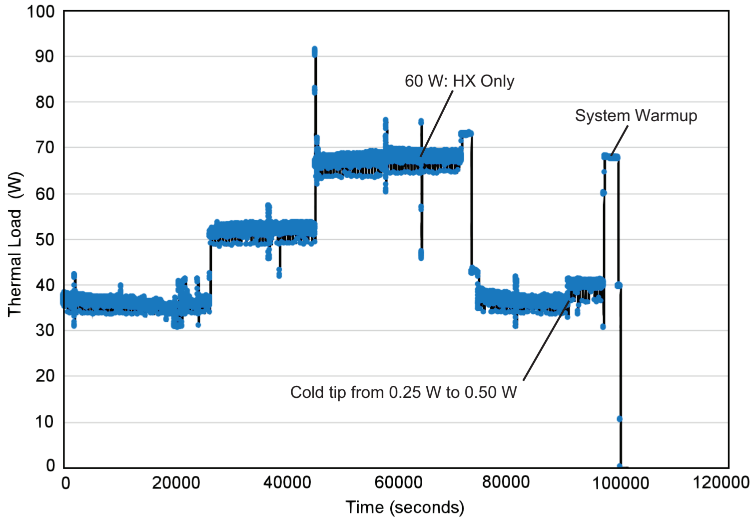

Figure 6. Total thermal loading of the ACCS system for each step of the test procedure

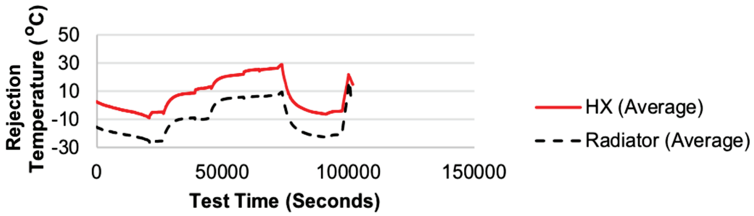

Figure 7. Average temperature of the heat exchanger and radiator for a typical test run

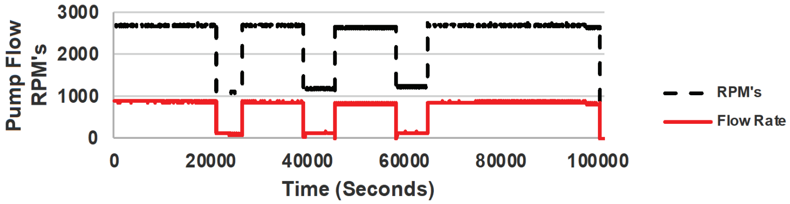

Figure 8. Average flow rate of the Novec-7000 coolant. Note the transitions from a laminar to turbulent regime. (Laminar ~100 mL/min) & Turbulent ~900 mL/min

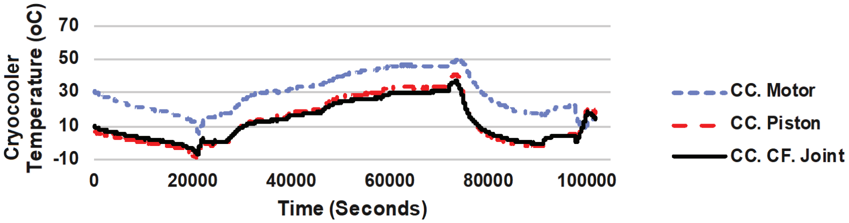

Figure 9. Selected temperatures of the Ricor K508N cryocooler surface temperature for a typical characterization test.

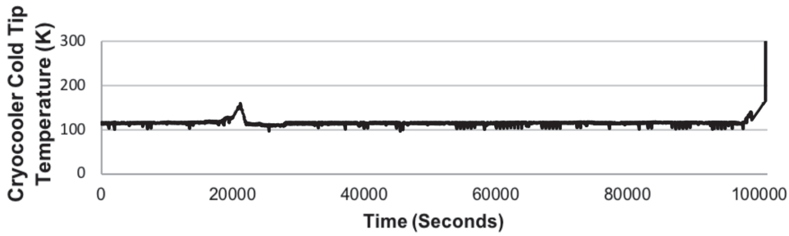

Figure 10. Ricor K508N cryocooler cold tip temperature as maintained by the setpoint and cold rejection environment of the heat exchanger

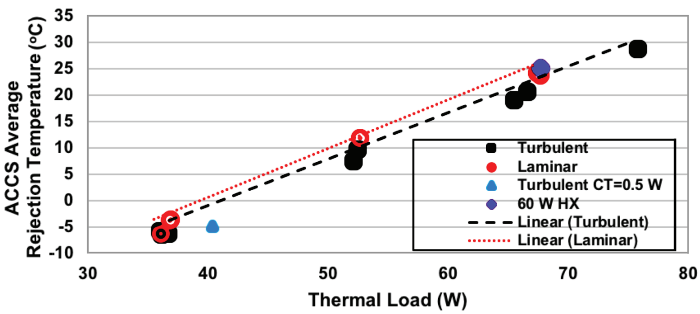

Figure 11. Overall performance and characterization of the ACCS system. Steady state temperature vs thermal load for the given test procedures.

The overall performance of the ACCS system is represented by the total power vs. HX rejection temperature plot shown in Figure 11. The results from all test runs indicate that the system is capable of rejecting more than 65 W at a temperature of less than 30°C. It should also be noted that the difference in performance between laminar and turbulent is small, typically less than 5°C. This would indicate that the system could easily be operated within the laminar flow regime and reduce the power requirements of the pump. The tests also indicate that when the thermal load is shared between the radiator and HX, as in the case of environmental loading on the spacecraft, the temperature is less than if the entire load is introduced on the HX. In addition, when the cold tip load is increased to 0.5 W, the system shows an increase in power and rejection temperature above that of the baseline 35 W.

Finally, an observation made by the team was that the thermal gradient across the radiator was much larger than expected. This indicates that the preliminary analytical and numerical analysis performed by the team in the design of the radiator did not adequately describe its complex thermal behavior. Additional work will be required to fully understand the radiator and optimize its performance. A thermal view of the HX is given in Figure 12; note the temperature distribution across the HX surface as well as the variation in the pump and cryocooler.

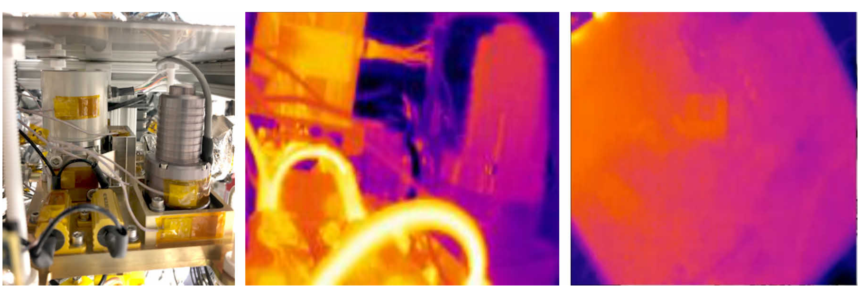

Figure 12. Flir Lepton IR images of the cryocooler, micro-pump, and HX plate. (Left) camera view. (Middle) IR camera view. (Right) Bottom of the HX plate

FUTURE WORK

The ACCS project is still in the preliminary testing and analysis phase. Therefore, a great deal more work is required before the system can be considered fully characterized. In a parallel research effort, the CSE team is working with Dr. Randy Christenson of USU to develop a feedback and control algorithm for setpoint thermal rejection and temperature control of the heat exchanger environment. Finally, a new grant has been awarded to the CSE team to further develop the technology of the ACCS system. The new grant, Active Thermal Architecture for Cryogenic Optical Instrumentation, will explore the thermal and vibrational isolation of an active thermal control subsystem within a CubeSat and the method of deployment and control of an external radiator.

CONCLUSIONS

The ACCS project has successfully developed an active thermal control and management system targeting CubeSat platforms and demonstrated it in a relevant thermal vacuum environment. The system is capable of maintaining an appropriate thermal environment for a Ricor K508N miniature cryocooler with a cold-tip load of up to 0.5 W and rejecting more than 60 W, with required input powers of less than 10 W and cold plate rejection temperatures of less than 30^{o}C. The preliminary results indicate that each of the stated requirements and objectives for the research project has been met. Ultimately, the ACCS project hopes to enable a new generation of advanced CubeSat missions and instrumentation.

ACKNOWLEDGMENTS

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