SSC18-WKVII-08

The Active CryoCubeSat Project: Testing and Preliminary Results

Lucas Anderson, Ryan Davidson, Charles Swenson
Center for Space Engineering
Utah State University
4130 Old Main Hill
Logan, Utah 84321
l.s.anderson@aggiemail.usu.edu

A. J. Mastropietro, Elham Maghsoudi, Simon Luong, Ian Mckinley, Stefano Cappucci
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
A.J.Mastropietro@jpl.nasa.gov

ABSTRACT

The Center for Space Engineering at Utah State University and NASA's Jet Propulsion Laboratory have jointly developed an active thermal control technology to better manage thermal loads and enable cryogenic instrumentation for CubeSats. The Active CryoCubeSat (ACCS) project utilizes a two-stage active thermal control architecture with the first stage consisting of a single-phase mechanically pumped fluid loop, which circulates coolant between a cold plate rejection heat exchanger and a deployed radiator. The second stage relies upon a miniature tactical cryocooler, which provides sub 110 K thermal management. This research details the experimental setup for a ground-based prototype demo which was tested in an appropriate, and relevant thermal vacuum environment. The preliminary results, which include the input power required by the system, rejection and environmental temperatures and the total thermal dissipation capabilities of the ACCS system, are presented along with a basic analysis and a discussion of the results.

INTRODUCTION

Thermal control for CubeSats currently relies upon external surface emissivity and absorptivity properties and in some cases heat pipes to transport internal heat loads to external points. This approach has proven sufficient for many applications operating at power levels consistent with body mounted solar cells or small deployed solar panels. However, for higher power CubeSats with larger deployed solar panels and associated higher internal thermal dissipation, alternative control methodologies are required. An example is the use of a cryocooler within a 6U spacecraft in which 30 to 60 watts is deposited over 5 cm^2 of internal area from a mechanical cooler and support electronics. The CubeSats' thermal control system is required to maintain a target temperature at the interface of the cryocooler while transporting significant thermal energy to be radiated away. An approach to this thermal management problem, which has not been demonstrated at the sizes acceptable for CubeSats, is a mechanically pumped fluid loop.

This paper presents some initial results of the thermal vacuum testing of a miniature mechanically pumped fluid loop and cryocooler system that can reasonably be accommodated within a 6U CubeSat. The team has made a particular effort to demonstrate a system that can reject the relatively large thermal loads generated by the cryocooler while maintaining the necessary cryogenic temperatures for an IR detector. This technology development and demonstration is a joint effort between The Center for Space Engineering at Utah State University and NASA's Jet Propulsion Laboratory as sponsored by NASA through the University Technology Partnership Program within the Space Technology Mission Directorate at NASA HQ. The grant targets the development of small-satellite thermal control systems that can better manage thermal loads and enable cryogenic instrumentation for future CubeSats missions[1].

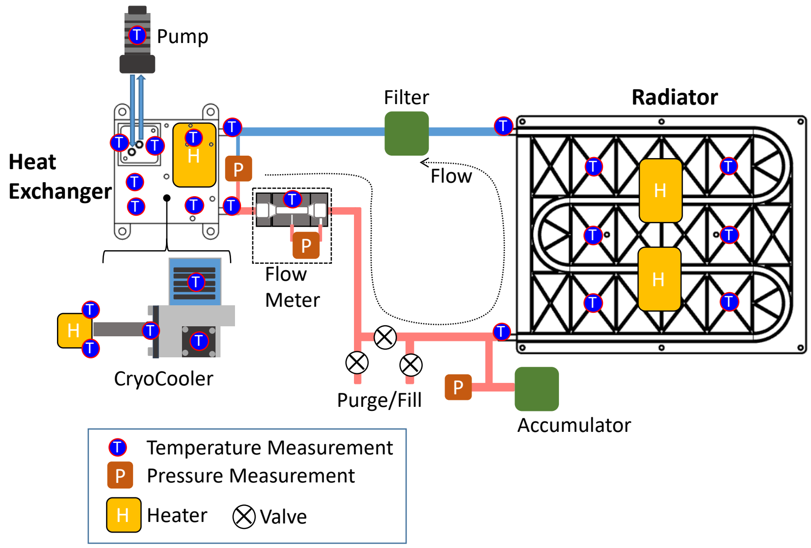

Figure 1 A system diagram of the Active CryoCubeSat mechanically pumped fluid loop test bed.

OBJECTIVES

The Active CryoCubeSat (ACCS) test bed is a two-stage thermal management architecture. The first stage consists of a Mechanically Pumped Fluid Loop[2] which circulates a working fluid (Novec-7000[3]) in a closed loop between a heat exchanger and a thermal radiator. The second stage utilizes a Ricor K508N[4] miniature cryocooler to provide cold tip cryogenic cooling in the range of 70 – 110 K. A TCS M510[5] micropump drives the fluid in the loop as illustrated in Figure 1. Both the heat exchanger and the radiator were fabricated using additive manufacturing in aluminum via ultrasonic consolidation[6-8]. This allowed for the embedding of fluid channels within these structures, enabling miniaturization. The objective has been to transition these technologies from TRL 3 to 5 by ground-based testing of the elements in a relevant thermal vacuum environment.

The ACCS test bed was constructed to validate a set of models for both the systems engineering and conceptual design of a CubeSat pumped fluid thermal subsystem. These models have been developed from basic principles of fluid flow with conductive and radiative thermal transport. The mathematical models have been implemented into Excel spreadsheets for rapid study of conceptual mission designs such as might be used within a team employing concurrent engineering methodologies. Using these models, the ACCS test bed was designed to reject heat loads of 30 to 60 W while maintaining the heat exchanger at less than 30 °C. References 9 and 10 contain additional information on the design of the ACCS system.

EXPERIMENTAL SETUP

Figure 1 illustrates the key components of the ACCS test bed and its conceptual operation. The ultrasonic additive manufactured heat exchanger and radiator were connected with a purge and fill system, a flow rate meter, an accumulator, and pressure transducers. The system recorded both the static pressure as well as the differential pressure developed across the pump. Both the Ricor K508N cryocooler and the TCS M510 micro pump were mounted to the heat exchanger (Figure 2, right) and integrated into the test cube shown in Figure 4. The test cube provided a closed system in which the ACCS performance and behavior could be characterized. The test cube also provided thermal isolation via Kevlar, G10, and UHMW standoffs as well as liquid Nitrogen cooling shrouds to simulate the

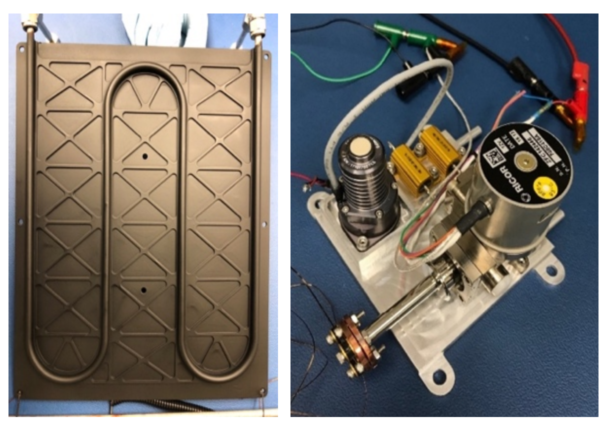

Figure 2 UAM fabricated radiator (left) and heat exchanger (right)

radiator in deep space. Surface mount heaters were added to the heat exchanger, cryocooler cold tip, and radiator to simulate additional thermal loading on the system. Instrumentation for the ACCS included type T thermocouples distributed across the radiator, heat exchanger, cryocooler, and pump (see Figure 1) as well as the structure of the test cube. Lakeshore RTD DT 670 diodes were used to monitor the cryogenic temperature of the cryocooler's cold tip. A Venturi type flow meter was used to monitor the volumetric flow rates in the mechanically pumped fluid loop while Honeywell pressure transducers monitored the differential and static pressures of the mechanically pumped fluid loop. A National Instruments DAQ and LabVIEW were used to acquire data and process/control the testing. A dedicated electronics box was built for the ACCS system which integrated with the TVAC chamber, the test cube, and the controller PC. Figures 4 and 3 show the test cube and the electronics box.

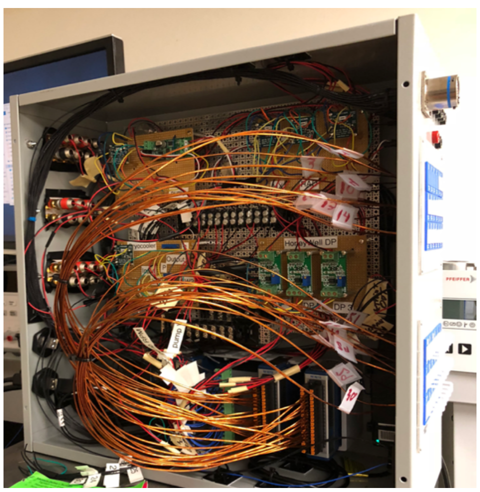

Figure 3 ACCS Electronics Box

TESTING PROCEDURE

The testing procedure for the ACCS system consisted of placing the test cube within the CSE/USU TVAC chamber and connecting the PC and electronics via feedthrough cabling. Liquid nitrogen for the cooling shrouds was provided by flex line from an external tank and controlled via an Omega setpoint PID controller. The TVAC chamber was pumped down to $<10^{-5}$ mbar and the LN2 shrouds were ramped to a black-body rejection temperature of <95 K. Once a steady state baseline temperature was achieved, a preset testing procedure could be executed. For the preliminary results presented here, the testing procedure consisted of measuring the steady state temperature and power values of the ACCS system at three thermal loads. The proposal objectives stated a required a thermal load of 30 W and

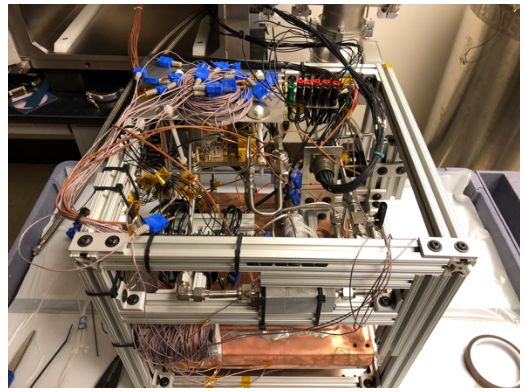

Figure 4 Integrated ACCS test cube

a goal of 60 W. Therefore, 30 W, 45 W, and 60 W were investigated first. Figure 5 shows the steady state thermal values of the given results. It should be noted, since the Ricor K508N cryocooler is on a separate closed PID controller, its power load is variable and dependent upon its rejection environment. Therefore, its additional thermal loading of ~6 W on the ACCS system is added to the required and objective values given above.

Since the ACCS is mechanically pumped, the team investigated the difference in thermal rejection between various flow rates. At each of the steady state thermal loads given in Figure 5, the working fluid was toggled by ramping the pump's working power between two turbulent regimes (Re=~7400, flow rate ~850 mL/min) and (Re=~3000, flow rate ~350 mL/min). Figure 6 shows the variation in working fluid flow rate and pump RPM's for a preliminary test run with the cryocooler cold tip set to ~110 K and a 0.25 W load. Figure 6 also shows the average heat exchanger and

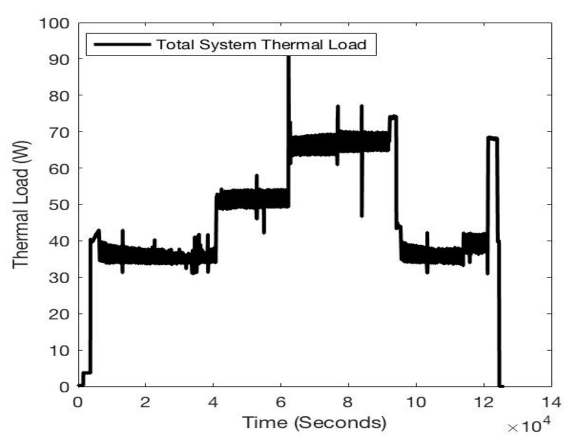

Figure 5 ACCS thermal load for a preliminary characterization test

radiator temperatures for an example test run. Additional bulk thermal loads and cold tip loads were also explored. It should be noted that due to a voltage conversion error, which has since been resolved, the flow rates shown below were calculated from experimental data and then corrected by the use of pump similarity laws and validated by a modified Bernoulli pressure drop model.

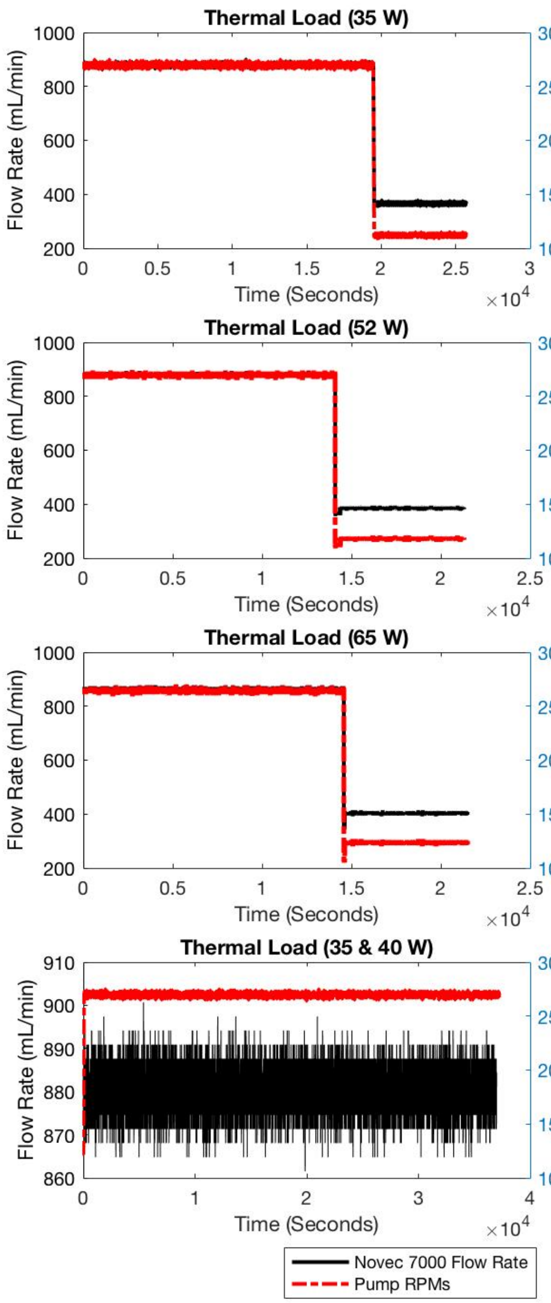

Figure 3 Preliminary results. Mechanically pumped fluid loop flow rate and pump RPMS's.

PRELIMINARY RESULTS

The requirements of the ACCS project were to reject 30 W with an interface rejection temperature of less than 30 °C and a goal of >60 W with an interface temperature of less than the same. From Figure 10, which shows the overall performance of the ACCS, it is clear that not only the original requirement was met, but the goal as well. The preliminary results indicate thermal loads of well over 70 W are possible while maintaining the CubeSat environment at an appropriate temperature of less than 30 °C. Figure 8 shows the average temperatures of the heat exchanger, cryocooler, and radiator at each of the preliminary tests thermal loads. In addition, the results indicated that lower flow rates are still effective which would indicate that significant power savings are possible while reducing system complexity. Figure 9 demonstrates that the system is energy balanced. The total power inputted into the system is absorbed by the heat exchanger and rejected by the radiator. Slight differences exist due to the variable efficiencies of the pump and cryocooler as well as the fact that any thermal load introduced to the radiator will not be felt by the rest of the system and will simply be rejected to the cold environment. Cold-tip thermal loads of 0.5 W at an overall thermal loading of ~35 W indicate the cold tip is more than capable of maintaining the desired setpoint despite variations in tip and system loading. Figure 7 shows the cold-tip temperature throughout the given test run. Figure 11 shows an infrared view of the thermal distribution of the heat exchanger, cryocooler, heaters, and pump as well as the variation in temperature across the surface of the heat exchanger. It should be noted the heat exchanger experiences a thermal gradient with an increased temperature corresponding to the surface mount heaters and cryocooler.

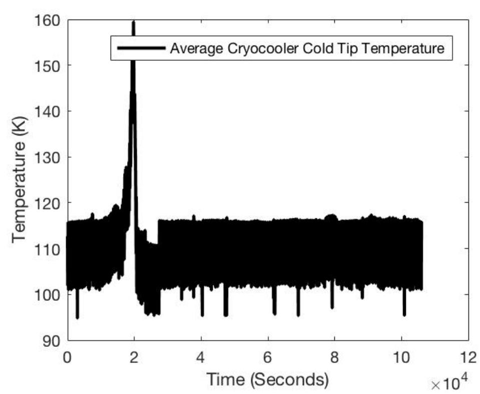

Figure 7 Preliminary results. Cold tip temperature

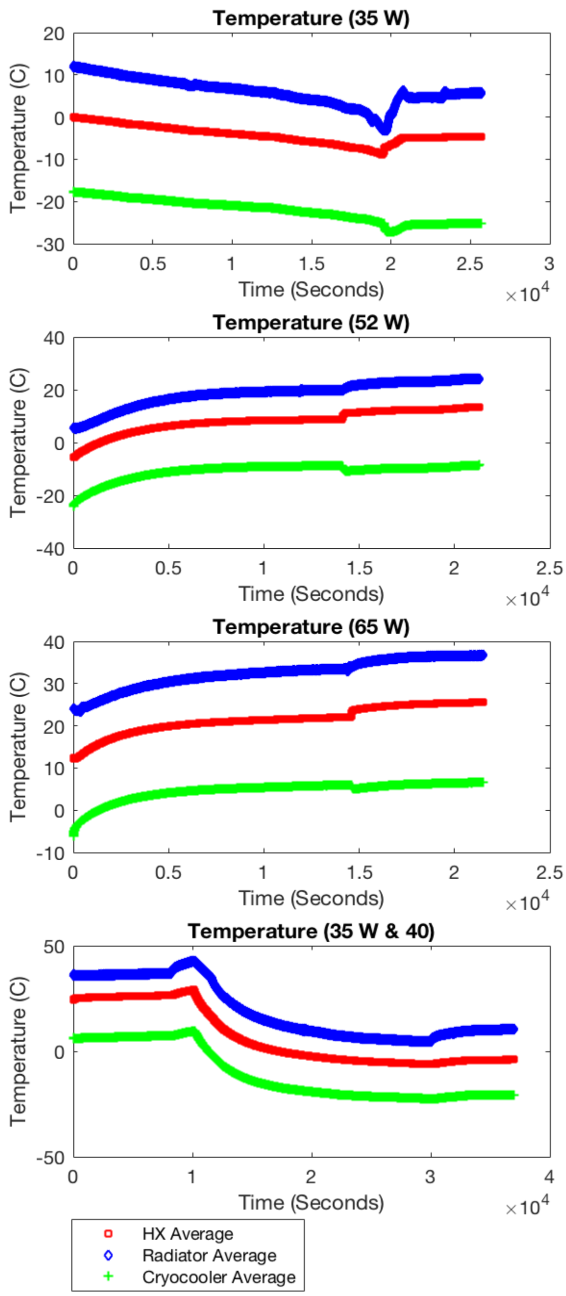

Figure 8 Preliminary results. Mechanically pumped fluid loop flow rate and pump RPMS's.

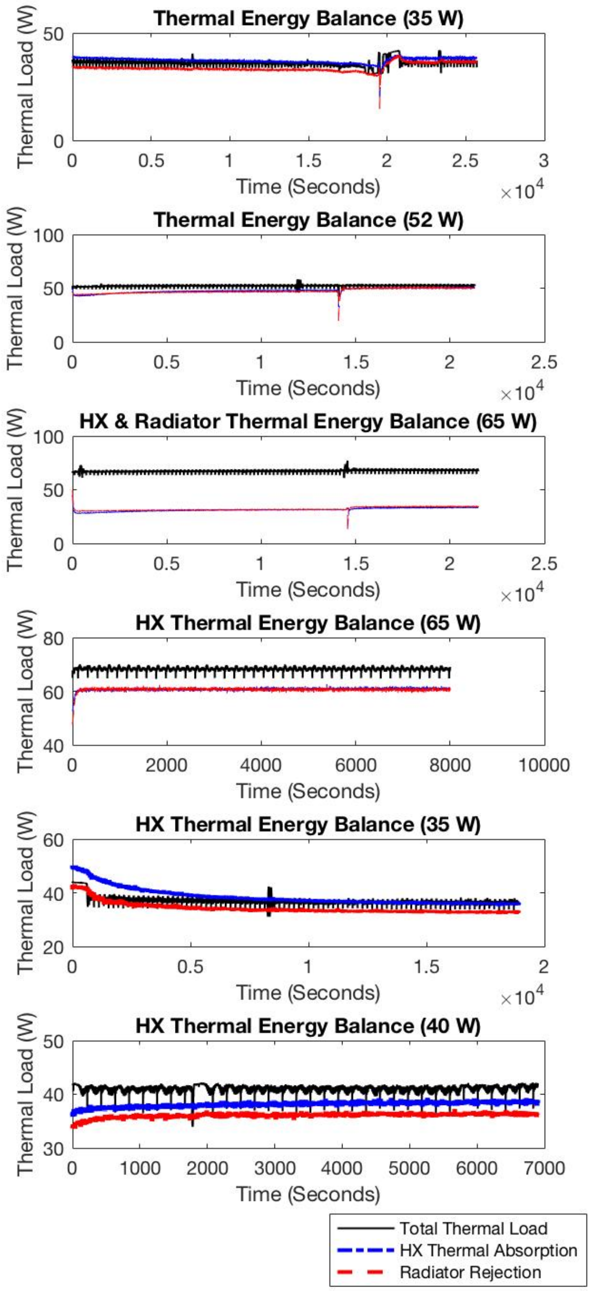

Figure 9 Preliminary results. Thermal Energy Balance. Absorbed vs. rejected.

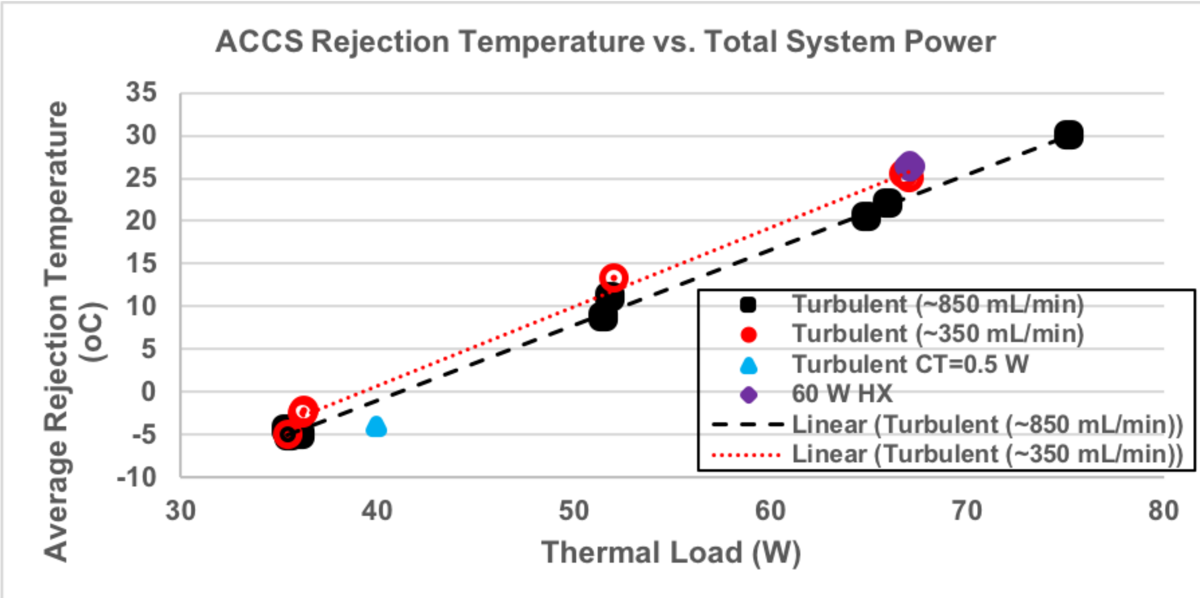

Figure 10. ACCS system performance compiled from multiple test runs

The collected data indicates significant thermal gradients across the radiator exist, which implies the assumption of an isothermal radiator and the team's preliminary Thermal Desktop modeling did not sufficiently capture the complexity of the thermal distribution within the radiator. Additional work will be required to accurately model the radiator. This will allow the team to refine the design process and fabricate a better radiator for future work[11].

Ultimately, the ACCS system behavior is excellent and better than anticipated. The system's performance trends were as expected, and the team is in the process of reconciling the experimental results with both the analytical and numerical models developed in the early stages of the project.

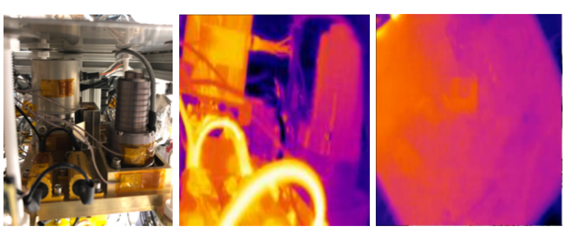

Figure 11 Flir Lepton IR images of the cryocooler, micro-pump, and HEAT EXCHANGER plate. (Left) camera view. (Middle) IR camera view. (Right) Bottom of the heat exchanger plate

FUTURE WORK

The ACCS system is still undergoing extensive characterization. This includes sweeping each of the system's variable parameters through the full possible range of states. In addition, USU and the CSE is currently developing a controller algorithm that should allow the ACCS system to autonomously adapt, via feedback, to changes in the CubeSats' environment, thermal loading on the system, and mission requirements. This will enable the ACCS to operate as a standalone thermal subsystem capable of maintaining CubeSat and instrumentation thermal environments. Finally, the current design of the radiator and its performance must be explored further. The team will accomplish this by developing a series of PDE based analytical models backed by a full numerical simulation. These will then be checked by a series of benchtop experiments focused on characterizing the thermal distribution across the radiator's embedded fluid channels and the light-weighted aluminum structures between them.

CONCLUSIONS

The ACCS team accomplished its goal of developing an active thermal control system appropriate for managing large thermal loads on CubeSats. The team designed and fabricated a two-stage mechanically-pumped fluid loop and cryocooler based thermal architecture and tested it in a relevant environment. The system performed beyond the stated requirements or goals and is, in fact, capable of handling thermal loads greater than 70 W while maintaining a rejection environment of less than 30 °C for the integrated cryocooler. This system shows the possibility of a new era of advanced CubeSat and instrumentation by removing temperature control and thermal power dissipation as limiting factors in mission design.

REFERENCES

[1] Sunada, Eric, and Rodriguez, Jose, "JPL Advanced Thermal Control Technology Roadmap," Spacecraft Thermal Control Workshop, El Segundo, CA 2017.

[2] Mastropietro, A. J., Bhandari, Pradeep, Birur, Gajanana, et. al., "Summary and Status of 5 Mechanical Pumped Fluid Loop (MPFL) Projects Currently in Process at the Jet Propulsion Laboratory (JPL) for the Planned Europa Mission, Mars 2020, Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS), Orbiting Carbon Observatory (OCO-3), and Cold Atom Lab (CAL)," Thermal and Fluids Analysis Workshop (TFAWS), Mountain View, CA, August 2016.

[3] 3M™ Novec™ 7000 Engineered Fluid [Online] June 2017, http://multimedia.3m.com/mws/media/121372O/3m-novec-7000-engineered-fluid-tds.pdf

[4] Integral Rotary Integral Stirling 1/2W Micro Cooler K508N [Online] June 2017, http://www.ricor.com/products/integral-rotary/k508n/

[5] TCS Micropumps-High Performance Miniature Pumps [Online] June 2017, http://www.micropumps.co.uk/

[6] Maghsoudi, Elham, Mastropietro, A. J., Roberts, Scott, and Kinter, Bradley, "Experimental Thermal Performance Comparison of 3D Printed Aluminum Heat Exchangers vs Traditionally Manufactured Heat Exchangers," Spacecraft Thermal Control Workshop (STCW), El Segundo, CA, March 2017.

[7] Mastropietro, A. J., Roberts Scott, Hofmann Douglas, Maghsoudi, Elham, and Luong, Simon, "NASA Development of Complex Heat Exchangers Leveraging Additive Manufacturing," Propulsion Safety and Sustainment Conference, Phoenix, AZ, May 2017.

[8] Mastropietro, A. J., Pauken, Michael, Hofmann, Douglas, D'Agostino, Saverio, "Ultrasonic Additive Manufacturing (UAM) of Heat Rejection System (HRS) Heat Exchangers," Innovative Spontaneous Concept R&TD, Annual Report to JPL's R&TD Program Office, 2014.

[9] Lucas S. Anderson "The Active CryoCubeSat Project: Design and Status" [Online] June 2017, https://digitalcommons.usu.edu/smallsat/2017/all2017/154/

[10] NASA, Active CryoCubeSat [Online] June 2017, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160007914.pdf

[11] Taig Young Kim, Su-Young Chang, and Sang Soon Yong, "Optimizing the Design of Space Radiators for Thermal Performance and Mass Reduction" [Online] July 2018, https://ascelibrary.org/doi/10.1061/%28ASCE%29AS.1943-5525.0000676