Status of Development of a Solid-State Thermal Management System of a MW-Scale Electric Aircraft

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Thermal management represents a significant challenge for electric aircraft due to the large quantity of low-grade waste heat that must be dissipated. To solve this challenge, a lightweight solid-state thermal management system for MW-scale hybrid electric aircraft is being developed. The system utilizes a thermoacoustic heat pump to actively cool electronic components and elevate the temperature of the heat. The waste heat is then recycled by distributing it throughout the aircraft via a network of thermosyphons. This paper will present the status of development of the whole thermal management system. In addition, preliminary results will be incorporated into the final manuscript and presented at the conference.

I. Nomenclature

ACT	=	Advanced Cooling Technologies
DC	=	Direct Current
EDU	=	Engineering Demonstration Unit
GRC	=	NASA Glenn Research Center
ID	=	Inside diameter
K	=	Kelvin or Potassium
MW	=	Megawatt
OD	=	Outside diameter
SS	=	Stainless steel
TAHP	=	Thermoacoustic Heat Pump

II. Introduction

Electric aircraft propulsion systems, for MW-scale aircraft, come in a variety of configurations and many of these configurations share the need to utilize DC circuit breakers to provide protection against electrical faults. For MW-scale electric aircraft, solid-state DC circuit breakers provide important benefits, including extremely fast response time, simple structure and low mass.[1] The drawback to a solid-state circuit breaker is the high conduction losses compared to other breaker technology.[2] Approximately 5-10kW of low-grade waste heat is produced for each MW-scale circuit breaker in the system. These losses reduce the overall efficiency of the system and present a significant thermal management challenge due to relatively low temperature of the waste heat. By elevating the temperature of the circuit breaker waste heat and then recycling the waste heat on board the aircraft, it is possible to maintain a high system efficiency while taking advantage of the benefits of solid-state circuit breakers.[1,3]

A solid-state (no moving parts) thermal management system for hybrid-electric aircraft, that elevates the temperature of low-grade waste heat via a thermoacoustic heat pump (TAHP) and then distributes that waste heat to various end users on board the aircraft via a network of passive thermosyphons, is being developed by NASA Glenn

Research Center (NASA GRC) and Advanced Cooling Technologies (ACT).[1,4,5,6,7] In this system, acoustic waves are generated by waste heat from the hybrid electric aircraft turbine engines/generators and the TAHP is used to actively cool the solid-state DC breaker.[1] A thermosyphons network[5,6,7] is used to extract the waste heat from the hot end of the heat pump and passively distribute the thermal energy throughout the aircraft. Diebold et al.[7] described the design, fabrication, and testing of a reduced-scale water-titanium thermosyphon prototype capable of carrying 5 kW of waste heat to the wings and various end users.

ACT and NASA GRC are currently fabricating a complete engineering demonstration unit (EDU) of the proposed solid-state thermal management system. The system is illustrated in Figure 1. The focus of this paper is to present the development status of the design and fabrication of a complete thermal management system incorporating the thermoacoustic heat pump designed by NASA GRC and the water-titanium thermosyphon designed by ACT. In addition, preliminary results will be presented. This will be the first demonstration of a fully integrated high-power thermal management system with no moving parts based on thermoacoustic refrigeration.

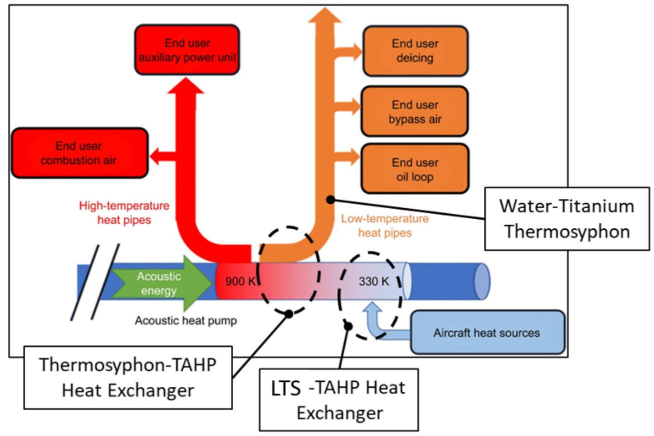


Figure 1. Illustration of thermoacoustic heat pump and thermosyphon based thermal management system. Acoustic waves generated by waste heat are used to refrigerate "Aircraft heat sources". High and low temperature thermosyphons are used to transport electronics waste heat at elevated temperatures to various end users. Previous work focused on the water-titanium thermosyphon development.[7] This paper discusses the development and integration of the whole system (i.e., TAHP, circuit breaker-TAHP heat exchanger, thermosyphon-TAHP heat exchanger, high temperature thermosyphon-TAHP heat exchanger, etc.)

III. Overview of the Engineering Demonstration Unit (EDU)

Figure 2 shows a CAD model of the whole EDU including a total of 5 technologies (i.e., TAHP, titanium-water (Ti-H2O) thermosyphon, stainless-steel-potassium (SS-K) high temperature thermosyphon, stainless-steel-water (SS-H2O) loop thermosyphon, and 1MW circuit breaker) integrated together. The Ti-H2O thermosyphon, SS-K high temperature thermosyphon, and SS-H2O loop thermosyphon are all integrated into the TAHP via annular jackets (i.e., annular space resulted by welding a larger pipe to the TAHP).

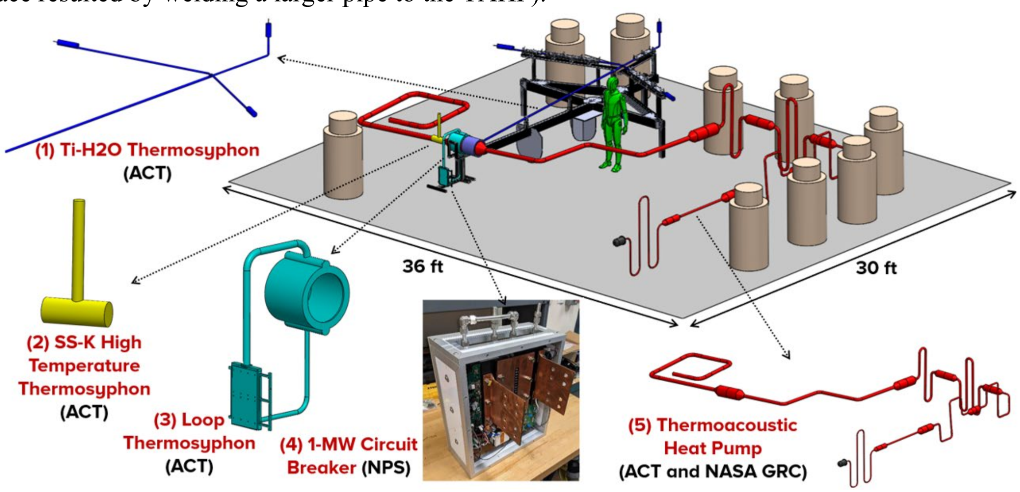


Figure 2. A CAD model of the whole EDU. Four technologies (i.e., Ti-H2O thermosyphon, SS-K high temperature thermosyphon, SS-H2O loop thermosyphon, and 1MW circuit breaker) are integrated into the TAHP.

For example, Figure 3 shows how the Ti-H2O thermosyphon is integrated with the TAHP via the annular evaporator. The TAHP is a closed system that contains pressurized helium gas. The TAHP starts with a wave generator followed by a thermal buffer tube (TBT) and 7 stages connected in series. Each stage consists of a transition tube (conical shape), heat engine (straight tube), cascade tube (conical shape), and thermal buffer tubes. Each heat engine consists of one copper and one aluminum heat exchangers and stainless-steel mesh stacked in between them. Each stage (heat engine) of the TAHP consists of three components: two heat exchangers and a stainless-steel mesh stack between them. The copper heat exchangers have multiple holes where the helium flows through. Stages 1-6 are amplification stages. At Stage 7, the TAHP will remove the heat (about 2.6 kW at 282K) from the fault management system and supply it to the titanium thermosyphon at 350 K. In addition, at Stage 8, a high-temperature thermosyphon is integrated to the TAHP to transfer the high-temperature heat generated at the end of the TAHP. The water thermosyphon and the potassium thermosyphon will transport that heat to the required end users on the aircraft (e.g., deicing, cabin air, combustion, etc.). Heat will be supplied to the TAHP in the first 6 stages (amplification stages) by high temperature band heaters while liquid nitrogen will be used for cooling. Note that the band heaters are used to mimic the waste heat from the engine in the real application. Figure 3 represents the baseline integrated evaporator concept that ACT is considering for the integration between the water titanium thermosyphon with the TAHP at Stage 7. In this baseline integrated design, the evaporator of the thermosyphon and the TAHP share a common wall. A similar annular evaporator design will be used for the high temperature thermosyphon integration with the TAHP at Stage 8.

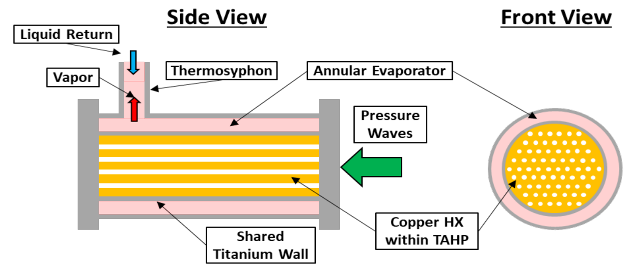


Figure 3. Illustration of baseline thermosyphon evaporator integrated into the thermoacoustic heat pump. Pressure waves travel through a cylindrical copper heat exchanger (HX). Heat then conducts to a titanium wall that serves as the interface between the TAHP and the thermosyphon.

Zhang et al.[8], Shahsavarian et al.[9], and Ravi et al.[10] developed a high-density, high-efficiency megawatt (MW) medium-voltage (MV) solid-state circuit breaker (SSCB) for aviation hybrid electric propulsion applications. The proposed SSCB is based on the mature silicon (Si) insulated gate bipolar transistor (IGBT) devices. With reduced IGBT gate voltage, the proposed SSCB can limit the peak fault current without the fault current limiting inductor. Thus, the specific power density of the SSCB is substantially improved compared with the traditional design. Figure 4 shows the development steps of the circuit breaker. Figure 4b shows the IGBTs mounted on a cold plate whose function is to remove the waste heat from those IGBTs. Each IGBT generates up to 3 kW of waste heat (4 IGBTs are used in this circuit breaker). The developed circuit breaker will be shipped to ACT to be integrated with the TAHP. ACT will replace the cold plate with a passive two-phase heat transfer device (e.g., loop thermosyphon) which will passively transport the heat from the IGBTs (circuit breaker) directly into the TAHP as discussed later.

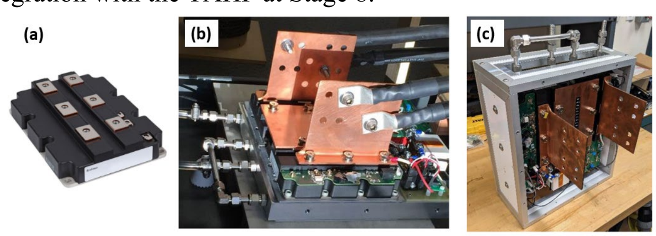


Figure 4. The developed circuit breaker. (a) IGBT; (b) IGBTs mounted on a cold plate; and (c) the final circuit breaker prototype.[8,9,10]

a. Development of the Thermoacoustic Heat Pump (TAHP)

The construction procedure of each stage includes multiple steps. The full procedure is summarized below.

- The heat exchangers (copper and aluminum for the hot and cold sides, respectively) of each stage consist of multiple stacked discs since small size holes cannot be drilled for such lengths. Each heat exchanger has two key rods (with their corresponding key holes) for alignment (Figure 5a).
- Inserting the key rods into their corresponding holes and tack-welding the key rods ends (top and bottom discs). Now, the HEX is one assembly (Figure 5b).
- Fabricating a simple holding structure to lift the HEX (Figure 5c).
- Inserting the holding structure into the HEX and placing it into a bucket full of liquid nitrogen (Figure 5d).
- After taking the HEX out from the LN bucket, the SS sleeve/pipe is heated (extra room for insertion) and lifted and easily slid around the HEX (Figure 5e).
- The holding structure is cut and removed from the assembly (Figure 5f).
- The mesh discs are placed on top of both HEX (Figure 5g).

- Both assemblies are welded together and then welded to the cones. Then, welded to the thermal buffer tubes (TBT) (Figure 5h).
- Figure 6 shows actual photos of the TAHP prototype after the construction is completed. Please note that the high temperature thermosyphon and titanium thermosyphon are not welded to the TAHP yet.

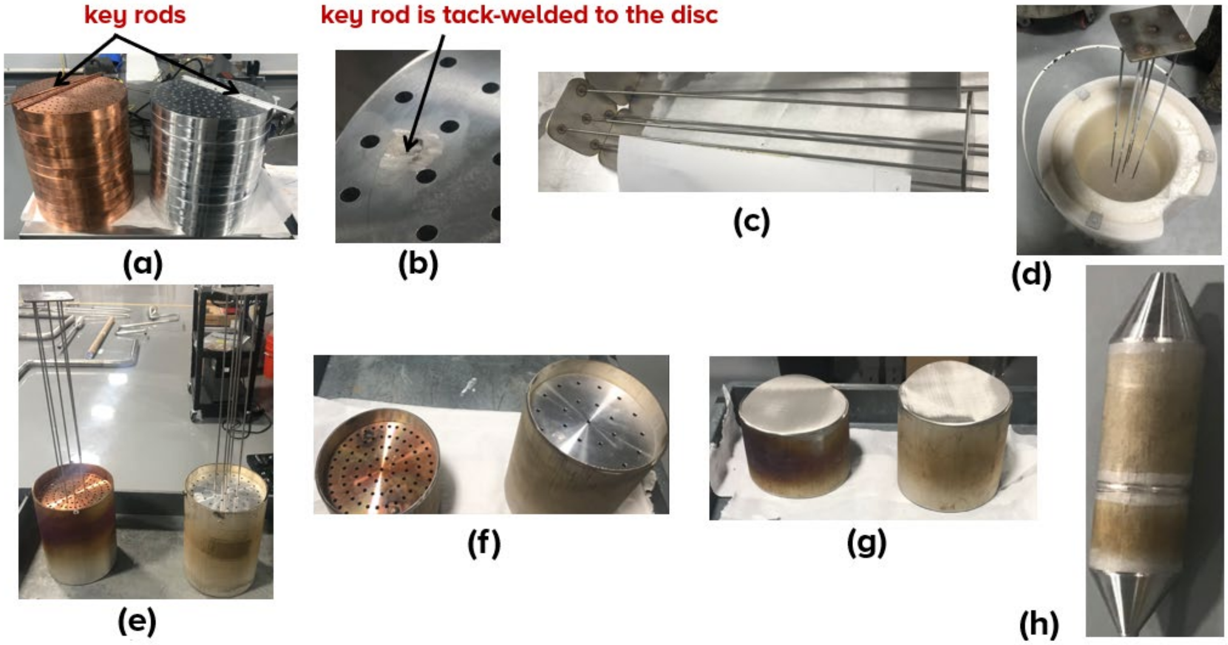
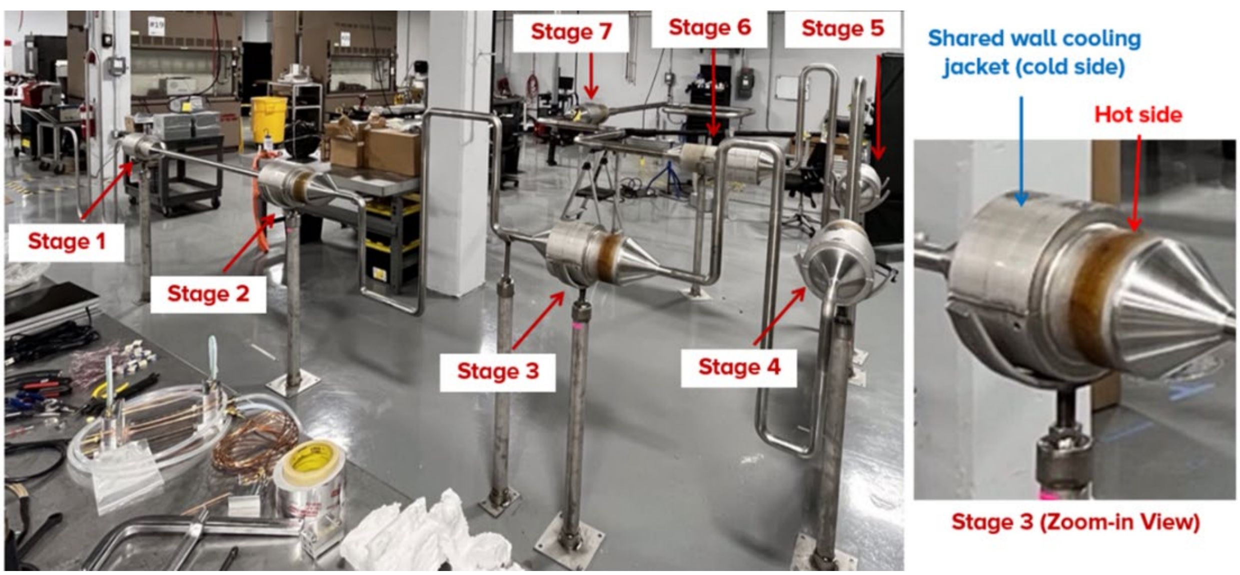


Figure 5. Actual photos of the assembling procedure of the heat engine stage. (a) Key rods of both copper and aluminum heat exchangers, (b) Tack-welded key rod into the heat exchanger, (c) Lifting structure, (d) A heat exchanger inserted into a liquid nitrogen bucket (before shrink fitting into the stainless-steel sleeve), (e) The heat exchangers after being shrink-fitted, (f) The heat exchangers after removing the lifting structure, (g) The heat exchangers after placing the mesh discs, and (h) The heat engine after welding.



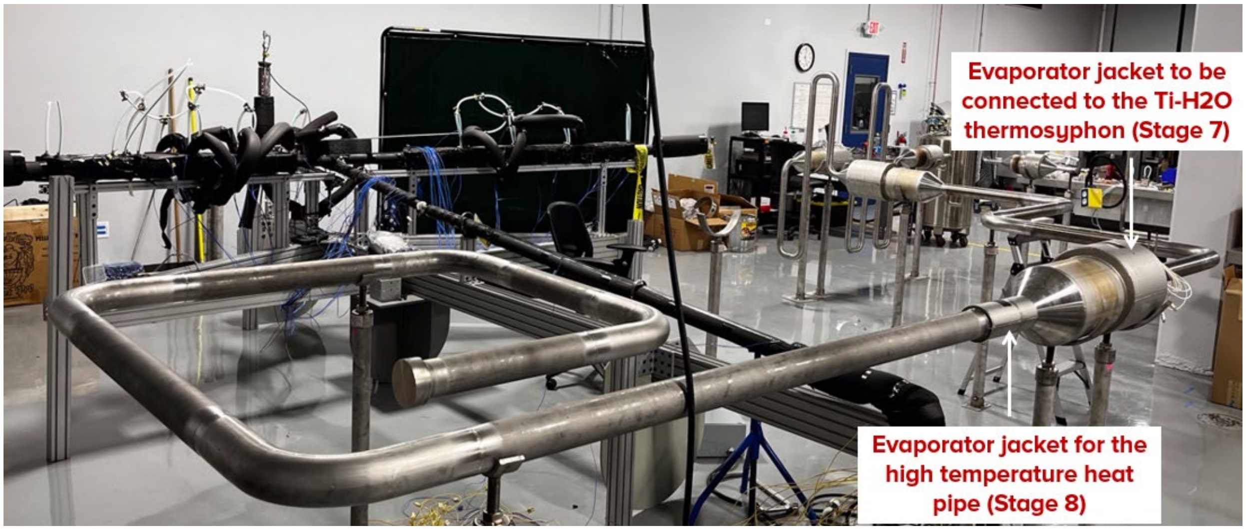
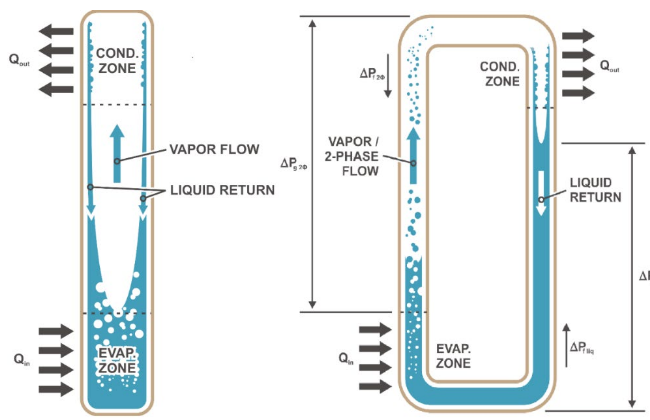


Figure 6. Actual photos of the development efforts of the TAHP. Please note that the integration of the TAHP and the Ti-H2O thermosyphon is not complete yet. The adiabatic and condenser section of the high temperature thermosyphon will be welded to the evaporator section at Stage 8.

b. Development of a Passive Two-Phase Heat Transfer Device as an Efficient Thermal Link Between the Circuit Breaker and the TAHP

An efficient passive thermal link between the TAHP and the circuit breaker is needed to effectively transfer the heat from the circuit breaker (i.e., IGBTs) to the TAHP. ACT has developed a loop thermosyphon (LTS) for this application. Before integrating the LTS to the TAHP, ACT developed a LTS prototype with heaters blocks and cooling jacket to mimic the IGBTs and TAHP, respectively. The operation of a traditional thermosyphon is illustrated in Figure 7(a). A loop thermosyphon is a specialized configuration of a single-tube thermosyphon that uses two-phase heat transfer (evaporation/condensation) to deliver heat effectively and passively. In a thermosyphon, a working fluid absorbs heat and boils in an evaporative region. Evaporated vapor rises along the tube to the condenser, where it condenses, releasing thermal energy. The condensed liquid returns to the evaporator via gravity, falling along the walls of the thermosyphon, counter-current to the vapor flow. The flooding limit constrains the maximum power of a thermosyphon and is imposed by shear forces between a high-velocity, upward vapor flow, and downward liquid return flow. The flooding limit can be bypassed by using a loop thermosyphon. LTS operation is illustrated in Figure 7(b). As in a traditional thermosyphon, heat applied in the evaporator boils the working fluid, which rises to the condenser. Unlike a traditional thermosyphon, when the working fluid is condensed, the liquid returns to the evaporator in a line separate from the rising vapor phase. With separate vapor and liquid lines, shear between the phases is eliminated, removing the flooding limit constraint. The gravitational head of the liquid condensate beneath the condenser ($\Delta P_{g,liq}$) is the passive pumping force in the loop thermosyphon and should overcome all the pressure losses in the loop. Resisting this positive head is the gravitational head of the two-phase flow ($\Delta P_{g,2\Phi}$) and frictional pressure drops in the liquid ($\Delta P_{f,liq}$) and two-phase lines ($\Delta P_{g,2\Phi}$). The sum of acceleration ($\Sigma\ \Delta Pa$) and minor pressure losses ($\Sigma\ \Delta P_m$) also resist the fluid flow and must be accounted for. During steady-state loop thermosyphon operation, these six pressure components must be in equilibrium. ACT developed a model to predict the total pressure losses and the thermal performance of a loop thermosyphon. To



(a) **(b)**

Figure 7. Operation schematics of (a) Traditional single-tube thermosyphon and (b) Loop thermosyphon[11].

estimate thermal losses from the thermosyphon and better predict heat transfer within the evaporator and condenser, heat transfer coefficients were calculated throughout the single and two-phase sections of the loop.

Figure 8 shows a schematic of the LTS system with the evaporator and condenser sections. The evaporator consists of 4 heater blocks to mimic the 4 IGBTs. Each heater block can generate up to 3kW, totaling 12 kW in the entire evaporator. The condenser consists of an annular space where the working fluid condenser is on the outer surface of a cooling jacket. The internal wall of the condenser and the external wall of the cooling jacket are the shared wall across which heat is transferred. The LTS is instrumented with several thermocouples and pressure transducer to test the system performance and provide relevant information regarding the state of the system. The instrumentation layout is shown in Figure 8. A total of 20 thermocouples are placed on the heater blocks at various elevations to measure the heat transfer characteristics in the evaporator. Two thermocouples are mounted on the vapor line to verify that the saturation temperature at the measured pressure and the measured vapor temperature are the same. Any difference between them indicates presence of non-condensible gases. Ten additional thermocouples are mounted on the liquid return line.

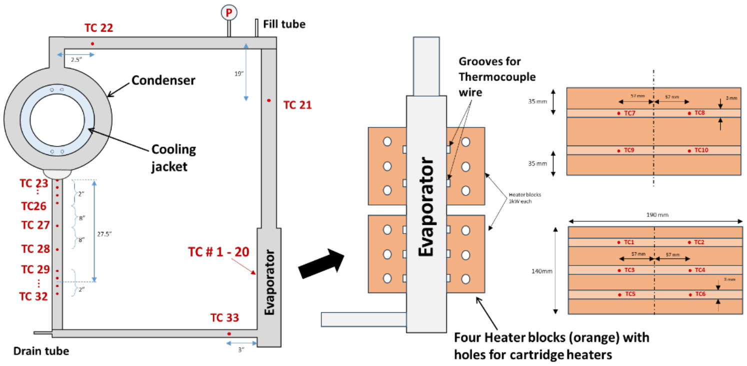


Figure 8. LTS instrumentation showing location of thermocouples on the system (left) and on the heater blocks in the evaporator (right).

Various auxiliary systems connected to LTS are shown in Figure 9. The power to the heater blocks is provided by variable transformers within the high-power control box working at 240V input AC power supply. The power to each heater block is controlled via a transformer capable of supplying 3 kW each. Each heater block is equipped with an over-temp controller. The condenser is connected to a Parker Hyperchill chiller capable of providing cooling loads of up to 22kW. The cooling water temperature can be set to within ±1°C of the desired set value. The chiller supplies cooling water at a flowrate of 7.25 gpm and a supply pressure of 60 psi. Various valves are strategically placed around the loop for removal of non-condensable gases (NCGs) that may build up during the tests. A drain valve is located at the bottom of the loop to drain out the working fluid at the end of a testing round.

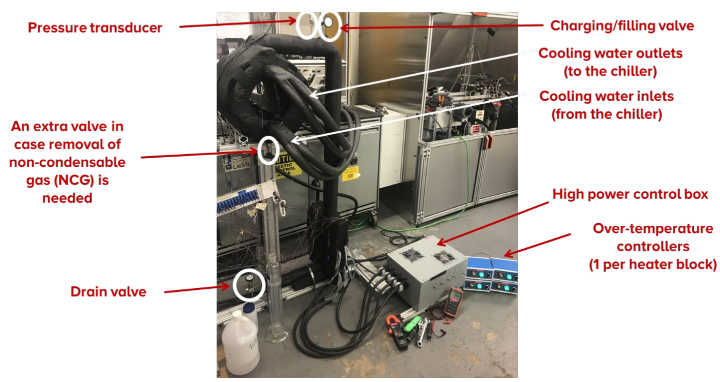


Figure 9. The experimental setup of the LTS.

The performance of the LTS system was tested with de-ionized water as the working fluid with a charge of 6.7 kg. The cooling water from the chiller to the condenser was set at 5°C at the outlet of the chiller. The heater power was stepped up to 750W in each block, totaling 3kW as shown in Figure 10. The system was allowed to reach a steady state. The temperature within the system showed transient oscillations within the heater and within the vapor line, due to the nature of the flow induced oscillations (i.e., oscillations of the liquid-vapor interfaces). At 2700s, the total power of the heaters was stepped up to 6kW and the system was allowed to reach a steady state. The temperature of the heater blocks (TC1-20) settled to an average value of about 85°C, while the vapor line temperature settled to about 55°C. The liquid return line showed some level of subcooling at a temperature of about 40°C.

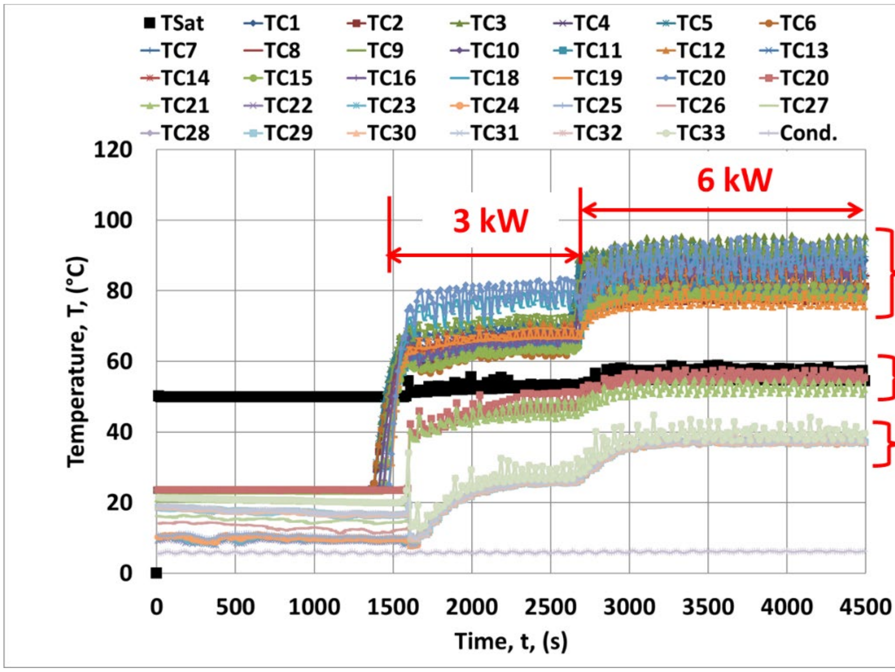


Figure 10. Transient temperature values across the LTS prototype. TCs 1-20 represent the thermocouples attached to the evaporator, TCs 21-22 are attached to the vapor line, and TCs 23-33 are attached to the liquid line.

This paper shows up-to-date development progress of the Engineering Demonstration Unit (EDU) of a complete thermal management system for hybrid electric aircrafts. The complete integration of the 5 technologies and their testing results will be presented in future publications.

IV. Conclusions and Future Work

Under a NASA SBIR Phase III program, ACT is designing, fabricating, and demonstrating a complete thermal management system incorporating the thermoacoustic heat pump (TAHP) designed by NASA GRC and the water-titanium thermosyphon, loop thermosyphon (LTS), and a high temperature thermosyphon designed by ACT. This will be the first demonstration of a fully integrated high-power thermal management system with no moving parts based on thermoacoustic refrigeration. The development efforts discussed in this paper can be summarized as follows:

- The TAHP has been designed, fabricated, and assembled. This includes 8 stages of heat transfer (15 heat exchangers).
- A passive two-phase heat transfer device (LTS) is developed to remove the heat from the circuit breaker (i.e., IGBTs) and efficiently transfer to the TAHP.
- The LTS was able to remove a total of 6 kW of heat while maintaining the heater blocks maximum temperature below 120°C.
- Testing results of the whole EDU will be presented in future publications.

Acknowledgments

This project is funded by NASA Glenn Research Center under a SBIR Phase III program (Contracts numbers: 80NSSC22CA024 and 80NSSC23CA197). The technical monitor is Dr. Rodger Dyson. The actual images of the circuit breaker were provided by Professor Di Zhang from Naval Postgraduate School in California. The authors would like to thank Jonathon Murray, Sam Martzall, Philip Texter, Eugene Sweigart, and Larry Waltman for providing technician support on this project at ACT.

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