Development of Solid-State Waste Heat Delivery System for Electric Aircraft

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***Abstract* — Advanced Cooling Technologies, Inc. (ACT) is developing a heat pipe-based thermal delivery system to efficiently manage the waste heat of an electric aircraft. The heat pipe system will be integrated with thermoacoustic heat pump tubes developed by NASA Glenn Research Center (GRC). This paper will discuss the design of a full-scale heat pipe layout for a MW-class commercial electric aircraft based on the NASA inputs, including operating temperatures, power and relative distances/elevations of heat sources, heat pump tubes and end users. Experimental results of a prototype long and curved thermosyphon designed to transport heat from the turbofan to the wing will be presented. Finally, a two-phase heat transport system with solid-state thermal switching/control capabilities based on variable conductance heat pipe technology that will be used to control the heat transfer rate to various end users will be introduced and experimentally demonstrated.**

Keywords—Electric aircraft, two-phase heat transfer, heat pipes, thermosyphons, variable conductance

I. INTRODUCTION

Electrified Aircraft Propulsion (EAP) systems utilizes electrical motors to provide some or all the thrust for an aircraft. Potential benefits of EAP include (1) low carbon emission (2) low noise (3) reduced fuel consumption (4) low operating cost and (5) high performance. NASA is currently leading the development of EAP technology in U.S. The near-term goal is to realize a MW-class, commercial electric aircraft by 2035. To fulfill this vision, an advanced thermal management technology that can handle (i.e. recycle, deliver and reject) all low-grade waste heat (~kW) generated within an aircraft is needed. Dyson [1] at NASA Glenn Research Center (GRC) is developing a novel system called "Thermal Recovery Energy Efficient System" (TREES), which uses thermo-acoustic heat engines to generate acoustic mechanical energy, distributes the acoustic wave via multiple acoustic tubes to acoustic heat pumps, where the low-grade waste heat is recovered and elevated to a high temperature.

As part of a Phase III NASA SBIR, Advanced Cooling Technologies, Inc. (ACT) is developing a heat pipe-based heat delivery system to integrate with the acoustic heat pump and deliver the high-grade waste heat from the acoustic heat pump back to various locations on the airplane requiring thermal energy (e.g. heating combustion air, wing de-icing etc.). These heat sinks will be referred to as "end users". Heat pipes represent a solution that fits the challenges encountered by the overall thermal management system. Heat pipes through their passive and two-phase nature of operation can provide thermal transport at large rates over large distances with minimal temperature drop. The passive solid-state nature of heat pipes also makes them a light-weight and reliable system ideal of aircraft applications.

This paper will discuss three aspects of the work conducted under this SBIR program to develop a solid-state heat pipe-based heat delivery system for electric aircraft thermal management.

1. Selection of a representative hybrid electric aircraft and development of heat transfer networks linking various heat sources to the end users requiring thermal energy. The different heat transfer networks are grouped based on the required temperature of the end user.
2. The experimental demonstration of a long curved thermosyphon designed to transport waste heat from the engine to the wing for deicing applications.
3. The development and experimental demonstration of a two-phase heat transport system with solid-state thermal switching capabilities.

II. HEAT PIPE THERMAL DELIVERY SYSTEM

The aircraft chosen for this program was the Single-aisle Turboelectric AiRCraft with Aft Boundary Layer propulsion (STARC-ABL) developed by NASA in 2017 [2]. The STARC-ABL is a 150-passenger class commercial transport with a traditional "tube-and-wing" shape. The plane relies on turboelectric propulsion, meaning that it uses electric motors powered by onboard gas turbines. As Fig. 1 shows, the aircraft has two traditional jet engines that are mounted under the wings, which are coupled to electric generators for power generation. Electrical power is sent to the tail of the aircraft,

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where an all-electric propulsion takes advantage of an aerodynamic benefit known as boundary layer ingestion (BLI).

Fig. 1. STARC-ABL Conceptual Design

Based on an extensive literature survey ACT identified the heat sources and heat end users of this type of aircraft [2,3,4,5,6]. Dominant heat sources on the airplane include power system, circuit breakers, cabin cooling and others(avionics, actuation, gearboxes etc). Their power, temperature and locations are summarized in Table 1. ACT also identified potential heat end users. The temperature and location information of the end users are listed in Table 2.

According to the temperature and relative locations of the heat sources and end users, three groups of heat pipe heat delivery system are shown in Fig. 2. The first group is located at the tailcone. Waste heat generated from motor, inverter and circuit breakers can be transferred by low temperature heat pipes to the cold end of the acoustic heat pump. Another set of low temperature heat pipes with thermal switching capability (i.e. multi-condenser VCHP described in Section IV) will be used to distribute heat from the hot end of the acoustic heat pump to the outer mold line of the tail for de-icing purposes. The remaining waste heat can be dumped into exhaust stream. A high temperature heat pipe will be used to recycle the high-grade heat at the hot side of heat pump to the Auxiliary power unit (APU) or combustion air. Similar configurations are shown

Table 1. Heat Sources of the Electric Aircraft

Components	Qty	Power	Max. Allowable Temp.	Locations
Generator	2	50kW each	<100°C	Under wings
Rectifiers	2	15kW each	<100°C	Under wings
Circuit Breakers	4	7kW each	<100°C	Along cables
Inverter	1	25 kW	<100°C	Near tailcone
Motor	1	100 kW	<100°C	Near tailcone
Cabin Cooling	1	10 kW	< 30°C	Bottom
Others	n/a	2 kW	<100°C	Bottom

Table 2. List of End Users on Electric Aircraft

Preheat Combustion Air	>600°C	Near Turbofans
Preheat Air into Auxiliary Power Unit (APU)	> 400°C	Near Tailcone
Anti-icing System	> 20°C	Wing, engine cowlings and tail flight control surfaces
Warm by-pass Air for Thrust Enhancement	> 50°C	Near Turbofans
Warm the Ram Air	> 30°C	Near Turbofans

in the other two groups of heat pipe systems to handle underwing heat sources and bottom heat sources.

The working fluid of the heat pipes will be based on the required temperature range, power and considering the envelope material. Potential working fluids for the low temperature heat pipes are toluene, methanol, ammonia or water. Water-based heat pipes can transfer more power but freezing of working fluid and start-up could be a challenge. Ammonia heat pipes have a maximum temperature limit of approximately 100°C. Toluene heat pipes have a much wider operating temperature range but less power can be carried. Ammonia and toluene are both compatible with aluminum envelopes. Methanol can carry more power than toluene and has a similar temperature range but is only compatible with stainless steel and copper envelopes which may have mass penalties. The high temperature heat pipes will use an alkali metal such cesium, potassium or sodium. These high temperature fluids are compatible with stainless steel, Inconel and Haynes 230.

The elevation of the end users is higher than the heat sources, which is favorable for heat pipe design because the heat pipes will operate as thermosyphons (gravity-assisted heat pipe). In a typical heat pipe, liquid is passively returned from the condenser to the evaporator through capillary pumping of a wick structure. When the heat source is below the heat sink gravity can be used to return the liquid to the evaporator.

Fig. 3 shows an example of a detailed layout of the high-temperature and low-temperature heat pipe delivery system for the tailcone. A high-temperature heat pipe is used to preheat air entering the APU while a system of low-temperature heat pipes distributes waste heat along the tail for deicing or dump the waste heat into the exhaust stream.

III. EXPERIMENTAL DEMONSTRATION OF A LONG AND CURVED THERMOSYPHON

Fig. 4 shows an example of using a long and curved gravity assisted heat pipe (thermosyphon) to serve an end user at lower operating temperature. In this configuration, the waste heat generated from the acoustic heat pump (located at the bottom of the turbofan) is delivered to the wing tip by the heat pipe, which has a curved adiabatic section to accommodate geometry of the turbofan and a long and straight condenser to cover the entire wing. This heat pipe is designed for wing deicing and/or

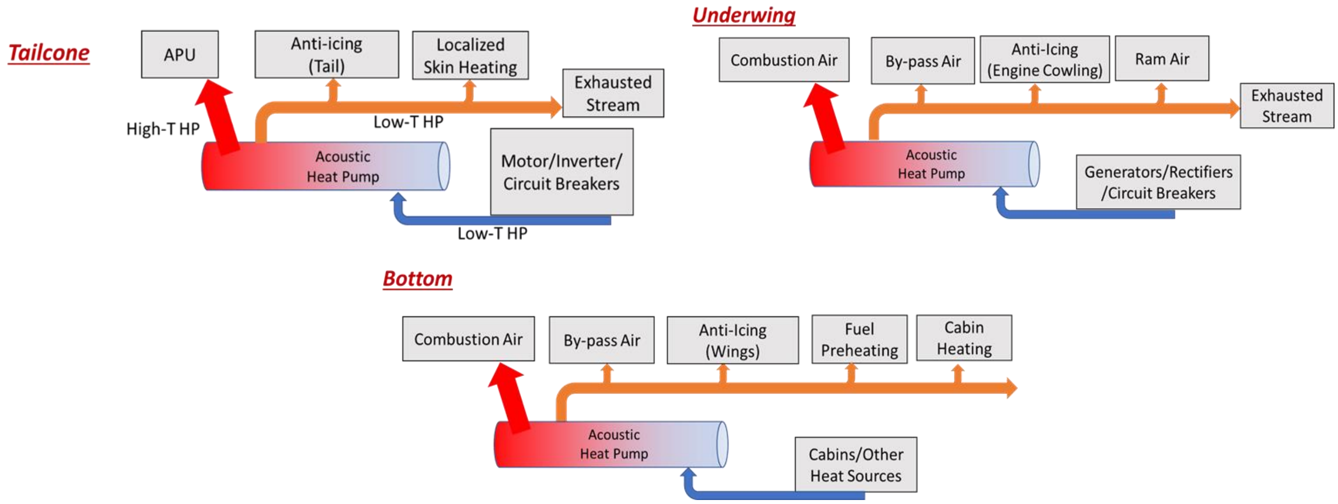


Fig. 2 Three groups of heat pipe heat delivery system for the electric aircraft.

mold line warming for drag reduction. The low temperature heat pipes can use acetone, toluene or ammonia as working fluids. Although it would be the highest performer, water is temporary ruled out because of freezing problems.

ACT fabricated a scaled-down version of the long curved thermosyphon illustrated in Fig. 4 in order to (1) demonstrate that a long and curved thermosyphon can transfer heat from the turbofan to the wing tip with very low thermal resistance and (2) to validate that the flooding limit correlation developed by Faghri [7] can be used to predict the power capability of long thermosyphon with a curved adiabatic section. The long thermosyphon is shown mounted on the test stand in Fig. 5a.

The heat pipe is made of aluminum tube with 1 in. OD and 0.049 in. wall thickness. It has a curved section with bending diameter of 1 meter (3.3 ft) to mimic the turbofan shape. After the bent section, there is a 5 meter (16.4 ft) long straight adiabatic section with 6° tilted angle to mimic the angle of aircraft wing. Heat is supplied to the evaporator (12 in.) using a heater block and is rejected at the wing tip to a chiller block (12 in.). Note that in the actual application the condenser would be the entire length of the wing. The thermosyphon was equipped with thermocouples for measuring the temperature distribution along the length.

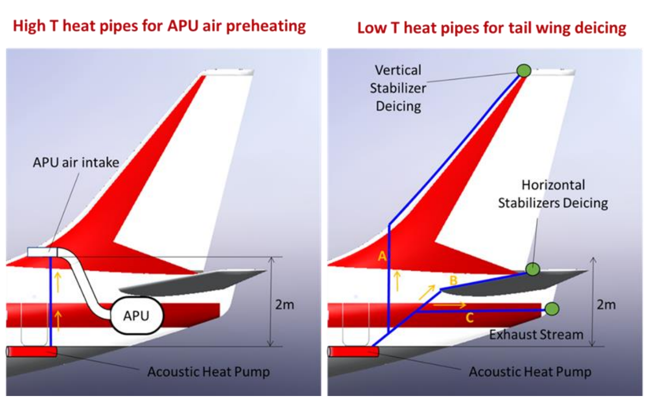


Fig. 3 Tailcone heat pipe layout (a) high temperature heat pipe for APU preheating (b) low temperature with multiple condensers for tail wing deicing.

The thermosyphon was tested using both acetone and toluene as the working fluid at four operating temperatures (0°C, 20°C, 40°C and 60°C). b) Experimental data for long-curved thermosyphon

Fig. 5b compares the experimentally measured heat transfer limit of the thermosyphon with both fluids to the predicted flooding limit [7] based on the inner diameter, working fluid and operating temperature. Overall, the agreement between the correlation and experimental measurements was very good indicating that this correlation can be used for a full-scale design.

As an example, Fig. 6 shows the temperature distribution along the long thermosyphon from the evaporator end cap (TC#1) to the condenser end cap (TC#28) with the heat input of 775W and operating temperature at 60°C. The temperature drop between the two end caps is around 8.04°C and the corresponding thermal resistance is 0.01 °C/W. The distance of heat transfer is 8.15 m (320 inches) and the cross-section area of the pipe is 5.07 cm^2. This results in an extremely high equivalent thermal conductivity of 1.6 MW/m/K.

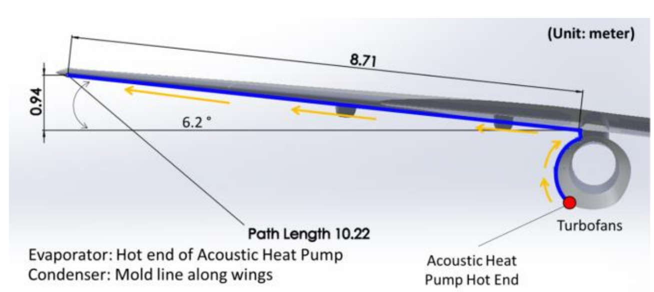
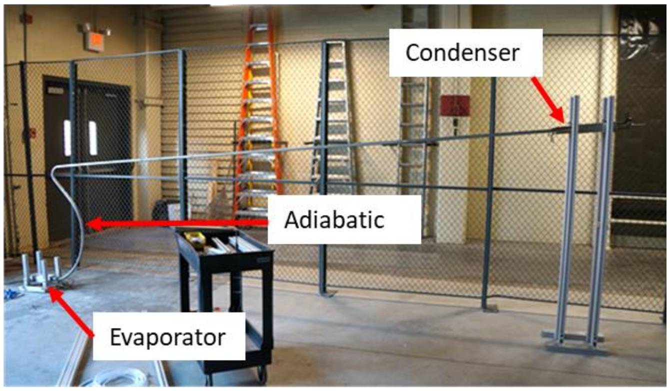
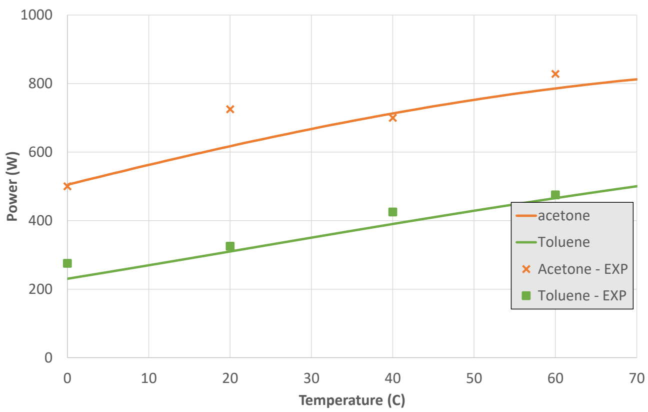


Fig. 4 Low temperature heat pipe for wing heating



a) Long-Curved Thermosyphon Experimental Setup



b) Experimental data for long-curved thermosyphon

Fig. 5 (a) Long thermosyphon mounted on the test stand. (b) Power capability of long thermosyphon: Prediction vs Experiment

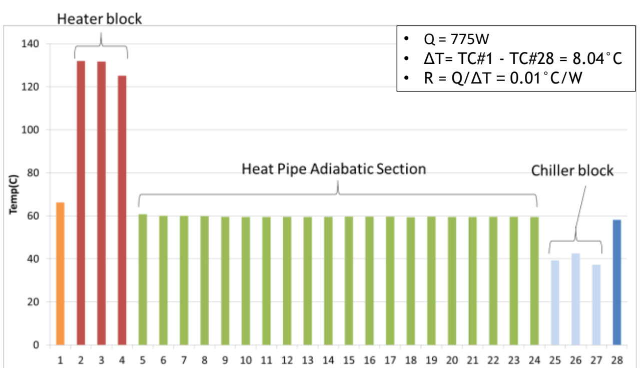


Fig. 6 Temperature distribution along the long thermosyphon with 775W heat load. TC2 to TC4

IV. Two Phase Heat Transport System with Solid-State Thermal Switching Capability

The proposed heat pipe heat delivery systems shown in Fig. 2, shows thermal energy being transported from a single source to multiple heat sinks or "end users". For example, waste heat under the wing can be carried from the acoustic heat pump and used to warm by-pass air, for anti-icing and warming ram air. In order to minimize the number of heat pipes required to transport this power ACT is developing a two-phase heat transport system with solid-state thermal switching/control capabilities based on a variable conductance heat pipe (VCHP). A VCHP contains a reservoir of non-condensable gas (NCG). The NCG volume expands and contracts due to changes in the thermal conditions (sink temperature and power input). As the NCG expands into the condenser, the area available for heat transfer is reduced. VCHPs are typically used when it is necessary to minimize the influence of the thermal conditions on the vapor temperature.

In the system developed by ACT, a single heat source is connected to multiple end users via a multi-condenser VCHP (MCVCHP) as shown in the schematic in Fig. 8. This figure illustrates a system with a single evaporator connected to three separate condensers (vertical branches) that each have their own reservoir of NCG. Vapor is free to travel from the evaporator into any of the condensers. The system operates as follows:

- In Fig. 8a all three condensers are fully open and the maximum amount of heat transfer through the system is occurring. Vapor is free to travel from the evaporator to the condensers.
- Solid-state control (no moving parts) is achieved by applying heater power to the individual reservoirs raising the temperature of the NCG. As the NCG temperature increases, the NCG expands and begins blocking vapor from reaching a portion of the condenser, Fig. 8b.
- By controlling the temperature of a given reservoir it is possible to adjust the active length of the condenser from fully open to fully closed. This is illustrated in Fig. 8b:
    - Reservoir 1 is unheated and the condenser is fully open.
    - Reservoir 2 is heated so that approximately half of the condenser is blocked. This reduces, but does not eliminate, the heat transfer to Condenser 2.
    - Reservoir 3 is sufficiently heated to fully block the condenser, shutting down heat transfer to Condenser 3.

The key to designing this system is properly sizing the reservoirs in order to ensure the correct amount of NCG is captured in each branch during the startup process. The startup phase begins from a state in which the entire system is at an ambient temperature and no power is being applied to the evaporator. In this state, the working fluid will be nearly all

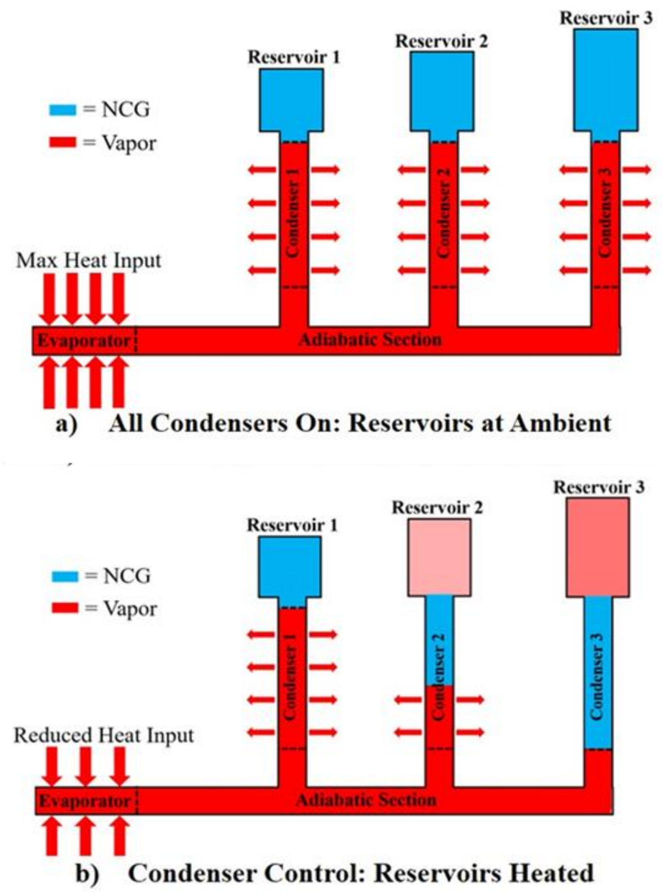


Fig. 8 Multi-Condenser VCHP (MCVCHP) solid-state thermal switching concept

condensed liquid or may even be frozen in the evaporator region, and as a result most of the system will be occupied by NCG at a relatively low pressure. As power is applied to the evaporator the working fluid will be begin to evaporate and the pressure will begin to increase pushing the NCG front towards the condensers. ACT modeled the motion of this NCG front using Flat-Front Theory. The fundamental assumptions of this theory are:

- Infinitely thin interface between vapor and NCG.
- Discontinuous step in temperature between vapor and NCG
- Pressure is continuous across the interface.
- The pressure in the system is controlled by the temperature of the vapor due to the saturated nature of the working fluid.

The model developed by ACT can be used to size the various reservoirs and determine the proper amount of NCG to be added to the system based on two factors.

- The size of an individual reservoir controls the maximum reservoir temperature required to fully close the corresponding condenser. The sensitivity of the NCG front location to reservoir temperature increases as the size of the reservoir is increased. In other words, the control sensitivity of the condenser is higher when larger reservoirs are used.
- The relative sizes of the individual reservoirs must be selected in order to ensure that at the design vapor temperature the NCG fronts are all located at the entrance to the reservoirs, see Fig. 8a.

Using the Flat-Front Theory model, ACT designed the prototype MCVCHP shown in Fig. 7. The prototype was constructed from stainless steel and used toluene as the working fluid and nitrogen gas as the NCG. The system was designed to operate at a design vapor temperature of 90°C and was cooled to the ambient environment. In Fig. 7 it can be seen that the system was tilted in order to operate as a thermosyphon. The reservoir volumes are listed in Table 3, the reservoirs are numbered from left to right. Each vertical branch was 11.0 inches tall. The top 4.5 in. of each branch was considered to be the condenser and the lower 6.5 in. was an adiabatic section. The adiabatic sections were covered with insulation. At the ambient temperature the working fluid was in a liquid pool in the evaporator and the remainder of the system was occupied by NCG.

Thermocouples were used to obtain temperature distributions along the adiabatic section, condensers and reservoirs during the various stages of operation in order to demonstrate the thermal switching capabilities of the system.

Table 3. Reservoir volumes of the multi-condenser VCHP.

Reservoir 1	Reservoir 2	Reservoir 3
10.0 in.^{3}	12.6 in.^{3}	21.7 in.^{3}

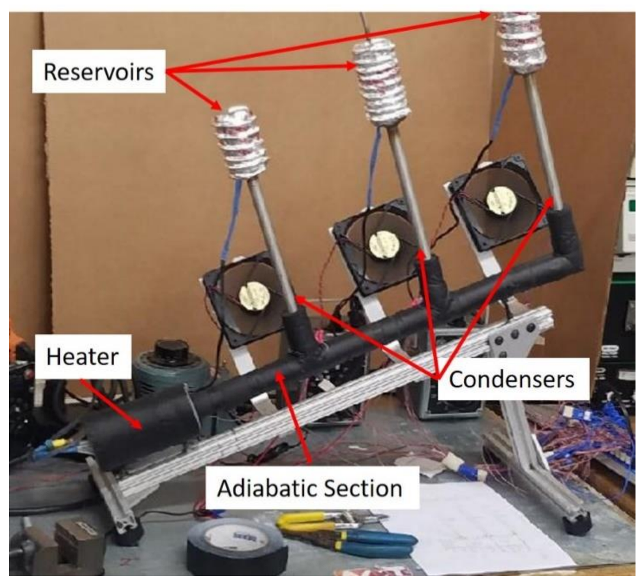


Fig. 7 Prototype MCVCHP. The prototype was constructed from stainless steel and used toluene as the working fluid and nitrogen gas as the NCG.

These temperatures are assumed to represent the vapor and NCG temperature. Fig. 9 shows the temperature distribution on the surface of the MCVHP at the design setpoint with vapor temperature of 90°C. Note that the different sections of the system are color coded. At the design setpoint no heater power was applied to the reservoirs and all three condensers were fully open. This state represents the maximum heat transfer through the system. The adiabatic section and condensers are essentially isothermal due to the nature of the saturated working fluid. The reservoir temperatures were slightly greater than ambient due to conduction from the condensers through the walls and natural convection in the NCG.

In Fig. 10, heater power had been applied to Reservoir 3 causing the NCG to expand into the condenser and partway into

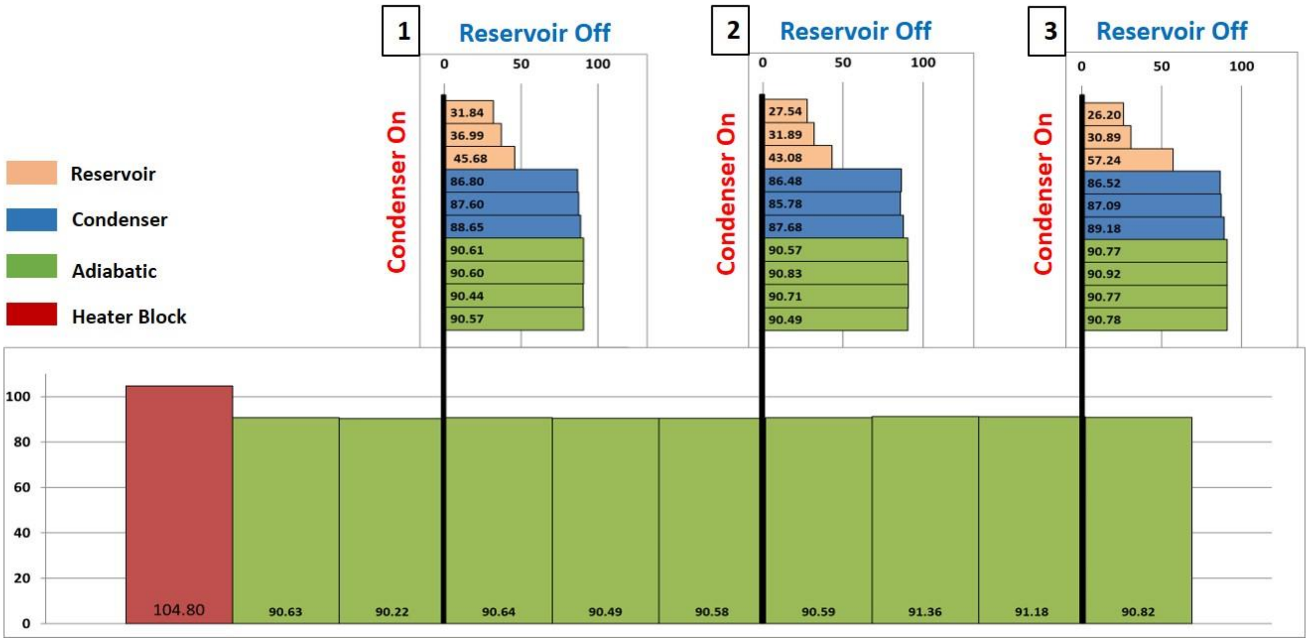


Fig. 9 Temperature distribution of MVCHP when all reservoirs are unheated. All condensers are fully open.

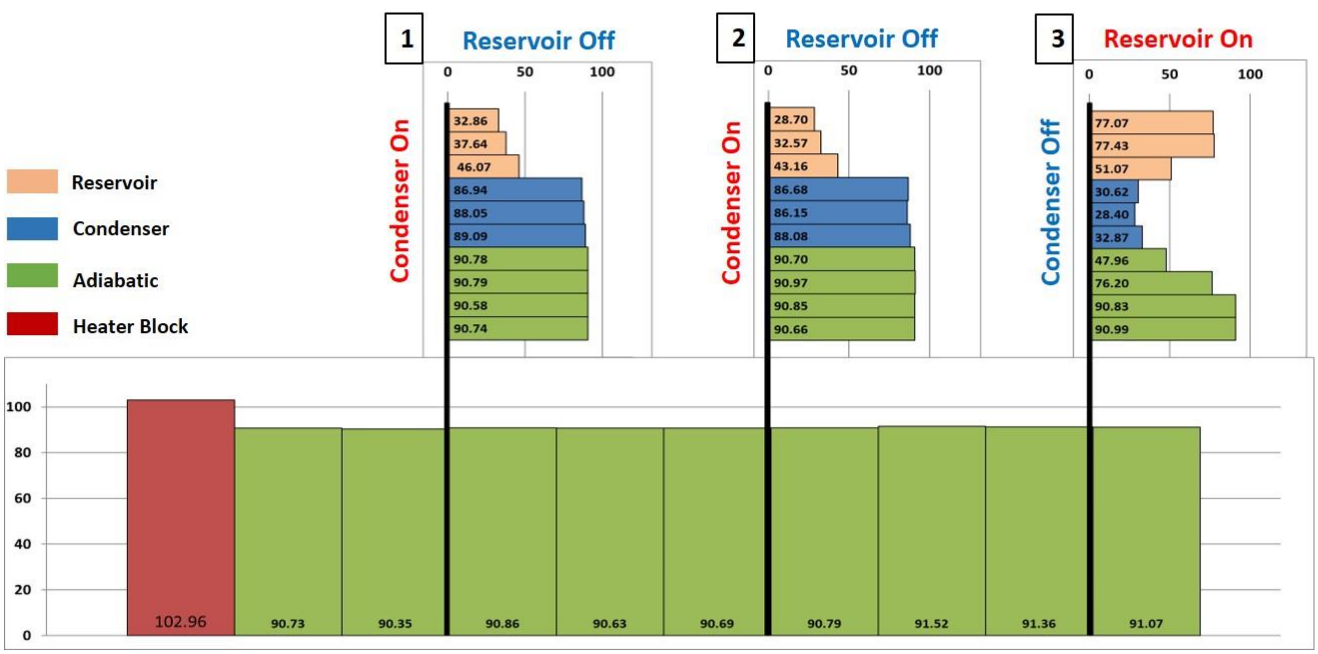


Fig. 10 Temperature distribution of MCVCHP with heater power applied to Reservoir 3. Condenser 3 is shutdown.

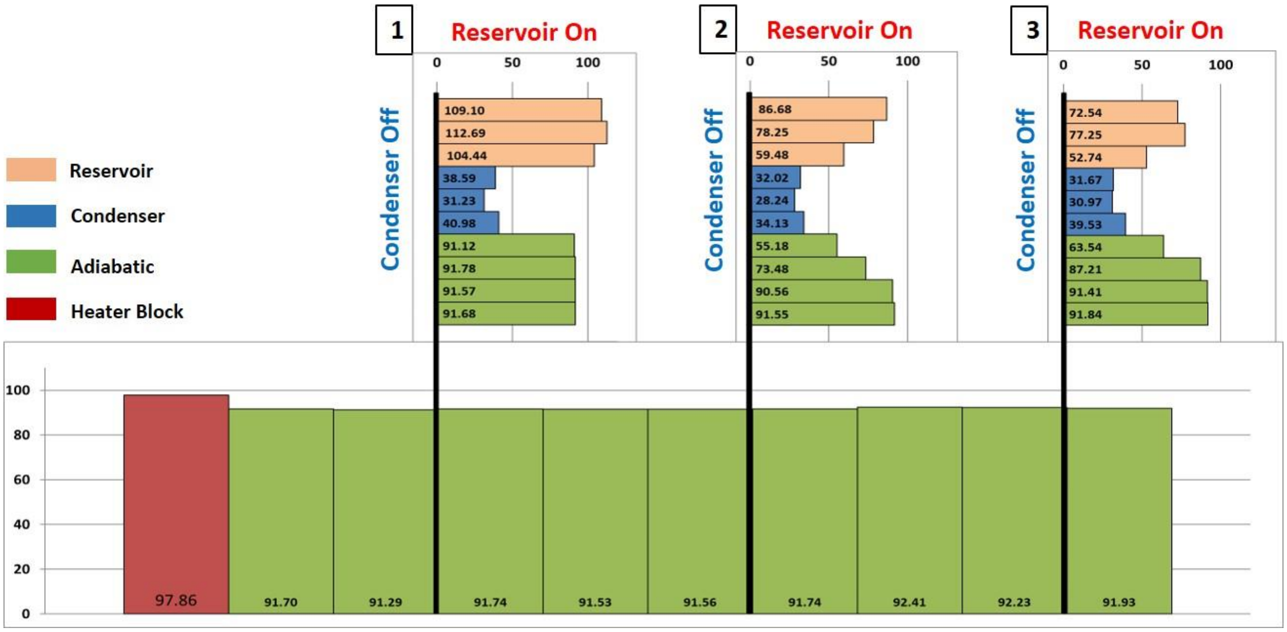


Fig. 11 Temperature distribution of MCVCHP with heater power applied to all reservoirs. All condensers are shutdown.

the adiabatic section of Branch 3. The temperature of Condenser 3 approached the ambient temperature and heat transfer through Branch 3 was effectively shut down.

In Fig. 11 heater power was applied to all three reservoirs blocking vapor to all three condensers effectively shutting down heat transfer throughout the entire system. The results show that the three reservoirs did not require the same temperature to shut down the respective condenser. The largest reservoir (Reservoir 3) required the lowest temperature in order to shutdown the condenser while Reservoir 1 required the highest temperature. This is consistent with general VCHP operation in which a larger reservoir results in a larger sensitivity of NCG front location with respect to reservoir temperature.

CONCLUSION

This paper discusses the development of a two-phase solid-state waste heat delivery system for electric aircraft. An acoustic heat pump developed by Dyson [1] will be used to elevate low-grade waste heat throughout the aircraft to a higher temperature. This high-grade waste heat will then be delivered, using a heat pipe-based thermal delivery network developed by ACT, to various end users throughout the aircraft requiring thermal energy. Using NASA's STARC-ABL as a representative aircraft, ACT identified the temperature and relative locations of the heat sources and end users and designed three groups of heat pipe heat delivery systems based on the temperature and power requirements. ACT successfully demonstrated the operation of a long curved thermosyphon that conforms to the shape of the engine nacelle and wing. This thermosyphon can be used to transport waste heat from the engine to the wing for de-icing. Finally, a novel two-phase heat transport system with solid-state thermal switching/control capabilities based on a variable conductance heat pipe was introduced and experimentally demonstrated. This system will reduce the number of heat pipes required for transporting heat to the various end users.

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