Cooling High Power Processing Devices Onboard Satellites: Testing Considerations for Space Copper-Water Heat Pipes (SCWHPs)

Pete Dussinger, Chief Engineer, Products; Jens Weyant, Manager, Def/Aero Products; Ryan Spangler, Lead Engineer, Space Products. Advanced Cooling Technologies, Inc., (Lancaster, PA).

Introduction

For years, copper water heat pipes have been used in thermal solutions for electronics systems in terrestrial applications. More recently they have gained interest from the space community. Space copper water heat pipes (SCWHPs) are desired by design engineers for use in managing waste heat from payload electronics because of their compact size, their ability to accept high heat fluxes, and their ability to operate against gravity during ground testing. Gravity independence removes a significant design constraint for applications that require ground-based testing in various orientations.

When incorporated properly, SCWHPs can accept waste heat from high power chips and spread it to a more manageable heat flux along the surface where the payload is attached to the spacecraft. At the lower heat flux, the waste heat can be transferred to the spacecraft radiator panels by conduction through aluminum structure or by conventional aluminum-ammonia heat pipes. The main limitation in adoption is that the space satellite environment is one where freezing can be expected under standby and other conditions, creating conditions not seen by heat pipes manufactured for terrestrial purposes. Testing designed for heat pipes in space conditions signaled a need for significant modifications to manufacturing process in order to meet stringent qualification regimes.

Space Heritage and Adoption

ACT flew its first SCWHPs in 2017 together with NASA Marshall Space Flight Center and NASA Johnson Space Center, under the Advanced Passive Thermal experiment (APTx) project. The SCWHPs were embedded in a HiK™ plate for validation testing on the International Space Station (ISS). The objectives for testing flight hardware on the ISS were to demonstrate the operation and flight worthiness of the SCWHP embedded HiK™ plate, and the program achieved success.

Heat Pipes have been used for decades to remove heat from electronics systems and their benefits include passive operation and long life with no maintenance. They use a combination of evaporation and condensation of a working fluid, taking advantage of the high heat transfer coefficients of these two-phase processes. Thermal conductivities can approach 10,000 to 100,000 W/m-K for long heat pipes, in comparison with ~400 W/m-K for copper.

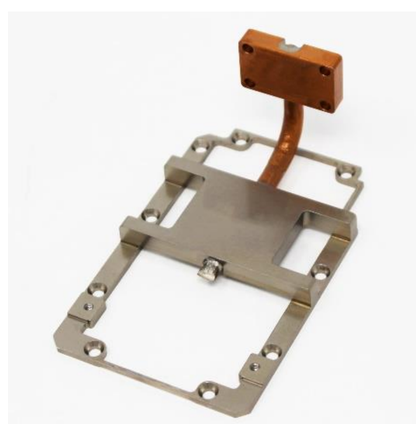

Figure 1: Copper Water Heat Pipe Assembly

Heat pipes, using water as the working fluid, will freeze at 0°C, which will halt two-phase heat transfer until temperatures again rise. Note that water expands nearly 10% when it changes from a liquid to a solid. This physics-based phenomenon cannot be avoided, but can be accounted for when designing. With this understanding, SCWHPs have been designed to survive freeze-thaw cycles in excess of what is needed for long term missions.

In any environment, management of the fluid inventory and a rugged, robust design are key to maintaining long-term operation. In space environments, it is especially important that there is only enough working fluid (water) in the heat pipe to saturate the wick. Any excess fluid will create a puddle (droplet or large meniscus) in the pipe. When a puddle exists, it can bridge the inside diameter of the heat pipe and upon freezing expand outward, potentially resulting in mechanical deformation. The mechanical deformation will continue to occur with each freeze-thaw cycle. Damage is cumulative and will eventually result in rupture of the pipe wall. Therefore, it is critical that SCWHPs, at most, have a fully saturated wick, meaning there is just enough water in the pipe to wet the wick, but no excess resulting in a puddle.

On orbit, freezing can occur in three primary modes of operation and are as follows; static freeze/thaw, cold start, and powered freeze/thaw. SCWHPs must be carefully designed and verified to ensure that the design is tolerant of these types of freeze/thaw cycles. One means to increase design tolerance during powered freeze-thaw is to increase the pipe diameter and starve the wick of fluid inventory. The increased diameter is favorable and the lean fluid charge lowers the amount of water available for a puddle.

The Venn-diagram shown in Figure 2 shows the region of acceptable fluid charge required to simultaneously meet thermal performance specifications and achieve powered freeze-thaw cycling tolerance. The area of overlap between these regions results in a heat pipe that meets both thermal performance and powered freeze-thaw requirements. Careful selection of heat pipe geometry, wick structure, and fluid charge is necessary to assure a freeze tolerant SCWHP solution is possible.

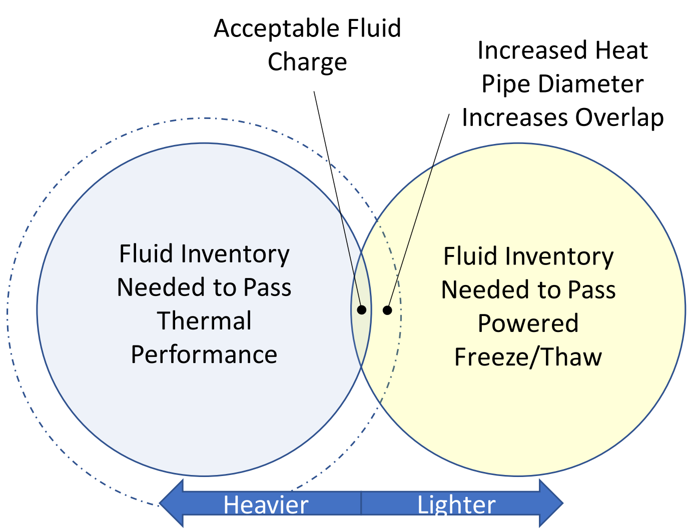

Figure 2: Venn-Diagram showing the overlap between fluid inventory needed to meet thermal performance and the fluid inventory needed to pass powered freeze thaw.

Static Freeze/Thaw

After launch, before powering up the satellite or when a satellite is in standby mode, it is possible for the heat pipes to experience freezing and thawing when the heat pipe is not operating as a two-phase heat transfer device. In this case, the pipe is at thermal equilibrium and is isothermal as it freezes and thaws. The wick structure within the SCWHP has a low elastic modulus which means it has an ability to deform significantly and elastically recover. As the water freezes, it expands and grows toward the inside diameter of the heat pipe. As it thaws, the water turns to liquid and the wick returns to its original state.

Frozen Start-up

This mode is often referred to as frozen start-up or cold start freeze/thaw. In this case, the heat pipe freezes as described above in static freeze-thaw. The pipe is isothermal and all of the fluid inventory is contained within the wick structure. During the thaw cycle however, power is applied, starting from the coldest condition. The water in the evaporator thaws first, evaporates, and travels towards the condenser. As the vapor condenses, it releases the latent heat of vaporization to the frozen adiabatic and condenser sections of the heat pipe, resulting in an increase in temperature. For some time, the water condenses on heat pipe sections that may be below 0°C, refreeze, and therefore not return back to the evaporator.

The test is run to determine whether or not the pipe, during this transient condition, will be able to thaw to an extent necessary to allow the heat pipe to startup and keep the electronics below the maximum allowable temperature or if it will experience evaporator dryout to an unrecoverable state, causing the electronics to reach their critical temperature. This testing is highly dependent on the heat pipe's geometry, the lengths of the evaporator, adiabatic, and condenser sections, the power applied, and the mass of the electronics and heatsinks attached to the heat pipe. Since this could be a real condition of the satellite, the testing is performed to verify that the heat pipe can restart under the expected conditions, without overtemperature of the electronics; and, whether repeated cold start freeze/thaw cycles will damage the heat pipe in any way.

Powered Freeze/Thaw

During powered freeze/thaw, power is continuously applied to the evaporator while the condenser temperature is forced to vary from maximum to minimum expected temperature extremes, including dwells at the high and low extremes. This is considered one of the most challenging freeze/thaw tests for SCWHPs because the test by definition, evaporates water from the evaporator section and transports it to the condenser section while continuing to extract power from the condenser section, forcing the condenser into a below 0°C condition while the evaporator is above 0°C. This results in a dried-out evaporator section and excess fluid in the condenser section. Should a puddle or meniscus of excess fluid occur that spans the diameter of the heat pipe before freezing occurs, the resulting expansion of the ice has the potential to damage the heat pipe envelope. Additional cycles have the potential to accumulate damage to the point of failure.

It's believed that the ratio of evaporator length (including conduction through the pipe wall toward the adiabatic section) to pipe diameter is an important factor in the design of powered freeze/thaw tolerant SCWHPs. The longer the evaporator, the longer the puddle or pool created at the condenser end. The longer the pool, the higher the likelihood of trapping liquid behind the freeze front. Flattening a heat pipe, thereby reducing the internal effective diameter, also exacerbates the likelihood of powered freeze-thaw damage. Essentially a lower evaporator length to diameter ratio is beneficial for SCWHPs exposed to powered freeze-thaw.

Summary

Copper water heat pipes are a viable thermal solution for cooling payload electronics in spaceflight applications. ACT has worked with space industry leaders to define test regimens and qualification requirements since our first launch with NASA in 2017; in that time SCWHP manufacturing has evolved into a highly precise and robust process.

SCWHPs are well suited for the temperature range of most electronics cooling applications in space and are capable of accepting high heat flux(es) from electronic components and spreading it to a heat flux more suitable for transport to the radiator panels by more traditional means, such as aluminum structures or aluminum-ammonia heat pipes. As mentioned earlier, SCWHPs provide the additional benefit of being able to operate against gravity, which is beneficial for ground-based testing.

The current GEN3 process has passed static freeze-thaw, frozen start-up, and powered freeze-thaw of various cycle counts defined by customers. Although the water within the heat pipe will freeze and expand below 0°C, SCWHPs can be designed to simultaneously meet the thermal transport requirements and be tolerant to repeated static freeze/thaw, cold start, and powered freeze-thaw cycling for reliable, long-term missions.