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LOOP HEAT PIPE DESIGN, MANUFACTURING, AND TESTING – AN INDUSTRIAL PERSPECTIVE

W. G. Anderson, P. M. Dussinger, S. D. Garner, J. R. Hartenstine, and D. B. Sarraf
Advanced Cooling Technologies, Inc.
Lancaster, PA. U.S.A.

ABSTRACT

Loop Heat Pipes (LHPs) are two-phase devices that can passively transport heat over long distances relative to other passive two phase systems such as heat pipes. Most of the art of LHP fabrication is in the primary and secondary wick. The manufacturing steps for an LHP are described, including the tests to validate the LHP during manufacture. The tests include wick property testing (pore size, permeability, and thermal conductivity), secondary wick testing, and parallel flow balance design and testing. The required tests after the LHP is fabricated include low power starts, shutdown through compensation chamber heating, unbalanced condenser temperature tests, transient testing - both power cycling and condenser temperature changes, and maximum power tests.

LOOP HEAT PIPES

LHPs are high thermal conductance devices that are self-contained and passive. Figure 1 shows a schematic of a LHP. Note that the figure is not to scale; the vapor and liquid lines can be made much longer. Figure 2 shows the LHP evaporator in more detail. Heat enters the evaporator and vaporizes the working fluid at the wick outer surface. The vapor is collected by a system of grooves and headers as shown in Figures 2 and 3. The vapor flows down the vapor line to the condenser where it condenses as heat is removed by the cold plate. Most of the condenser is filled with a two-phase mixture. A small section at the end of the condenser provides a small amount of sub-cooling.

The heart of the LHP is the evaporator and compensation chamber, which contain the primary and secondary wicks. The Compensation Chamber (CC) (or reservoir) at the end of the evaporator is designed to operate at a lower temperature than the evaporator (and the condenser). Since the temperature is lower, the pressure of the saturated fluid in the compensation chamber is also lower. This lower pressure allows the condensate to flow from the condenser through the liquid return line to the compensation chamber. The fluid then flows into a central bayonet where it feeds the wick. A secondary wick in the evaporator and compensation chamber allows the liquid in the compensation chamber to feed the evaporator wick to make up for the heat leak.

The liquid in the compensation chamber and the interior of the wick must be returned to the exterior surface of the wick to close the cycle. Capillary forces accomplish this passively, drawing liquid back to the surface, just as water will be drawn up into a sponge.

Loop heat pipes are made self-priming by carefully controlling the volumes of the compensation chamber, condenser, vapor line and liquid line so that liquid is always available to the wick. The compensation chamber and fluid charge are set so that there is always fluid in the compensation chamber even if the condenser, vapor line and liquid line are completely filled with liquid. The LHP is thus inherently self-priming.

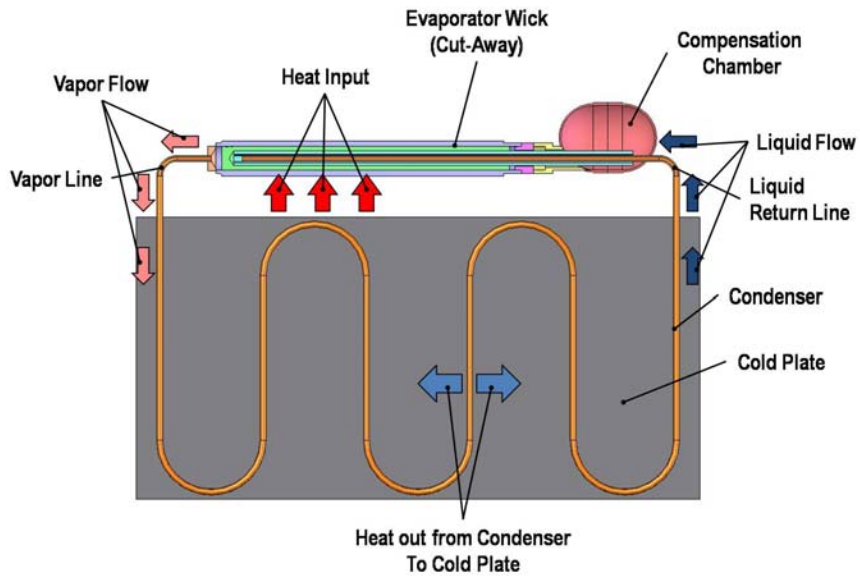

Figure 1. Loop Heat Pipe Schematic (Not to scale). For example, the vapor and liquid return lines can be much longer.

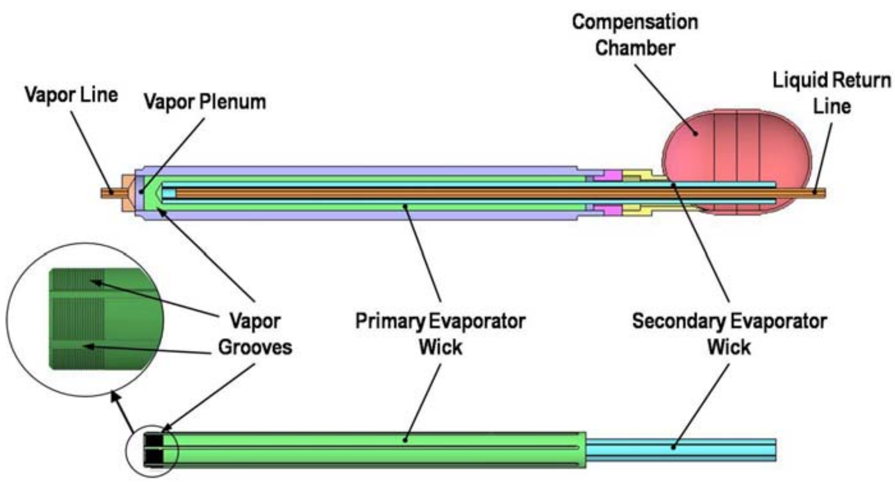

Figure 2. Loop Heat Pipe Evaporator.

LHP MANUFACTURING

The evaporator/compensation chamber and vapor line/condenser/liquid return line sub-assemblies are manufactured in parallel. Most of the "art" of LHP manufacture is in the evaporator/compensation chamber fabrication, especially the LHP wick fabrication and testing. The wick is typically fabricated by sintering a powder metal that is compatible with the LHP working fluid. Typical materials are nickel, stainless steel, and titanium. They are compatible with ammonia, and have a low thermal conductivity to minimize conduction through the wick to the compensation chamber.

After sintering, a sample is taken from the wick to verify that the wick properties are in the desired range. Typical wicks have a pore size between 1 and 5 μm, and a permeability between 1 and 5 x 10^{-14} m^2. The wick is machined as described below, and the wick properties tested to verify that the wick was not damaged during the machining process. The wick is then inserted into the evaporator, and the properties measured again. The secondary wick is inserted into the primary wick, and then the evaporator/compensation chamber sub-assembly is joined to the vapor line/condenser/liquid return line sub-assembly.

With the exception of the parallel condenser flow balancer, discussed below, the vapor line/condenser/liquid return line sub-assembly is relatively simple, since it is basically plumbing (although with stringent maximum leak requirements). This sub-assembly is fabricated with the following steps:

1. Fabricate and Test flow balancer
2. Fabricate vapor line, condenser, and liquid return line
3. Attach to the evaporator and compensation chamber
4. Performance testing

Loop Heat Pipe Evaporator Wick

The LHP evaporator wick uses capillary forces to passively supply liquid to the heated surface from the lower pressure condenser. In a heat pipe wick, heat enters from the liquid side of the wick. In contrast, an LHP has an inverted wick, with the vapor located adjacent to the heated surface. LHP wicks are fabricated by sintering metal powder to form a porous body. A typical LHP wick is shown in Figure 3. When the wick is inserted in the evaporator, the outer surface of the wick is in contact with the heated surface. Circumferential and axial grooves are necessary to provide flow channels for the vapor to flow to the vapor line. In this case, the axial and circumferential grooves are machined in the wick, although they can alternatively be machined into the evaporator body.

Wick Sample Measurements

After sintering, the first step in qualifying the evaporator wick is to measure the wick properties. Samples are taken

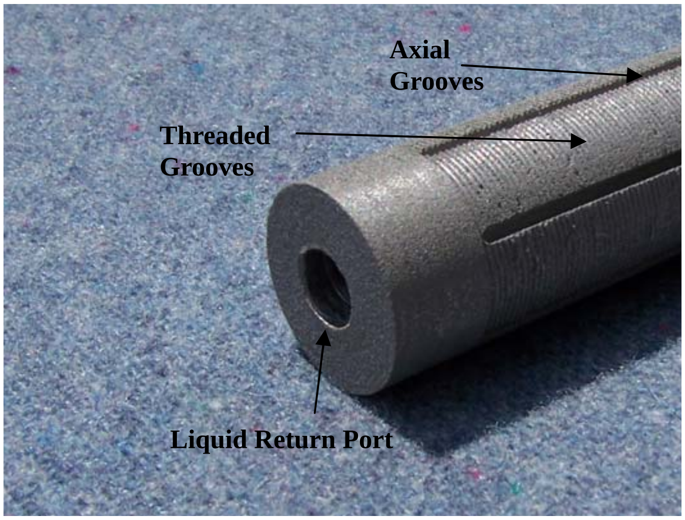

Figure 3. Titanium LHP evaporator wick. After sintering, threaded grooves and axial grooves must be machined into the wick to remove vapor generated in the evaporator. The liquid return port is also machined, as well as a flat surface for the knife edge seal.

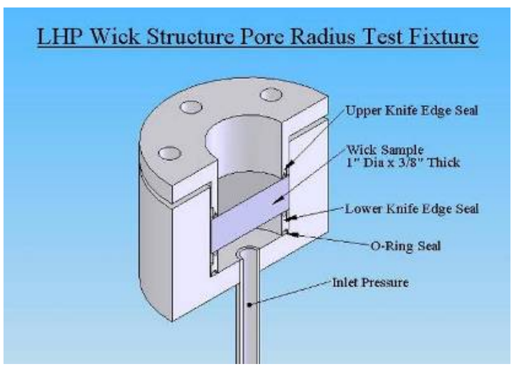

Figure 4. Wick Pore Radius Test Fixture.

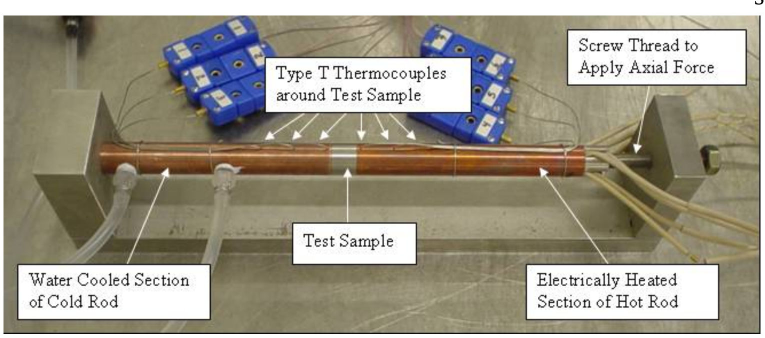

Figure 5. Wick Thermal Conductivity Test Fixture.

from the ends of the sintered blank to verify that the wick has suitable pore size, permeability, and thermal conductivity. The wick pore radius test fixture is shown in Figure 4. The wick sample is saturated with methanol, and has a thin layer of methanol above it. The nitrogen pressure in the lower chamber is increased until a bubble breaks through the top of the wick. Wick permeability is calculated with a similar apparatus that measures the flow rate of methanol as a function of pressure differential through the wick.

Minimizing wick thermal conductivity is desirable, since it minimizes the heat leak into the compensation chamber. The wick thermal conductivity test fixture is shown in Figure 5. A known heat load is applied to the wick sample by electrical resistance cartridge heaters embedded in the "hot end" copper rod. The heat removal is accomplished by a water cooled "cold end" copper rod. Thermocouples are installed in the cold and hot rods along the heat flow path. The temperature between the thermocouples, the cross sectional area of the rod, and the thermal conductivity of the rod material are used to calculate the power being transferred along the length of the rod. Careful evaluation and correction for the interface resistances is factored in to achieve an accurate result.

Evaporator Wick Fabrication and Insertion

Assuming that the wick blank has suitable properties, the next step is to machine the grooves and liquid return port for the wick. A second set of pore size and permeability measurements are then made on the actual wick. These measurements are not meant to be extremely precise, but instead are used to verify that there was no damage during the machining steps (for example, cracking the wick, or blocking the pores). The apparatus used to measure the pore size on the as-machined wick is shown in Figure 6. The wick is saturated with methanol, then immersed in a methanol bath. Gas is supplied through the pressure inlet, and the pressure at which the first bubble appears is measured.

As shown in Figure 7, the same apparatus is used to measure the permeability of the as-machined wick. The wick is saturated with methanol, and the interior liquid return port is also filled with methanol. Methanol is supplied to the wick, while the methanol pressure in the wick interior is measured. The rate at which methanol weeps through the wick is also measured, and the flow rate is used to calculate the permeability.

The wick is then inserted into the evaporator body with an interference fit, to prevent vapor from traveling from the grooves into the compensation chamber. Figure 8 shows the wick after it is inserted in the evaporator. Once the wick is inserted, the wick pore size is measured for a final time, to verify that the wick was not damaged during the insertion.

SECONDARY WICK FABRICATION AND TESTING

Secondary wicks are used to hydraulically link the fluid in the compensation chamber to the primary wick in the evaporator. This is important in both steady state and transient

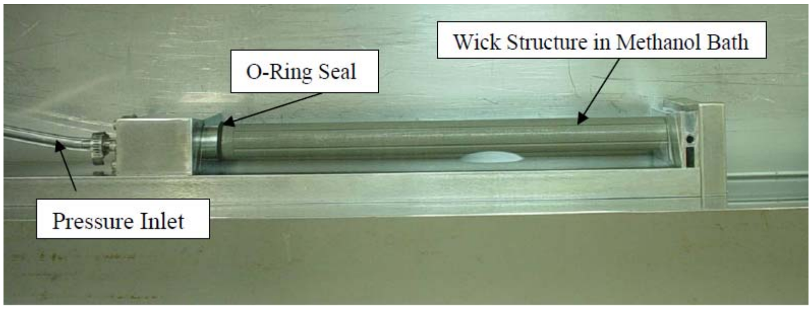

Figure 6. Pore-size measurement on the as-machined wick.

situations. For example, under steady state operating conditions the inner diameter of the primary wick is at a slightly higher temperature than the saturation temperature in the compensation chamber. This causes a small portion of the heat input to the primary wick to be "back conducted" to the compensation chamber, through two-phase evaporation and condensation, similar to a conventional heat pipe. This is often referred to as a "heat leak". Without a secondary wick to transfer the equivalent amount of working fluid from the compensation chamber back to the primary wick, the primary wick would become starved for fluid and ultimately result in failure (overheating). Certain transient conditions, such as an instantaneous power change and/or rapid condenser temperature change can also cause an imbalance between the liquid returning from the condenser section and the liquid being removed from the primary wick. During these transients, the secondary wick is required to make up the mass flow rate difference by transferring sufficient liquid from the compensation chamber to the primary wick.

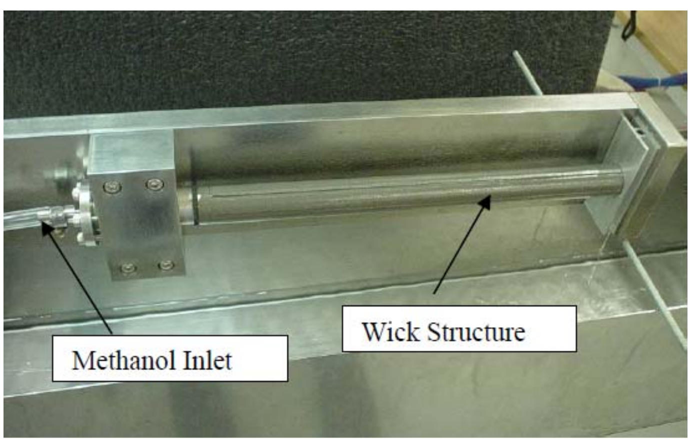

Figure 7. Permeability measurement on the as-machined wick.

The secondary wick transport capability is measured for both the stand-alone wick, and after the secondary wick is integrated into the primary wick assembly. Figure 9 shows the secondary wick being tested in a stand-alone condition. A custom heater block was designed and built to input heat and allow vapor to escape simultaneously. A cross-sectional view of the heater block is shown in Figure 10. The secondary wick is oriented at a 2° adverse tilt such that only the last bit of the wick was in contact with a pool of methanol. The wick was allowed to wet itself through capillary action. Once the wick is saturated, the heater power is increased stepwise, boiling off methanol that is transported through the wick. The power input and the effective length between the wick-puddle interface and the heater are used to calculate the transport capability in Watt-m.

After the secondary wick testing is completed, it is installed into the primary wick. In this configuration, the wick transport capability and the interface or hydraulic connection between the primary and secondary wicks are also demonstrated. Basically, the LHP evaporator is operated under open atmosphere conditions using methanol as the working fluid. The fluid is being supplied to the primary wick through the secondary wick only, and the vapor is discharged through the vapor outlet end of the evaporator as it would be in normal service.

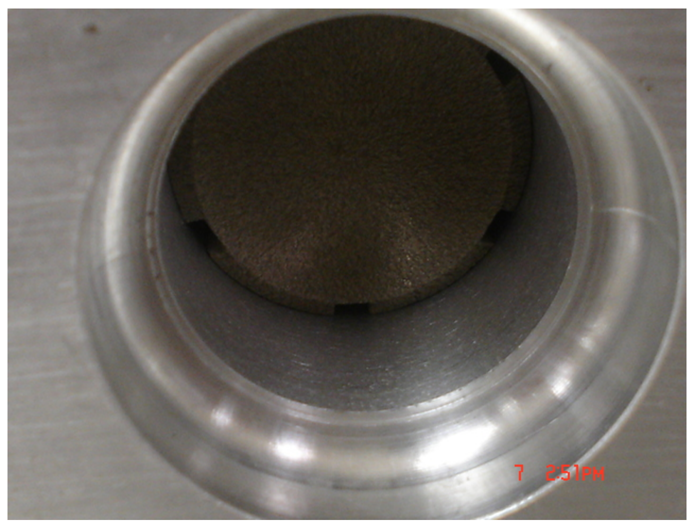

Figure 8. LHP wick inserted in the evaporator body. Note the axial grooves, which deliver the vapor to the vapor line.

After inserting the secondary wick into the primary wick, the evaporator body is positioned in the 2° adverse tilt orientation and the tip of the secondary wick, which would normally be in the compensation chamber, is allowed to dip slightly into a pool of methanol as shown in Figure 11. A heater, sized to provide uniform coverage, is attached onto the heat input surface of the evaporator; and, a series of thermocouples are attached to the evaporator body along its length. The heater power is increased stepwise as the thermocouples are monitored for uniformity. A non-uniform temperature profile indicates a hydraulic coupling flaw between the primary and secondary wicks.

Once the evaporator and secondary wick tests are completed, the evaporator/compensation chamber is welded together and leak tested. It is then ready for integration with the vapor line/condenser/liquid return line sub-assembly.

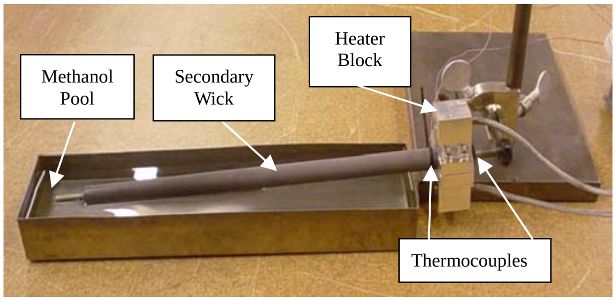

Figure 9. Secondary Wick Performance Testing.

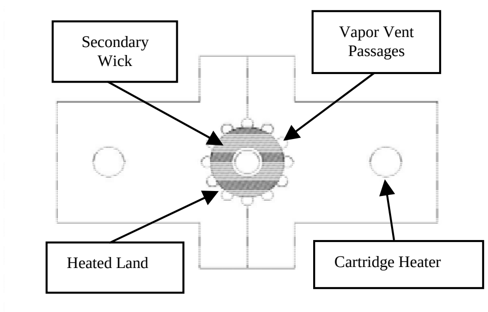

Figure 10. Cross-Section of Heater Block Showing Vapor Vents and Heated Lands.

PARALLEL CONDENSER FLOW BALANCER

LHPs used in spacecraft thermal control applications often have parallel condensers attached to dual radiator panels. There are times when the solar heating load is quite high on one side of the satellite, while the other side sees a much colder environment. LHPs can be designed so that the LHP rejects the waste heat to the cold side condenser while the hot side condenser is inactive, and filled with superheated vapor. As the hot and cold sides switch, a parallel condenser flow balancer insures that the LHP always passively rejects heat to the coldest condenser.

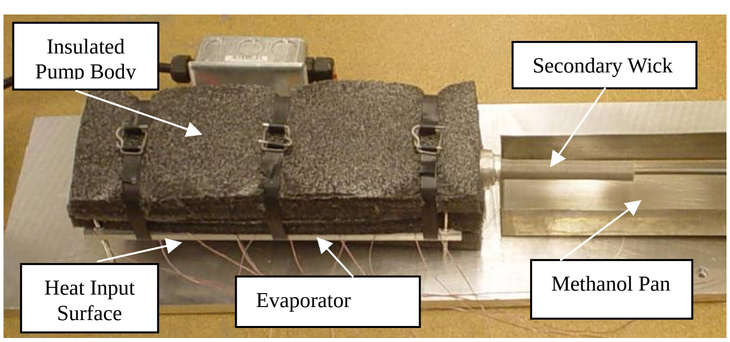

Figure 11. In-Situ Primary and Secondary Wick Test - Pumping Capacity and Hydraulic Coupling (Temperature Uniformity).

With dual condensers, the vapor flowing out of the pump body enters a tee that branches into the two, parallel condenser loops. The loops are connected again through a second tee which collects liquid from the condensers and returns it to the pump body. If the solar load is particularly high on one of the two LHP condensers, it is possible that the temperature of that condenser will be greater than the LHP operating temperature. In this case, the warm condenser segment will be filled with relatively static superheated ammonia vapor. If this vapor were allowed to mix freely with the sub-cooled liquid returning from the other condenser segment, the superheated vapor would condense into the sub-cooled liquid and this would result in canceling the sub-cooling which would likely cause an uncontrolled rise in the loop temperature. A parallel condenser flow balancer, shown in Figure 12, is installed to prevent the superheated vapor from one condenser segment from mixing with the sub-cooled liquid returning from the other segment. The flow balancer works by establishing a liquid – vapor interface on a porous membrane.

There are three requirements for the parallel condenser flow balancer:

1. Use capillary forces to prevent superheated vapor from entering the liquid return line
2. Minimize the liquid pressure drop from the active condenser
3. Supply liquid from the active condenser to the inactive condenser through a capillary link, to replenish liquid evaporated from the screen on the inactive side.

The parallel flow balancer in Figure 12 uses composite screen membranes to meet the three requirements. The pore radius of the screen was small enough to hold-off vapor penetration and the membrane was thin enough such that the pressure drop from liquid flow through the membrane was small. The screen capillary link supplies liquid to the screen adjacent to the vapor. A fourth consideration is preventing conduction from the hot side vapor from canceling the sub-cooling in the liquid return line. The tee length must be long enough that conduction though the tubing walls and the stagnant liquid slug in the non-flowing side of the tee would be negligible. This distance is on the order of 2.5 cm.

After the secondary flow balancer has been tested, it is installed in the LHP liquid return line. The remainder of the vapor line/condenser/liquid return line sub-assembly is fabricated, tested, and mated to the evaporator/compensation chamber sub-assembly. After leak checking, the LHP is ready for processing and performance testing.

LHP PERFORMANCE TESTING

For a spacecraft LHP, performance testing typically includes:

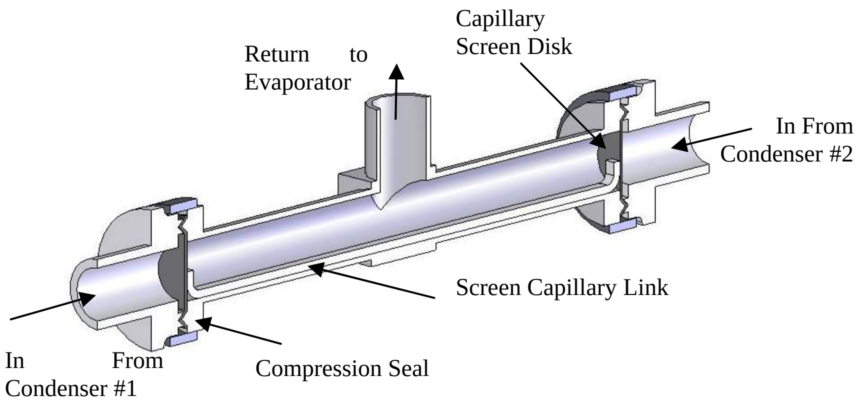

Figure 12. LHP Parallel Condenser Flow Balancer

- Low power start-up
- LHP shutdown by heating the compensation chamber
- Unbalanced condenser heating (for LHPs with more than one condenser)
- Transient power testing
- Condenser sink change transient tests
- Maximum power and LHP conductance

Low Power Start-Up: Historically, some loop heat pipes have been difficult to start at low power levels. This generally occurs when the evaporator grooves are flooded with liquid and the mass attached to the evaporator is large. In some cases, a low power input may simply warm-up the pump assembly very slowly and never create vapor to set up the pressure difference required to initiate circulation. Start-up heaters are installed on the LHP evaporator to prevent this problem. These heaters apply a large heat flux to a small portion of the evaporator grooves, initiating a vapor bubble that clears the grooves. During startup testing, the LHP is cooled down in a manner that maximizes the chances for the grooves to fill with liquid, and then restarted with the startup heaters.

LHP Shutdown: In some spacecraft applications, the electronics to be cooled operate intermittently. During the portion of the orbit when the electronics payload is turned off, it is desirable for the loop to stop transferring power to maintain the temperature on the payload deck and minimize the magnitude of the temperature swing of the electronics through an orbit. Typically, a working LHP will continue to transfer power from the evaporator to the condenser, until the evaporator and condenser temperatures are nearly equal. In many applications, this can occur during the coldest portion of the orbit.

A small heater is attached to the compensation chamber to prevent the LHP from over-cooling the payload when the electronics are not operating. When activated, this heater raises the saturation temperature and pressure of the compensation chamber. This in turn cancels the pressure difference that is required to circulate the sub-cooled liquid from the condenser to the evaporator, shutting down the LHP. During the LHP shutdown testing, this heater is activated and the performance monitored.

Unbalanced Condenser Tests: As discussed above, multiple condenser LHPs can have different sink conditions at each condenser. In some cases, the highest temperature condenser can be filled with superheated vapor. The unbalanced condenser tests verify that the parallel flow balancer can prevent this superheated vapor from entering the liquid return line.

In an unbalanced condenser test, the temperature of one condenser is rapidly increased to deactivate the condenser. The LHP operation is monitored to verify that the LHP continues to operate without failure or thermal runaway.

Transient Testing: Two types of transients have been shown by previous researchers to cause thermal instabilities or failures in LHPs:

- Power cycling
- Fast condenser sink changes

In the power cycling tests, the power supplied to the evaporator wick is increased and decreased in step changes, while the LHP performance is monitored. The second test rapidly changes the condenser sink temperatures. Both of these tests are designed to stress the LHP secondary wick. During steady state operation, the secondary wick transfers only a small amount of fluid, to make up for the parasitic heat transfer from the evaporator wick to the compensation chamber. During transients, the secondary wick must carry more liquid when the liquid returning from the condenser is inadequate. For example, when the power is suddenly reduced, the vapor flow from the evaporator is reduced, which in turn reduces the liquid flow supplied to the evaporator wick from the liquid return line. The secondary wick must supply the liquid that is no longer supplied from the liquid return line, until the system equilibrates. These transient tests verify that the LHP has an adequate secondary wick to hydraulically couple the compensation chamber to the primary wick.

Maximum Power and LHP Conductance: Finally, tests are conducted to determine the maximum power that the LHP can carry. These tests raise the LHP power in steps, and look for temperature increases that indicate dryout. At the same time, the LHP conductance is measured, which is the thermal resistance between the outside of the LHP and the LHP vapor.

Dussinger, Sarraf, and Anderson (2009) present the results of ground testing for a spacecraft LHP. After the ground testing of a spacecraft LHP, the LHP is integrated with the spacecraft. This is followed by a series of tests in a thermal vacuum chamber to verify LHP operation after it is integrated with the rest of the satellite thermal control system.

LHP APPLICATIONS

Compared to heat pipes, LHPs are more expensive. Applications to date have mostly been confined to spacecraft and aircraft, where the thermal performance benefits outweigh the cost considerations. Spacecraft radiators can only dissipate heat by radiation, which requires large radiator areas. LHPs allow the use of long condenser lines, effectively transporting the heat evenly across the entire radiator area. In addition, the radiator conditions change drastically, depending on whether the sun is shining on the radiator or not. These effects can be compensated for by applying a small heating or cooling load to the compensation chamber, allowing the electronics to operate at a steady temperature.

Most of the LHPs used in spacecraft applications to date have either ammonia or propylene as the working fluid, and operate in the temperature range from roughly -60ºC to 80ºC. The evaporator and condenser are generally fabricated from aluminum.

More recently, cryogenic LHPs for spacecraft systems have been developed. Many military satellites require an instrument, such as an infrared camera, to operate at lower temperature than the remainder of the satellite. One way to remove the heat is to use a cryocooler. However, vibrations caused by the moving parts of the cryocooler can disturb the camera. Cryogenic LHPs can isolate the camera from the cryocooler, through the use of long coiled lines. The coiled lines allow the heat to be removed across a gymbal, minimizing the torque required to operate the gymbal. Cryogenic LHPs have been fabricated over the temperature range from 100 K down to 4 K, using oxygen, nitrogen, neon, hydrogen, or helium as the working fluid.

Loop heat pipes have also been considered for a number of aircraft applications. A military aircraft can operate under high transient accelerations, typically ~ 9g. The high pumping capability of a LHP allows it to continue operating under these conditions. One aircraft application is anti-icing, where an LHP is used to transport engine waste heat to a location requiring anti-icing, such as the engine cowl. Another aircraft application is avionics cooling, while a third is aircraft actuator cooling. Some aircraft applications require LHPs that operate at higher temperatures than the maximum of 80°C with ammonia. A titanium/water LHP has recently been developed that operates at temperatures in excess of 260°C (Hartenstine, Anderson, and Bonner, 2008).

Electronics cooling could also benefit from LHP cooling. The LHPs could be used to remove heat from a board. The flexible lines can be routed between the evaporator and the condenser. Conventional LHPs are currently too expensive for general electronics cooling, however, work to develop lower cost LHPs is underway.

CONCLUSIONS

LHPs are two-phase devices that can passively transport heat over long distances relative to other passive two-phase systems such as heat pipes. Most of the art of LHP fabrication is in the primary and secondary wick. The manufacturing steps for an LHP are described, including test procedures for verifying proper operation of the wicks.

Once the LHP is fabricated, it must be tested. Testing for spacecraft LHPs includes low power starts, shutdown through compensation chamber heating, unbalanced condenser temperature tests, transient testing - both power cycling and condenser temperature changes, and maximum power tests.

To date, most LHPs have been used for spacecraft thermal control due to their ability to passively transfer heat over long distances to radiator panels, where the waste heat from the spacecraft electronics is radiated to space. LHPs have started to be used in aircraft applications. Lower cost LHPs are being developed for terrestrial electronics cooling.

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