Loop Heat Pipes and Capillary Pumped Loops – an Applications Perspective

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Abstract. Capillary pumped loops (CPLs) and loop heat pipes (LHPs) are versatile two-phase heat transfer devices which have recently gained increasing acceptance in space applications. Both systems work based on the same principles and have very similar designs. Nevertheless, some differences exist in the construction of the evaporator and the hydro-accumulator, and these differences lead to very distinct operating characteristics for each loop. This paper presents comparisons of the two loops from an applications perspective, and addresses their impact on spacecraft design, integration, and test. Some technical challenges and issues for both loops are also addressed.

INTRODUCTION

The use of two-phase thermal control systems such as Capillary Pumped Loops (CPLs) and Loop Heat Pipes (LHPs) has been increasing substantially in the last several years. They offer greatly increased heat transport capabilities compared to conventional heat pipes. There have been many publications on CPLs and LHPs with regard to their operating characteristics, with some comparisons of these two-phase heat transfer systems, such as Ku (1993,1997,1999), Maidanik (1997) and Cullimore (1998). However, these papers have focused on the detailed technical and analytical attributes of the systems, without an emphasis on their applications. There have been some publications addressing applications such as Baker (2001), Chalmers (2000), Ku (1998), and McIntosh (1999). However, these papers focused on specific applications, without addressing generic design considerations that apply to two-phase system implementation. This paper attempts to provide a guide to the attributes and limitations of these systems, including the requirements on the spacecraft builder for their utilization. A comparison of the two systems is also offered, to assist in the determination of which system is best suited for a particular application.

LOOP HEAT PIPE AND CAPILLARY PUMPED LOOP OVERVIEW

Both LHPs and CPLs are two-phase heat transfer devices that utilize boiling and condensation to transfer heat and the surface tension force developed by the wick to circulate the fluid. As shown schematically in Figures 1 and 2, each device consists of an evaporator, a condenser, a vapor line, a liquid line and a hydro-accumulator. The wick is required only in the evaporator and hydro-accumulator; the rest of the loop is made of smooth walled tubing. In the literature, the hydro-accumulator is usually called a reservoir in CPLs and a compensation chamber (CC) in LHPs. Both loops work based on the same principle: as the heat load is applied to the evaporator, liquid is vaporized and, at the same time, a meniscus is formed at the liquid/vapor interface in the wick. The surface tension force develops a pressure gradient that moves the vapor to the condenser where it condenses. The liquid is pushed back to the evaporator by the same surface tension force.

A major difference between the two loops is the construction of the evaporator and hydro-accumulator, and the physical location of the latter. In a LHP, the CC is made as an integral part of the evaporator, and is connected to the evaporator by a secondary wick. In addition, the CC is located directly in the path of the liquid flow. The reservoir in a CPL is usually located remotely from the evaporator and is outside the path of fluid circulation. Another difference between the two systems is that LHPs use a sintered powder metallic wick with pore sizes on the order of 1 micron while CPLs use a polyethylene wick with pore sizes on the order of 15 microns. As will be

discussed in the following section, these differences have great impacts on all aspects of the loop operation, including start-up, robustness, operating temperature, control heater power requirement for the hydro-accumulator, design flexibility, and loop deprime and recovery.

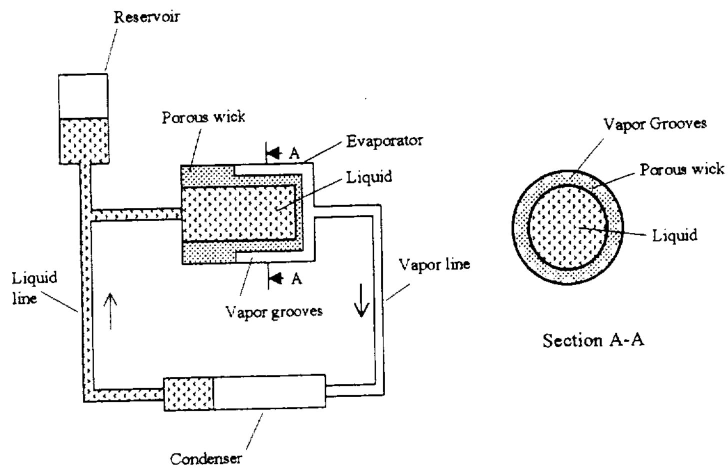

Figure 1. Schematic of a CPL.

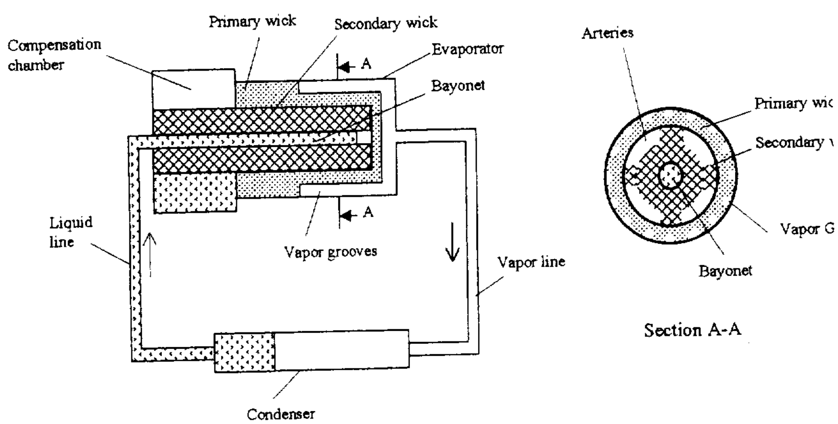

Figure 2. Schematic of a LHP.

DISCUSSION

There are a number of important parameters that have to be considered with the use of Loop Heat Pipes and Capillary Pumped Loops. The following discussion addresses some of these parameters and examines their impact on spacecraft applications.

Start-up and Starter Heater

Both systems generally require starter heaters to initiate flow in the loops to get them started. This is especially true if they are attached to a large thermal mass (i.e. instrument or electronics box) or they transport relatively low

amounts of power. A CPL requires pre-conditioning in order to ensure that the wick is wetted prior to applying power to the evaporator for start-up. This involves pre-heating the reservoir to "prime" the evaporator pump and collapse any vapor bubbles. In contrast, the LHP can self-start by applying power directly to the evaporator without pre-conditioning. However, self-start does not necessarily imply a quick start-up. With a low heat load to the evaporator and/or a large thermal mass attached to the evaporator, the LHP start-up may take a long time, and incur a substantial temperature overshoot. In some cases, the LHP may not even start. The issue of CPL start-up with a large thermal mass is that a severe cold shock can occur when fluid circulation is initiated, that may lead to loop failure. To enhance the chance of start-up success, both CPL and LHP systems generally utilize starter heaters with power ranges from 30 Watts to 75 watts per loop, depending on the evaporator size and the attached thermal mass. Startups often take several hours before the flow circulation starts. Starter heaters are most effective if placed directly on the evaporator, with the maximum watt density possible. This will assist in creating the superheat necessary to start the loop

Reservoirs/Compensation Chambers

The hydro-accumulator, or chamber containing both liquid and vapor refrigerant is called the reservoir for the CPL and the compensation chamber (CC) for the LHP. It is used to control the system saturation temperature and maintain the proper fluid inventory in the loop. The CC for the LHP is an integral part of the evaporator, and connected to it by a capillary structure called the secondary wick. This arrangement typically provides for a more robust operation of the LHP compared to a CPL, since the secondary wick draws liquid directly from the CC to the evaporator. This allows it to operate with vapor in the evaporator core, which can cause an evaporator pump failure (deprime) in a CPL. However, the LHP CC location can be detrimental in that it has to be accommodated next to the evaporator, so space must be made available for it. Also, this arrangement also affects the LHP operating temperature as well as the control heater power requirement, which will be discussed in more detail in the next section.

The CPL reservoir is typically located remotely from the evaporator, usually on the radiator. This allows for a cold bias of the reservoir, and a fixed heat leak can be designed in so that the control heater power can be established definitively. The remote reservoir location also provides greater design flexibility and can allow the CPL to run at colder temperatures than a LHP for a similar environmental condition. However, an additional plumbing line is needed to connect the CPL reservoir to the evaporator

Loop Operating Temperature

Since the saturation temperature of the hydro-accumulator governs the loop operating temperature, any factor that affects the hydro-accumulator temperature will affect the loop operating temperature. Because its reservoir is located outside the path of fluid circulation, and it is cold-biased, the CPL can maintain a fairly constant operating temperature regardless of changes in the heat load or the condenser sink temperature. One exception will be a rapid flow of cold fluid into the reservoir during the start-up, known as the "cold shock", which can rapidly reduce the loop temperature, and in extreme cases, cause the loop to deprime. This occurs when cold liquid from the radiator is displaced into the reservoir at startup. The reservoir heaters will eventually return the loop to the control temperature, but it can take a few hours depending on the thermal environment and available heater power.

The Compensation Chamber in a LHP is located in the flow path, and its temperature is determined by the energy balance between the "heat leak" and subcooling of the returning fluid. Since the CC is directly attached to the evaporator, the heat that flows from the evaporator to the CC is known as the "heat leak." It directly affects the loop operating temperature, especially at low power levels with low flow rates, and can also affect the startup. Although LHPs are designed to minimize the heat leak, it is still a significant factor in LHP operation. Any change in the heat load and/or the condenser sink temperature will directly affect the CC temperature. LHP operating temperatures typically follow the well-known "U" or "V" shaped graph of operating temperature versus the heat load (figure 3). Further discussion of LHP performance characteristics is available from Ku (1999).

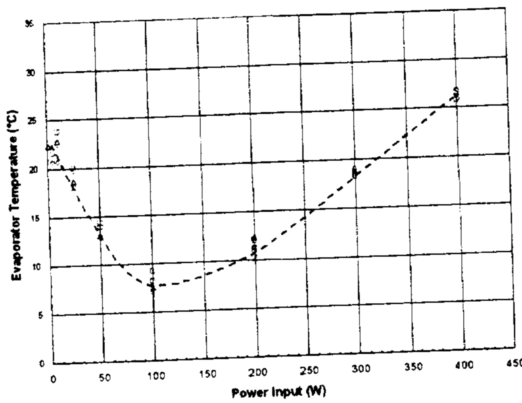

Figure 3. Typical LHP temperature profile.

Temperature Control

Many applications require control of the loop operating temperature, which is typically accomplished with the use of electrical heaters on the reservoir (CPL) or the CC (LHP). For CPLs, the reservoir is cold-biased and then heated to the desired temperature. For LHPs, temperature control is achieved by heating the CC to the desired temperature, which must be higher than its natural equilibrium temperature without the heater control. This means that the temperature can only be controlled to levels above the curve shown in Figure 3. In either case, thermostats can be used if the required control band is wide (in the 3 to 5 °C range). Tighter control (+/- 0.1 °C) has been demonstrated using electrical controllers with feedback circuitry, which typically requires a separate electronics box. These controllers have been uniquely designed for each application to date. (The development of a generic temperature control device would be beneficial to two-phase systems as well as other thermal control applications.) It should also be noted that CPLs always require a controlled heater on their reservoir for proper operation, while one is not necessary for LHPs when temperature control is not required.

Control Heater Power

As mentioned above, the control heater power for the CPL reservoir must be greater than its heat loss. The reservoir can be properly insulated such that the exposed area is big enough to allow the reservoir to be cooled to the low end of the operating temperature range, and small enough to minimize the heat loss. . Typical control heater power is on the order of 15 Watts. Additional heater power is needed to heat the liquid that enters the reservoir due to the cooling of the reservoir line. This is especially pronounced at startup, when there is a large displacement of cold liquid into the reservoir. There can also be some cooling during normal operation from the liquid displaced due to power changes in the loop, or oscillations that are typical of two-phase loops. Analysis of the additional power requirements due to the effects of in-rushing cold liquid is difficult. Therefore, sufficient margin in heater power allocated for reservoir control is needed, often relying on test data for accurate determination.

Determination of the control heater power required for the LHP CC is more complicated than that for a CPL reservoir (Ku, 1999). The control heater power for the CC must be able to overcome the liquid subcooling. Since the liquid passes directly through the CC, LHPs generally have larger control heater requirements than CPLs. In the case of a very cold sink and moderate evaporator power, the control heater power can be very large, on the order of 50 Watts or higher. Some innovative designs are being used to reduce the LHP heater power requirement. One design utilizes a conductive coupling between the vapor and liquid lines to preheat the returning liquid, analogous to a regenerative heat exchanger (Baker,1999). Another design utilizes a Variable Conductance Heat Pipe (VCHP) to conduct heat from the evaporator to the liquid line (Swales, 2001). These designs have reduced the control heater power to the 10 to 15 Watt range. Again, a large margin is recommended for control heater power, with test data needed as well.

Radiator (Condenser)

The radiator should be sized to accommodate the maximum heat load at the worst case hot, end of life conditions, with at least 10 C of subcooling on the returning liquid, and a suggested area margin of 15%. If the condenser can dissipate the maximum power applied to the evaporator, temperature control can be achieved over the full range of the heat load. On the other hand, if the condenser heat dissipation capability is exceeded, vapor will flow back to the evaporator. For the CPL, the presence of vapor bubbles in the evaporator is detrimental, resulting in eventual deprime of the loop. This means that if the radiator cannot reject the entire heat load, a CPL will fail. One advantage of LHPs over CPLs is that when the condenser is fully utilized, vapor will flow back to the evaporator and CC, automatically raising the CC temperature. Even though the temperature control feature is lost, the loop can continue to function. The LHP will increase in temperature, but continue to run.

Loop Shutdown

One of the greatest attributes of both of these systems is the capability to shut them down when they are not needed (diode action). This occurs when the power dissipating instrument or equipment is powered down, such as when the spacecraft enters a survival mode. The shutdown capability can provide a large savings in heater power. One of the best methods to accomplish the loop shutdown is with the use of a heater on the reservoir or CC. If a heater is already employed for temperature control, it can also be used to shut down the loop simply by raising the loop temperature and flooding the loop. However, this requires that the power to the evaporators be removed first. Other methods of loop shutdown include valves or heaters located on the liquid line.

Pumping Capability

The pumping capability of the two-phase loop is determined by the pore diameter of the wick material utilized in the evaporator, and is calculated from:

$$\Delta P = 2\,\sigma/r \tag{1}$$

where σ the surface tension force of the working fluid and r is the radius of curvature of the meniscus at the wick. To date, CPL systems have utilized polyethylene wicks that have typical pore diameters in the 15 micron range, yielding approximately 3000 pascal (0.4 psi) pumping capability with ammonia at 20 C. Use of lower pore size metallic wicks in CPL evaporators has been problematic due to the high thermal conductivity through the wick, which leads to bubble generation in the core and deprime of the loop. LHPs typically utilize metallic titanium or nickel wicks with pore sizes near 1.0 micron, which produce a much higher pumping capability, 40,000 Pascal (5.8 psi) with ammonia at 20 C. The higher pumping capability has facilitated the use of propylene working fluid in LHPs, which has only 1/3 of the surface tension of ammonia. It is advantageous for applications where the condenser temperature can drop below the freezing point of ammonia (- 77 °C). With propylene, heaters are not required on the radiator because the freezing point of propylene (- 185 °C) is well below typical sink temperatures. However, startup transients can be more severe when the cold condenser fluid enters the CC, so additional heaters may be required on the CC.

Number of Evaporator Pumps

Currently only single evaporator systems are flight qualified for both CPLs and LHPs. As demonstrated in ground testing, implementation of LHPs with more than two evaporators will be problematic due to the integral coupling between the evaporator and the CC, and the fluid volume requirements. CPLs can utilize more than one evaporator as long as start-up issues in microgravity are properly addressed. The CAPL 3 flight experiment, currently manifested for November of 2001 will provide a flight verification of a system with four evaporators and a starter pump (Ku, 1998). A multiple pump system provides multiple heat acquisition sites in a single loop, and can provide heat sharing, which is the capability to remove heat from an evaporator as well as add heat to it. This can significantly reduce heater power requirements as it allows redistribution of "waste heat" to equipment, which

would otherwise require additional heater power. A multiple pump system can function as a "central utility" for the spacecraft, whereas single pump loops are analogous to smaller "room size" units.

Transport Lines

Both LHPs and CPLs utilize transport lines for the liquid and vapor flowing between the evaporator and the radiator. They are typically smooth walled, standard stainless steel lines ranging from 1.6 mm. (1/16 inch) diameter up to 12.7 mm. (½ inch) diameter, depending on the heat transport requirements. Unlike heat pipes, transport lines in CPLs and LHPs do not have wicks, which greatly facilitates their implementation on spacecraft. Determination of the line diameter is a compromise between the desire to keep the lines small in order to minimize weight and fluid charge, and the need to keep the lines large enough to minimize the pressure losses. The frictional pressure losses in the liquid line and vapor line are inversely proportional to the 4th and 4.75th power of the line diameter for laminar and turbulent flows, respectively. Thus, the pressure losses increase rapidly with decreasing diameter. Also note that additional pressure drops occur in bends and transitions. A total system pressure drop analysis is required for the use of a two-phase system, including all of the pressure losses in the condenser, evaporator, and lines. It is recommended that at least a 50% margin exist between the calculated maximum system pressure loss, and the wick pumping capability (equation 1).

As previously noted, CPLs require an additional transport line from the reservoir to the evaporators. Furthermore, provisions have to be made to provide subcooling to the reservoir line to keep its temperature below the loop set point temperature so that bubbles are not introduced into the core of the evaporator and cause the loop to fail. The approach used on the Terra Spacecraft routes the reservoir line along with the liquid line, with a controlled thermal coupling between them. The subcooled liquid from the liquid line provides the necessary cooling for the reservoir line. More recently, an intriguing design which utilizes a reservoir line that is imbedded in the liquid line, has been employed for the upcoming Hubble Space Telescope (HST) CPL system (McIntosh 1998). This not only reduces the number of transport lines, but also provides direct subcooling to the reservoir line.

Careful attention has to be given to the thermal environment of the transport lines and reservoir lines (in the case of the CPL). It is recommended that the transport lines be insulated if possible. If the loop operating temperature is below the temperature of the surroundings, there will be a low power limit related to the minimum flow rate required to achieve the necessary subcooling on the working fluid as it enters the evaporator. This is true for both LHPs and CPLs, although it is more critical for CPLs. If CPLs loose subcooling, the loop can fail, whereas a LHP will just increase its operating temperature (although it may no longer be able to maintain temperature control). Again, careful analysis and testing in the anticipated Spacecraft environment is needed.

Adverse Height and Tilt considerations

CPLs and LHPs offer at least two orders of magnitude improvement in heat transport capability compared to traditional heat pipes and VCHPs. They also perform much better when considering adverse heights and tilts, which is important during the Spacecraft integration and test phase. In ground testing, heat pipes are generally limited to an adverse tilt on the order of 0.25 cm. (0.1 inch). Most CPL and LHP systems function with adverse tilts of 0.6 cm (0.25 inch) in any direction. CPLs can operate with the evaporator more than 25.4 centimeters (10 inches) above the condenser, and LHPs have been successfully tested with the evaporator located more than 3 meters (10 feet) above the condenser. Both systems work in the reflux mode (condenser above the evaporator), but they can also act as thermosyphons in this mode even when they are supposedly shut down, due to gravitational effects on the fluid. To insure that inoperative loops are shut down, the reservoir or CC temperature will have to be increased above the evaporator temperature.

Analysis Requirements

The state of the art of the analytical capability for two-phase systems seriously lags the capability for traditional passive thermal control systems, which are based on radiation and conduction heat transfer. This is due to the

relatively recent implementation of two-phase devices, lack of funding for the effort, and most significantly, the complicated behavior of the two-phase system. Stand-alone models of CPLs and LHPs exist, but implementation of a turnkey two-phase model with a Spacecraft SINDA model has yet to be developed fully. Steady state analyses are relatively straightforward, but transient analytical techniques still require development, especially related to system start-up. Some of the parameters that must be considered in the analysis of two-phase systems, along with recommended design margins are:

1. Pressure loss/Pumping capability – system pressure loss calculations per section 7 above, 50 % margin recommended.
2. Radiator capability – Heat rejection margin (15 % recommended) + 10 C of subcooling on the returning liquid.
3. Spacecraft internal environment – Effect on transport lines and the CC
4. Adverse Height – ground testing requirements
5. Startup Conditions – effect on startup time and power needed
6. Control Heater Power – how much power will be needed

It is recommended that the analysis of two-phase systems be performed by personnel experienced with this type of work.

Spacecraft/Instrument Integration

Spacecraft or instrument integration can be greatly facilitated with LHPs or CPLs, especially compared to conventional heat pipes. The use of flexible lines for part of the transport lines offers ease of integration, capability for deployable radiators, and mechanical de-coupling of the radiator from the remainder of the loop. This reduces the tolerance issues of the transport line locations and allows them to be routed around other Spacecraft equipment. This ability to accommodate change is especially useful later in the design process when equipment must be relocated. Another significant advantage is that the flex lines provide mechanical de-coupling of the radiator or other components from the remainder of the spacecraft, which reduces mechanical loading (CTE effects, vibration, etc.) in these areas. The flex lines also facilitate the use of deployable radiators, which can double the effective radiator area, and reduce weight. In addition, two-phase systems allow greater design flexibility in locating high power dissipating equipment. This equipment does not have to be located directly on or near to a radiator. One concern with two-phase loops during integration and test is that additional safety considerations are needed due to the refrigerant, usually ammonia or propylene. These are important concerns, but can be accommodated with proper planning. Also, the amount of refrigerant is usually no more than a few pounds for loops rated up to a few kilowatts.

Test Considerations

As stated previously, LHPs and CPLs offer much greater test flexibility than heat pipes, due to a much a larger pumping capability and static wicking height capability. Nonetheless, there are several issues that should be kept in mind for the test program. If the application differs from previous LHP or CPL applications, a high fidelity engineering development unit is highly recommended. This is particularly true for applications where there is a large thermal mass, extreme thermal environments, or power ranges and temperature ranges not previously tested. Thermal vacuum tests of two-phase loops are also highly recommended, since ambient tests of the loops do not accurately reflect the thermal environment that the loops will be exposed to. For example, startups can be significantly affected by cold condenser temperatures which can only be reached in thermal vacuum tests, and low power tests are affected by parasitic losses experienced in ambient testing (Baker, 2001).

Another consideration is the test configuration of the loop(s) after integration with the spacecraft. Both CPLs and LHPs have some limits on wicking height and extreme tilt situations. The Spacecraft TV test should include operation of the loops and accommodations have to be made in the test program to allow for this. Also, provisions for separate ground cooling lines may be required in order to test an item during its assembly and checkout on the ground, if it is impractical to do so using the two phase loop. Typical cold plate designs include provisions for separate cooling lines that are hooked up to a chiller to facilitate testing during the integration phase.

CONCLUSIONS

While there are a number of issues related to the implementation of two-phase systems, they do offer a substantial increase in capability. They provide a great deal of design flexibility, allow tight temperature control with minimal heater power requirements, and enable missions at lower power and weight levels (and cost) that would not be possible with conventional designs. This is demonstrated by their selection for spacecraft applications by a number of designers. Although CPLs and LHPs function under the same basic principles, differences in their design lead to different operating characteristics, which affects their potential uses. By comparing the similarities and differences of the two systems, it is hoped that this paper will help to identify these issues and raise the awareness of them to the spacecraft community.

DISCLAIMER

The opinions expressed in this paper are solely those of the authors and do not represent an official endorsement from NASA or the thermal engineering community.

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