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Review of "cold shock" cases in operation of loop heat pipes and related thermal instabilities

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Abstract. Loop Heat Pipes (LHP) are passive two-phase heat transfer devices, driven by capillary pumps that source energy for circulation of working fluid solely from the heat source. They have a proven track record in spacecraft thermal control as well as terrestrial applications. However, LHP may experience partial or complete wick dryout and thermal instabilities at rapid power-up steps or (and) rapid condenser cooling conditions change due to a rapid inflow of subcooled liquid from the condenser into the evaporator. Such cases do not have very wide coverage in literature and are usually presented as a little nuisance in testing of a particular LHP, for which some design workaround was found. Oftentimes suggested solutions trade performance or other design merits for robustness of operation. This article aims to review such case studies where phenomena similar to the described "cold shock" affected LHP performance. The aforementioned instabilities become even more pronounced in grid-like multievaporator LHP having multiple parallel connections between capillary pumps and compensation chambers, as heat and mass transfer between those elements becomes less definite and can eventually increase the heat leak into compensation chambers. Vulnerability of LHP with distributed network of evaporators to seemingly "safe" transient regimes fosters deeper analysis of the "cold shock" phenomenon. With comprehensive definition to the problem and a list of research questions, technical measures for getting rid of it in perspective LHP designs can be foreseen.

1. Introduction

Two-phase heat transfer systems are used for thermal control wherever mass, compactness, high heat flux density, and passive, maintenance-free operation is of great value. An example of such systems is Loop Heat Pipe (LHP). The LHP design (see figure 1) stems from a conventional heat pipe with the difference that capillary pump (primary wick) is localized in evaporator, while liquid and vapor transport lines are completely separated. LHP necessitates a reservoir (called compensation chamber, CC), that lets the device adapt to different working temperatures and loads by maintaining vapor-liquid equilibrium when more (at higher heat loads) or less (lower heat loads) liquid is contained in the CC. Despite having a track record in space applications (see [1]) and emerging terrestrial applications (like the consumer electronics [2]), the ongoing research still concerns LHP design and modelling aspects. It is still challenging to model how a particular LHP will respond to changing conditions in heat power or temperature.

A few design features of LHP need to be explained for further consideration. The evaporator (oftentimes cylindrical for containment of high-pressure fluids, but could also be a flat one) consists of a primary wick inserted into evaporator envelope with thermal interface to the heat load. In the core of the wick, there is a bayonet line that is a continuation of the liquid line that went through the CC and cools down the core of the evaporator, although this is not a mandatory part. Between the bayonet and the primary wick, a secondary wick is laid to make a capillary connection between the CC and the primary wick. The secondary wick has larger pores and feeds the primary one during startup and at transients. Vapor collecting grooves are made on both the outer and the inner surface of the primary wick. The outer ones collect the vapor and lead it to the vapor line to transfer the heat away from the heat source. The inner ones are necessary for vapor bubbles emerging due to heat leak through the primary wick that must be vented out to the cold CC [3].

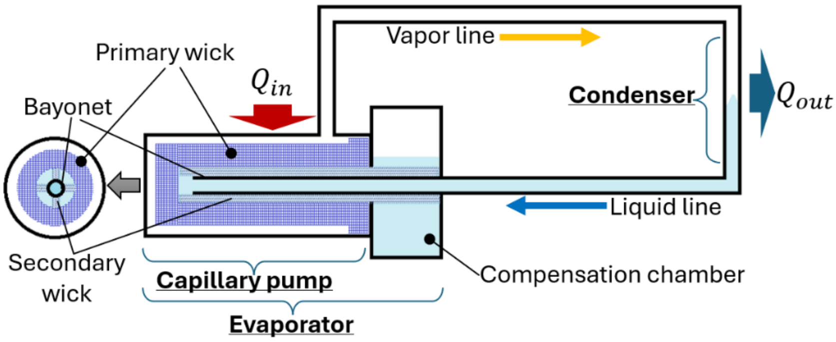

Figure 1. LHP schematic.

Presence of the secondary wick and a proximate location of CC to the evaporator give LHP a self-service feature, making startup possible regardless of LHP orientation and liquid-vapor distribution. However, it also provides a path for parasitic heat leak from the evaporator into the CC. Under normal operation the heat leak is below 10% of the heat load applied and is compensated by the subcooled state of the liquid coming from the condenser.

2. LHP problems in transients

[4] reported “cold shock” instabilities of >1kW LHP designed for space application. Momentary temperature overshoots at power steps up were explained by a rapid inflow of cold liquid into CC that created excessively high pressure drop between the evaporator and the CC, that stalled the fluid flow to the evaporator, and also created an excessive pressure drop between the vapor side of the capillary pump and the liquid side, allowing for total or partial wick dryout. Liquid temperature in the CC showed a decrease right after the power increase. The design was modified to limit the amount of subcooled liquid provided by the condenser and it was demonstrated to decrease the cold shock appearance in the CC.

[5] studied a small-scale LHP transferring up to 80W. At power steps up (like 30W to 60W) evaporator temperature showed a little overshoot that the authors attributed to the momentary primary wick starvation at the power increase and possible vapor penetration through the wick into the liquid side. The increase of the thermal mass at the hot side helped to avoid this behavior.

Another kind of thermal instability denoted TFO (thermal-fluid oscillations) was observed in a high-power (>1kW) LHP operation during power steps up (like 600 to 800W) [6]. A test setup with differential pressure transducer across the evaporator showed limitations of the secondary wick to supply the flow and causing repeated flow stagnation during those transients. A thin-tube bypass line between the vapor and liquid lines near the condenser was tested at both high-power steps up and down. It helped to reduce pressure and flow shocks and decreased requirements for the secondary wick operation.

In LHP testing transients usually denote change in external factors, like heat source power, heat sink temperature and alike. A LHP under test may respond to that independently from the operation history or show some sensitivity to that, denoted as hysteresis. [7] studied exactly that with a LHP of flat evaporator, but have encountered a situation when LHP evaporator temperature changed during a rather steady operation after a startup (see figure 2). Thus, the LHP showed at least two stable states and transitioned between them on its own, seemingly in dependence from the vapor-liquid distribution within CC and evaporator (see the differing charges of the LHP).

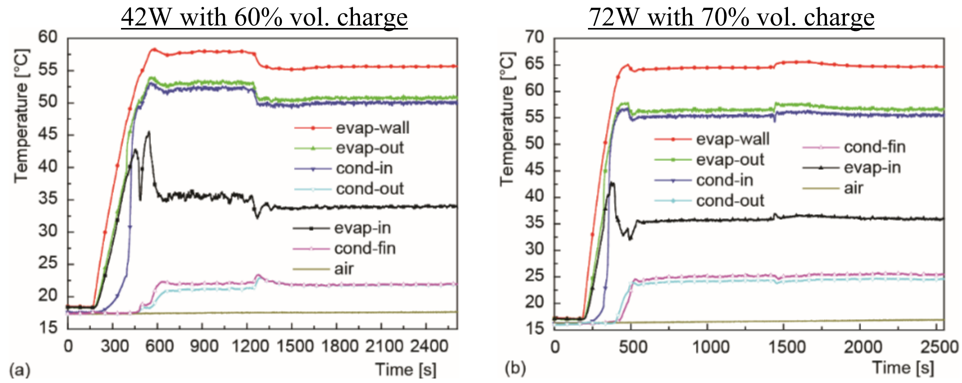

Figure 2. LHP switches from one stable condition to another one at steady operation (from [7]).

Experimentation with different LHP topologies does not end with shape of evaporator, but extend to combining multiple evaporators, CC and condensers in one system. Despite a long track of seemingly successful experiments on connecting various CC-evaporator units in a common hydraulic circuit ([8], [9]), a recent testing of a more integrated design by authors of the present publication revealed yet another undesirable LHP behavior. The design (shown in figure 3) was made up of grid-like connections of multiple capillary pumps and CCs to form a single evaporator capable of effectively collecting heat from 250×250 mm^2 large area. The technology is still under development, so a brief description of the found phenomenon is given.

The evaporator assembly comprised a 2×3 grid of individual capillary pumps (CP), connected both in series and in parallel between each other and 8 CC. The ammonia-charged LHP comprised such an evaporator (mounted on a heated plate) and serpentine condenser under forced convection. An example of a rather strange behavior is shown in figure 4.

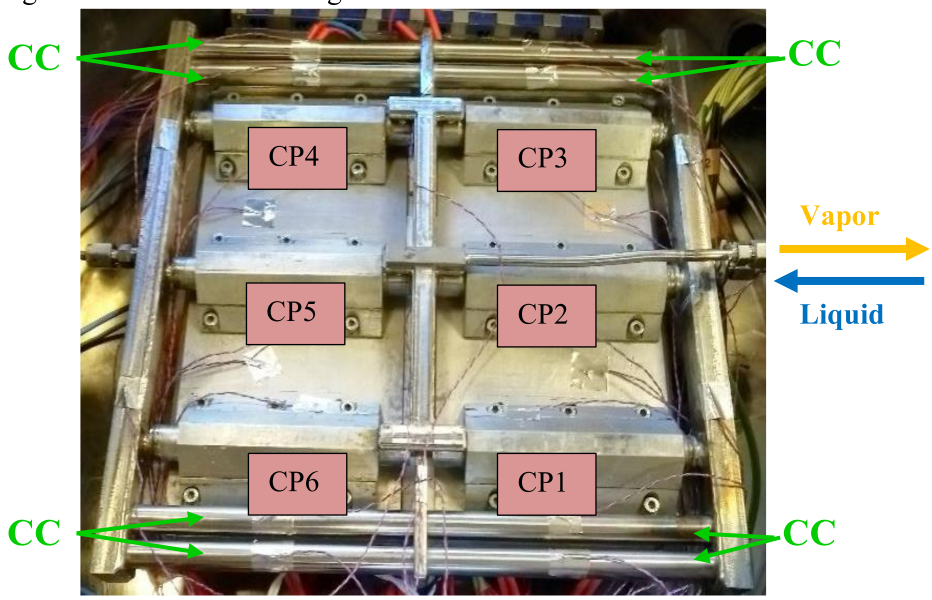

Figure 3. Evaporator with a grid of capillary pumps (CP) and compensation chambers (CC).

In the plot, the heat leak is estimated as $Q_{hl} = \frac{Q_{in}}{h_{ev}+c_p\cdot(T_{VL}-T_{LL})}$ and expressed as percentage of Q_{in}, where Q_{in} is the input power, h_{ev} – fluid specific heat of evaporation, c_p – specific fluid thermal capacity under constant pressure, T_{VL} and T_{LL} are vapor and liquid temperatures (measured at vapor and liquid lines). The LHP conductance [W/K] is calculated as $C = \frac{Q_{in}}{T_{EV} - T_{CD}}$ with T_{EV} measured under CP saddles and T_{CD} at the condenser. First, at 940 min the LHP showed a small, but distinct change in operation: vapor temperature increased a little together with the heat leak. However, at the power step down from 600W to 400W, the CP5 increased in temperature by several degrees. At the same time, there is a triple drop in conductance and duplication in heat leak fraction. Several CC reach the temperature of vapor line. In this regime LHP operated stably for at least 30 min, though with reduced performance. Together with trouble-free transfer of 800W (before 880 min), such a behavior was rather unexpected.

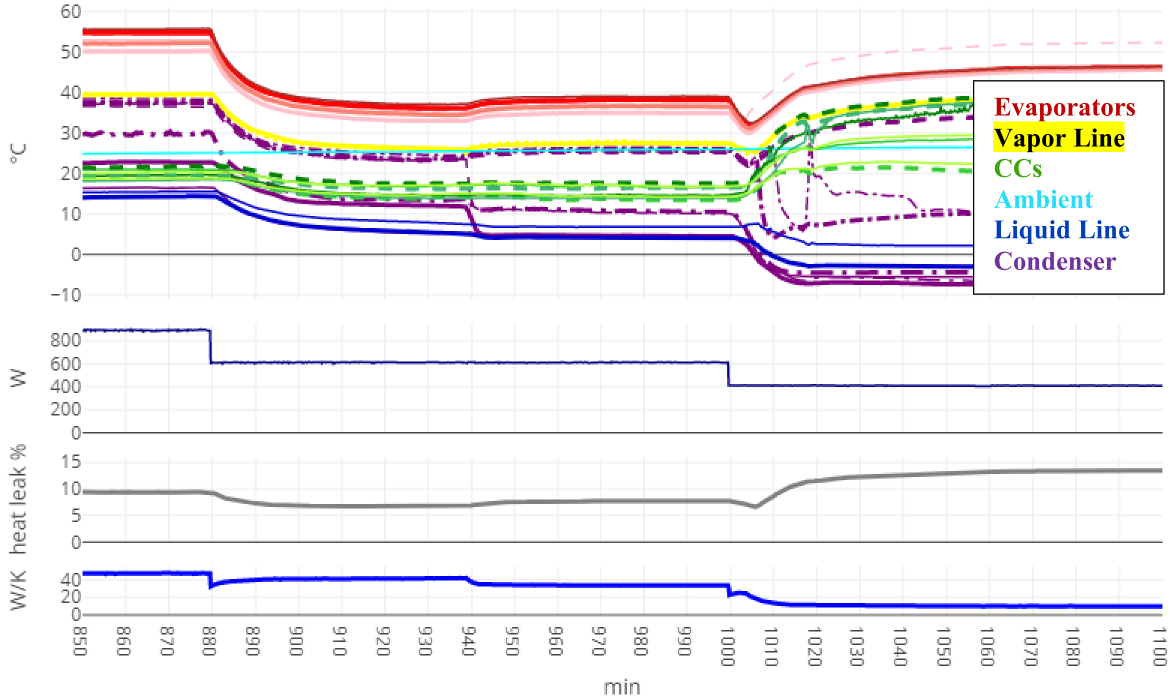

Figure 4. High heat leak encountered with a grid-like evaporator at step down in power.

3. Secondary wick design

Since troublesome operation cases occur during transients, it is clear that the secondary wick design has a large influence on the LHP ability to cope with these situations. Secondary wick design has been studied in a few works that are briefly reviewed here. The work of [10] defines the mass flow rates to be handled by secondary wick during transients and highlights that the use of a bayonet subcools the liquid in the evaporator core and suppresses the boiling, but in transient regime all the CC-condenser fluid transport happens through the secondary wick. In a bayonet-free design, the CC can exchange fluid with the condenser directly, but the secondary wick arrangement has to tolerate boiling in the evaporator core. Although authors of [10] specifically underline that evaporator-CC connection is not a heat pipe, HP model was used for secondary wick analysis in [11]. Moreover, researchers in [12] applied empirical approach to assess secondary wick design for LHP by constructing and testing it within a HP.

[13] developed a proprietary solution to estimate secondary wick requirements for stress cases:

- Stagnation of liquid line flow during power reduction or sink temperature reduction, so that only secondary wick sources the liquid to the primary wick
- When vapor travels from the condenser up to the CC and condenses there, the excess liquid must be evacuated from the CC by the secondary wick

No similar requirements are found for vapor transport capability between evaporator core and the CC.

In [14] analytical expressions are derived for the maximum feasible pore size of the secondary wick in the cylindrical evaporator, which looks like (simplified):

$$r_{sw} \leq \frac{\sigma + \sqrt{\sigma - (P_{pwc} - P_{cc}) \cdot C}}{P_{pwc} - P_{cc}}$$

Here r_{sw} – secondary wick pore size, σ – surface tension at vapor temperature, P_{pwc} and P_{cc} are fluid saturation pressures at temperatures of the primary wick core surface and the CC. The C term combines effects of fluid properties, flowrate and geometry of the secondary wick. This relationship shows that if $T_{cc} \ll T_{pwc}$, like if the CC gets cold well ahead of the evaporator, the secondary wick requires finer pores. This also demonstrates the influence of the heat leak due to primary wick conductivity, as it raises T_{pwc}. Furthermore, if the LHP primary wick produces high pressure difference ΔP to circulate fluid in the loop, then the secondary wick must have pores fine enough to tolerate high temperature differential between the evaporator and the CC. It is remarkable that when the secondary wick is omitted from the consideration, like in [15], the conclusions may say that active cooling of the CC improves the LHP startup, while experiments showed that LHP may fail to start with externally cooled CC, like in [16].

4. Core boiling

Challenge of understanding processes at the LHP evaporator partially lies in the two-phase processes happening at the evaporator (capillary pump) core. [17] demonstrated with a CC made transparent that LHP can operate with continuous stream of bubbles from evaporator into the CC. In [16], a series of experiments was conducted on hybrid CPL (capillary pumped loop) /LHP device with a borescope inside the evaporator. Observations included both continuous stream of bubbles from the evaporator into the CC and explosive onset of uncontrolled bubble stream at high heat loads that was attributed by author to breaking the capillary limit of the wick.

An even clearer picture of core boiling was obtained by [18] with both evaporator and CC being transparent (and no secondary wick). The formation, growth and transport of bubbles caused significant redistribution of liquid front inside the evaporator and CC alike, but no operation instabilities were observed. [19] developed a numerical steady state model of nucleate boiling inside the evaporator core. They have demonstrated the difference between convective heat leak and heat leak with liquid boiling inside the core, with the latter having good agreement with experiments involving direct visual observation of boiling in the core. A parametric study demonstrated as well that use of less conductive wick or fluid with high latent heat of evaporation limit the onset of core boiling.

5. Conclusions

Experimental research on LHP continues to reveal previously unseen or unexpected features, especially in transient operation. One such phenomenon is high heat leak regime, which was observed while testing LHP with evaporator made of multiple capillary pumps. It was very pronounced in that kind of LHP architecture, but some researchers have already noted that, under the same conditions, LHP may have differently looking operation modes, and this is related to liquid-vapor interaction within the evaporator.

Internal processes in the evaporator where bayonet, primary and secondary wicks come together, are difficult to set apart by temperature measurements. A borescope arrangement is cumbersome, while non-intrusive see-through techniques such as radiography requires expensive equipment.

LHPs are self-stabilizing systems, but stabilization means rearrangement of liquid and vapor phase. These processes are not instantaneous and may lag behind the changes in external conditions that affect temperature and (or) flow. If the lag becomes too significant, the LHP may fall out its operation domain and stagnate, without a way to recover. Even though novel LHP architectures emerge, a simple solution is sought after to make classical LHP resistant to shocks encountered in real applications.

A concise theory is needed for two-phase heat and mass transfer at evaporator core. This theory should be used for design specification of all the intrinsic features of the evaporator core, including:

1. Secondary wick (for this, a good amount of research work was done)
2. Non-wick part of the core (where both liquid and vapor transport takes place)
3. Bayonet with regards of liquid distribution and heat exchange with the core

Also, nonstationary heat and mass transfer inside of CC has to be well understood and modelled since it has direct impact on LHP proper operation in extreme transient cases.

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