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A METHODOLOGY FOR ENVELOPING RELIABLE START-UP OF LHPS

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ABSTRACT

The loop heat pipe (LHP) is known to have a lower limit on input power. Below this limit the system may not start properly creating the potential for critical payload components to overheat. The LHP becomes especially susceptible to these low power start-up failures following diode operation, intentional shut-down of the device, or very cold conditions. These limits are affected by the presence of adverse tilt, mass on the evaporator, and noncondensible gas in the working fluid. Based on analytical modeling correlated to start-up test data, this paper will describe the key parameters driving this low power limit and provide an overview of the methodology for predicting a "safe start" design envelope for a given system and loop design.

The amount of incipient superheat was found to be key to the enveloping procedure. Superheat levels have been observed to vary significantly based on evaporator design and even from unit to unit of identical designs. Statistical studies of superheat levels and active measures for limiting superheat should be addressed by both the hardware vendors and the system integrators.

INTRODUCTION

The LHP requires a pressure difference across the wick in order to start. This pressure drop is related to the temperature differential across the wick in accordance with the Clausius-Clapeyron relation. With no flow in the system and no heat load on the evaporator, no pressure or temperature gradient will exist across the evaporator wick. As heat is applied to the evaporator wall, a temperature gradient will develop across the wick, thus allowing the system to start pumping. For very low heat loads into the evaporator, the conductive paths to the compensation chamber and through the metal wick become dominant and the ability to achieve the temperature gradient required for start-up becomes elusive. This is evident in the characteristic LHP performance curve (loop temperature drop vs. heat load) in which the curve depicts an increase in the loop temperature drop at low powers. In the presence of adverse tilt (evaporator at a higher elevation than the condenser[*]) the required pressure/temperature gradient increases significantly making startup difficult at low powers. The reader is referred to reference 1 for more information regarding the behavior of LHPs.

[*] Adverse conditions are often difficult to avoid during ground operations such as thermal balance testing and possible launch pad operations.

The primary purpose of this effort is to establish the "safe envelope" under which these devices can be started passively. This envelope can be used by the system integrator to aid in design risk mitigation by insuring that if the system were to start under the worst case scenario (coming out of diode operation, or post-shut-down heating of the compensation chamber), the temperature of the electronics being controlled by the LHP will not exceed design limits.

Active measures can be employed to assist in the start-up. For example, a thermoelectric (Peltier) cooling device on the compensation chamber can be used to actively lower the evaporator core temperature thus allowing the LHP to start in a more reasonable amount of time, or with less initial power input. However, there are no guidelines for sizing and controlling this cooler. Establishing such guidelines is a secondary purpose of this investigation.

MODEL DEVELOPMENT

ANALYTICAL TOOLS

The application of analytical tools for modeling capillary two-phase transport devices has been very limited to date. Many developers and users of this technology have resorted to basic spreadsheet methods despite the fact they are limited in capabilities and are very design specific. These simplistic methods are not capable of assessing system-level integration issues or the hydrodynamic transient event of start up.

SINDA/FLUINT, the NASA-standard heat transfer and fluid flow analyzer (and its graphical user interface Sinaps*Plus),* is the most complete general-purpose thermohydraulic analyzer available. In addition, it is the only code that features special tools for dealing with capillarity and space and launch environments making it applicable both to detailed start-up transients and to top-level integration studies. SINDA/FLUINT provides tools for modeling the thermodynamic and hydrodynamic behavior of primary and secondary wicks, bayonet heat transfer, wick back conduction, in addition to the effects of mass, gas, and adverse tilt on startup. Reference 2 summarizes the SINDA/FLUINT capabilities applicable to various LHP design and simulation tasks.

MODEL OVERVIEW

The analytical model used in this effort was developed in Sinaps*Plus* and SINDA/FLUINT and required many of the features introduced in Version 4.1 (such as interface elements and dissolution and evolution of non-condensible gases). The goal of the analyses was to accurately simulate the effect on start-up of significant evaporator mass, adverse tilt and non-condensible gas in the loop. This required a transient hydrodynamic simulation to which the modeling of the compensation chamber and the evaporator wick were paramount.

The thermal side of the system was represented by a series of nodes representing the mass and the storage/release of energy, and conductors to describe how the energy is transported between nodes.

The fluid was modeled as a closed loop system using a series of lumps and paths to model mass transport, evaporation and condensation. Since we were interested in the transient behavior of the LHP and fluid inventory, tanks (control volumes which exchange energy with the thermal network) and tubes (lines with significant inertia) were used. In addition, advanced features such as capillary pumps, wicks (including capillary effects in the vapor grooves and liquid inertia in the wick), interfaces, non-equilibrium routines, and the dissolution and evolution of non-condensible gases were key to the model development. The model assumes a two-phase evaporator core and an ideal secondary wick. Network diagrams are depicted for both the thermal and fluid system in reference 3.

In order to develop a model capable of predicting LHP start up, the following features had to be captured in the analytical model. Reference 3 provides a discussion of each of these phenomena and how they are accounted for in the models.

1) Compensation chamber energy balance

2) Evaporator wick back conduction

3) Compensation chamber wall heat transfer coefficients. This is comprised of the heat transfer from the liquid to the wall and the vapor to the wall.

4) Vapor groove superheat.

5) Evaporator core superheat.

6) The effects of non-condensible gas present in the working fluid. The volume of gas present was assumed to be out-of-solution and present in the compensation chamber representing a worst case scenario for start-up.

7) Mass of the payload attached to the evaporator.

8) Adverse tilt (how high the condenser is above the evaporator).

Key to this development was the *preconditioning of the LHP prior to start-up in both the testing and the analysis*. Based on the adage, "you won't find failure if you don't try to create it" the system was intentionally preconditioned to create a worst case start up scenario: flooded vapor grooves. This condition has been identified as the most difficult for startup (reference 4).

To create this scenario in the test program, the compensation chamber was heated a minimum of 5 °C above the rest of the loop for a minimum of 30 minutes to ensure that all potential nucleation sites had been collapse. The heat load was then removed and when the compensation chamber temperature dropped to within 1 °C of the evaporator the heat load was applied to the evaporator.

CORRELATION OF ANALYTICAL METHODS

Parallel to the development of these analytical methods, both Dynatherm (reference 5) and Swales Aerospace (reference 6) conducted independent test programs to evaluate the effects of mass, tilt, and non-condensible gas on the startup of LHPs. Both contractors freely provided data for use in the development and correlation of the analytical models and methods.

The correlation effort for these models was comprised of two phases. First a top-level correlation of the system level parameters was performed. These parameters, (such as losses to the environment, wick back-conduction, interface conductances at the condenser and the evaporator mass) were correlated to steady state test results at various power levels using the automated data correlation techniques in SINDA/FLUINT.

The second phase of the correlation was more difficult since the remaining parameters had high uncertainties (such as internal film convection coefficients) or where stochastic (such as incipient superheat levels): they cannot be as easily measured or quantified through test. Rather, the parameters were qualitatively correlated based on trends of the transient behavior during LHP start-up. If a particular test proved successful, for example, the conditions under which this success could be duplicated in simulations were explored.

LHP STARTUP FAILURE

The two phenomena which cause LHP startup failures (defined as a failure to keep the equipment temperatures below their operating limits)[†] are:

1. *flooded grooves*: the inability to generate the temperature gradient across the wick required to cause nucleation in the vapor grooves, and

2. *circulation stall-out*: the inability to establish a high-conductance state and therefore to accept enough power to control payload temperatures. This case is often characterized by a failure to keep a minimum portion of the condenser open (assuming the vapor line environment is not cold enough to make condensation in that zone important). This is characterized

[†] Many technologists define a successful start-up strictly from an LHP perspective: boiling *did* occur, or the vapor line *did* clear, or a portion of the condenser *did* open up at least temporarily. Tests in which all three of these conditions were met can *still* be defined as a failure for an application if the LHP fails to achieve the required temperature control performance: if the payload overheats even temporarily or occasionally, the thermal control subsystem is a failure.

by the vapor front either in the vapor line or at the inlet of the condenser and the condenser flooded.

Note that neither of these definitions of start-up failure include the case where the LHP cannot keep the payload temperature below limits under steady conditions. Nonetheless, this seemingly obvious limit is mentioned here because (1) it is important for enveloping and (2) LHPs may actually start under such conditions, and therefore might be misrepresented as successful operating points simply because not enough time is allowed in test for the system to eventually overheat.[‡]

KEY STARTUP PARAMETERS

Several parameters were found to be intrinsic to the LHP startup process. These parameters are: the amount of heat entering the evaporator (which is not the same as the amount being dissipated in the remote and perhaps massive source); the amount of superheat required to initiate boiling in the vapor grooves prior to startup; the amount of superheat required to initiate boiling within the core of the evaporator; the static pressure head across the wick (adverse tilt); and the amount of non-condensible gas present in the compensation chamber. (Figure 1 depicts the various components of the LHP evaporator assembly.) These parameters determine the minimum temperature gradient that must be developed across the evaporator wick in order to start.

In any given system, the evaporator mass and the adverse orientation requirements (evaporator located above the condenser in a gravity environment) are known parameters. The amount of non-condensible gas at the end-of-life can be estimated, although considerable conservatism should be used in this estimate.

The degrees of superheat required to initiate boiling in the vapor grooves and the evaporator core are the only two unknown (and unknowable) parameters. Due to the stochastic nature of incipient superheat, its effect on startup over a reasonable range must be considered.

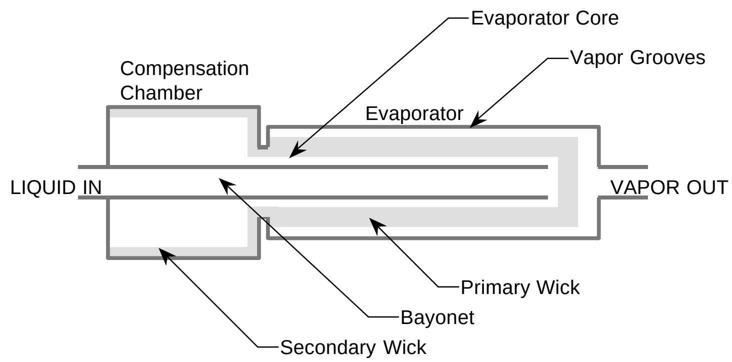

Figure 1: Depiction of LHP Evaporator

VAPOR GROOVE SUPERHEAT

Vapor grooves are usually flooded prior to startup if the system is coming out of diode mode or an intentional (commanded) shutdown.[§] They can occasionally be flooded if the LHP has been operating in a very cold environment. If the grooves are flooded, then when they are reheated the liquid within them may superheat somewhat prior to nucleation. The degree of superheat is technically defined as the liquid temperature minus the current saturation temperature (the equilibrium value at the current pressure) at the point of startup, but practically it can be measured as evaporator case temperature minus the compensation chamber temperature.

Many factors influence the degree of incipient superheat: case and wick materials and working fluids, temperature range (fluid properties), surface treatments and manufacturing methods, cleanliness, NCG, vibration level, prior history (how subcooled the grooves were and for how long), etc. Unfortunately, there is no way to predict the degree of superheat that will be experienced in any unit in any given circumstance. Values can

[‡] Again, this conflict occurs because of a technologist's definition of success ("the LHP worked") versus a system engineer's perspective ("it failed because it never achieves the required conductance for *this* application").

[§] This study focuses on single evaporator systems in single (nonparallel) systems. However, in multiple evaporator systems (such as reversible designs with two evaporators), any evaporator previously being used as a condenser will start from a flooded groove condition.

range from zero to about 12K (worst observed to date on ammonia LHPs and CPLs[**]).

At the low end (zero superheat), startup would be initiated at zero power and the LHP would be especially susceptible to circulation stall-out. Such a case is represented by operation at the left side (low conductance region) of the lower curve depicted in Figure 2.[††] In cases with low power into the evaporator (often much less than the rate of heat dissipation in the payload), startup is unlikely to generate sufficient flow to clear the vapor line, resulting in stalled flow and pressurization of the system (and continued heating of the payload).

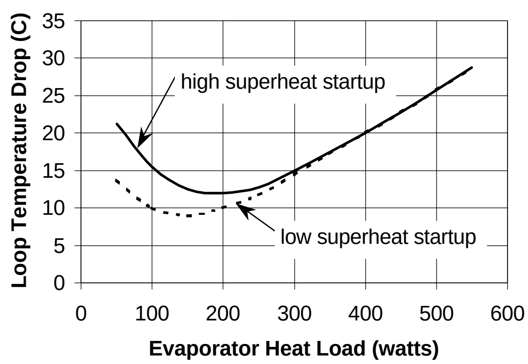

Figure 2: Phase Dependent Operational Curves of an LHP (NRL Loop Test Data, Reference 1)

At the high end of the potential range of groove superheat (12K), the payload will often overheat because it is very difficult to achieve the required temperature difference across the evaporator wick:[‡‡] the fluid in the grooves simply never boils.

At intermediate values (say 1-3K, which is a very common range in tests second only to zero superheat) the fluid in the grooves will probably boil if neither the attached mass or the wick back conduction are excessive. If this happens, the unit may fortuitously avoid the low power region (and therefore circulation stall-out) altogether if the sensible heat of the payload mass can "kick start" the LHP.[§§] In other words, if kick-started the LHP approaches steady state from a high power rather than a low power. For these reasons, *intermediate values of groove superheat are not conservative with respect to enveloping*: The upper and lower limits must be considered instead.

In the correlation tasks, the actual level of superheat for a given test was provided as an input to the models. For enveloping, both the minimum and maximum range must be used. Zero superheat is extremely common in tests and must be considered, but the high end is very rare. Because accommodating high superheat values will be extremely difficult (no valid envelope might result), a discussion of alternatives (including design considerations) is presented later.

CORE SUPERHEAT

Just as superheated liquid can persist in the vapor grooves, so can it persist within the evaporator core. Superheat limits on the evaporator core must be assumed similar to the vapor grooves (zero and 12K).

The result of core boiling without groove boiling is a temporary reversal of flow and is self-correcting with the onset of boiling in the grooves (until which time the payload continues to heat). Sustained

[**] This figure (12K) is anecdotal (authors' experience and memory) and should be checked with a literature survey and perhaps a dedicated test program since its value is critical to the enveloping.

[††] However, to be conservative the upper curve should be used. The upper curve results from harsh start-ups (with large superheats) and from previous operation at very high powers. It should be noted that the hysteresis effect noted in this figure is still being studied by technologists, and that its existence and magnitude are likely to be very dependent on the design of the LHP secondary wick and core.

[‡‡] This statement must be qualified for high temperature (say, >40C) applications since, as the saturation temperature rises, the actual degree of superheat required to nucleate will drop. By extension, however, low temperatures require even more superheat and thus low temperature applications (say, <0C) may require even more than 12K to nucleate. The 12K value comes from room temperature testing.

[§§] Even to the point of operating temporarily in a condition that cannot be sustained forever, as noted before.

vaporization in the core leads to pressurization of the loop more than flow reversal. (This was verified both by analysis and test.) In other words, no "credit" can be taken for significant heat removal in this reverse mode. If both the core and the grooves boil, as is usually the case, then the only concern is circulation stall-out.

When the core does not boil, then back-conduction is reduced by over an order of magnitude. In this case, boiling in the vapor grooves first becomes more likely (it is easier to develop the required superheat), and the unit is much less likely to suffer from circulation stall-out. *Start-up with a superheated core is not rare*, however it is metastable (may revert to a two-phase core with high back conduction). In this scenario, since the back conduction is so low, the system will operate with very little subcooling to the compensation chamber and potentially operate under a set of conditions (low power, etc.) which would normally result in circulation stall-out. This was observed in test under several occasions. In most cases, the core eventually nucleates and the performance of the LHP jumps to the upper curve in Figure 3.

Therefore, the worst possible scenario for start-up is precisely zero core incipient superheat creating increased potential for stalled flow and pressurization of the loop: back-conduction is maximized.

Despite not being an issue for startup enveloping, the persistence of core superheat after startup as evidenced in the test program*, is a concern* for the system integrator due to heater sizing in a cold case since the LHP operates with anomalously high conductance at low powers.

ADVERSE TILT

Adverse tilt (evaporator above condenser) generates a static pressure across the wick, and therefore a static temperature difference that contributes to back-conduction. Adverse tilt is primarily of concern for ground integration and test including system checkout and verification, thermal balance, pre-launch, vehicle spin and interplanetary missions. While adverse tilt has no effect on failure due to flooded grooves, it does increase the likelihood of failure due to circulation stall-out due to the effective increase in pressure drop across the wick for start-up. It also raises the loop operating point such that a minimum acceptable *steady* power will exist below which the loop conductance is inadequate to the task. Maximum adverse tilt is therefore conservative for the assessment of start-up.

NONCONDENSIBLE GAS (NCG)

Like adverse tilt, the presence of NCG causes an additional temperature difference across the wick that contributes to back-conduction. It therefore increases the likelihood of failure due to circulation stall-out, and may raise the loop operating point such that a minimum acceptable steady power will exist below which the loop conductance is inadequate to the task. Unlike adverse tilt, the presence of NCG *does* have an effect on failure due to flooded grooves: it makes that type of failure more likely as well. Maximum NCG is therefore conservative.

The amount of NCG is bounded by none and the maximum end-of-life (EOL) value. Limited data exists on the rate of gas generation within LHPs. An approximation can be obtained using a standard heat pipe rule-of-thumb of 2×10^{-7} gram-moles per year per gram of ammonia charge. However, given the uncertainties involved, significant factors of safety (perhaps an order of magnitude) should perhaps be applied to EOL NCG estimations. Furthermore, it is conservative to assume that all gas resides in the vapor phase (not adsorbed into metals nor dissolved into liquid) of the compensation chamber since that assumption maximizes back-conduction.

OVERVIEW OF ENVELOPING PROCESS

Start-up enveloping is not just a function of a particular LHP design, but also of its implementation in a particular application. Therefore the analytical tools for enveloping the startup process are somewhat unique for each LHP design and implementation. In addition system level factors must be taken into account with the modeling process such as payload mass and 1-g vs. 0-g performance. The enveloping process will require the development of multiple transient and steady state models. Some will be SINDA only models while others will require

SINDA and FLUINT. Due to the proprietary nature of the study, only an overview of the methodology can be provided here.

1) *Conductance Limit* - Determine the lower conductance limit of the unit in a hot environment. This will provide the minimum heat load below which the system will not operate reliably for any length of time while meeting temperature control requirements.[***]

2) *Flooded Groove Limit* - Determine the minimum power required to develop the maximum superheat across the wick before the payload allowable temperature limit has been exceeded. Note that in the case of NCG in the system, the superheat value will need to be augmented.

3) *Circulation Stall-out Limit* – Determine the minimum power required to locate the vapor front in the condenser region. Below a certain power level, the system will continue to warm up without the condenser opening.[†††] Above this power level, the loop will continue to increase its conductance, and the payload temperature will stop rising (and will perhaps drop). This threshold power level, which must be determined from a series of bracketing transient runs, becomes part of the operational envelope.

[***] Cases have been observed where the LHP *does* start below these thresholds if the evaporator core remains superheated liquid, drastically reducing the back conduction. Operation in this mode is metastable and can cease if the core nucleates or any void enters it. Core nucleation is characterized in a sudden and significant increase in the loop operational temperature. As noted before, the LHP can also be "kick-started" if sensible heating of the source mass causes the loop to overshoot the low power region, but this operation may not be sustainable at powers that are too low.

[†††] This assumes that the environment is not so cold that it can act as a sufficient sink for condensation in the vapor line.

DEALING WITH HIGH SUPERHEAT VALUES

It is anticipated that dealing with the 12K upper limit in superheat will be difficult, and that this criterion alone may render any LHP implementation invalid. Technologists and LHP vendors may counter that such conditions are rarely seen and should not be the basis for enveloping. After all, superheat itself is somewhat rare in LHPs and 12K is perhaps overly conservative. Unfortunately, "rarely seen" is not the same as "guaranteed not to happen." A failure in 1% of all starts can still lead to mission failure since superheat is not likely to diminish in a second try.

Therefore, this section describes potential means of dealing with high superheats.

REDUCING THE UPPER LIMIT

First, it should be noted that12K is a recommendation only, and this value should be revisited using a comprehensive literature survey and perhaps a dedicated test program using many samples. However, such a study could raise this factor instead of lowering it.

Second, if 12K (or whatever value is decided upon) represents an upper limit to observed incipient superheat, then it must be recognized to be a statistical limit: it would represent perhaps 2 or 3 standard deviations. A more detailed study of the distributions that can be expected might therefore reveal the degree of conservatism that is being applied with the given upper limit. In other words, a lower limit may be negotiated on the basis of taking a calculated risk.

DESIGN MEASURES

More likely, active measures will need to be taken to overcome an adverse start-up condition, perhaps not habitually but occasionally (autonomously detected or as a ground command option) in the event that a high degree of superheat is encountered.

Design measures that can be considered alone or in combination include:

1) Peltier (thermoelectric) elements to cool the compensation chamber, creating the required superheat not by heating the liquid but by lowering the saturation pressure. While it is doubtful that a large enough temperature difference can be created across the wick, this option has the unique advantage of also helping to overcome circulation stall-out (a separate cause of start-up failure that *is* more common). Furthermore, it can double as a temperature regulation heater in cold cases.

2) Starter heaters have been demonstrated (reference 7) with some success during development testing. These heaters are typically film heaters attached to the outer surface of the evaporator case. However this type of solution is not viable for all LHP integrations. In many situations, the evaporator case is not accessible (it may be embedded in a honeycomb panel, or embedded within the equipment) in which case you cannot install a heater directly on the evaporator case.

3) Button heaters (localized heating of an existing evaporator case) have been attempted before (on related capillary pumped loop evaporators) with no success because it is too difficult to concentrate heat: the extruded aluminum of the evaporator case spreads the heat too easily axially, circumferentially, and even radially (into the core)

4) An extended axial portion of the evaporator, thermally isolated from the attached mass (i.e., extending past the bond), and with a solid wick underneath (to avoid heating the core—the end of the wick is already solid to provide capillary sealing) could be created specifically for locating a button heater. The idea is to provide the high degree of superheat on the evaporator grooves without heating the core or the mass, and to provide a fluid pathway to the vapor grooves – perhaps simply an extension of the grooves themselves. Once vapor is pumped into a groove, superheat will not occur in that groove until it has again been flooded with subcooled liquid.

For LHP vendors to consider such design complications, they must first accept not only the existence of start-up problems, but they must also don a system perspective. They must use a more narrow description of start-up success, and they must realize the need to provide a guarantee of performance if not a quantification of the risks.

CONCLUSIONS

A methodology has been developed for predicting the safe envelope of start-up for LHPs. Due to the dependency on parameters such as mass, evaporator design, life, and gravity environments, the methodology and the analytical tools must be individually tailored for each system.

The combined test and analytic program was highly successful in showing the relative importance of the various phenomena involved, in interpreting test data, and in dynamically adjusting the test matrix as needed to locate the envelope of safe operation.

A key finding from this study was the impact of incipient superheat regarding the enveloping procedure. Superheat levels have been seen to vary significantly based on evaporator design and even from unit to unit of identical designs. Although high levels are not always seen, statistical studies should be performed to determine a reasonable upper limit. Further measures for limiting superheat should be addressed by both the hardware venders and the system integrators.

CONTACT

For more information on the modeling tools (SINDA/FLUINT and Sinaps*Plus*) or the development of analytical methods for modeling two-phase heat transport loops please contact Cullimore & Ring Technologies through their webpage at www.crtech.com or via email to info@crtech.com.

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