CAPILLARY HEAT LOOP TECHNOLOGY: SPACE APPLICATIONS AND RECENT CANADIAN ACTIVITIES

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Abstract

Capillary Heat Loops (CHL) are heat transfer designs with high-effectiveness, high-performance, high-reliability, high-flexibility, and anti-gravitation features of interest to the space community. At the Canadian space agency a project has been initiated since 2002 to develop an understanding of CHL technology. The technology is targeted towards the thermal control systems of miniaturized satellites.

This paper presents reviews of CHL modeling and space applications and introduces the recent development of Loop Heat Pipe (LHP) technology in Canada in the hardware development, application, performance testing, analytical prediction and numerical modeling.

KEYWORDS

Capillary Heat Loops, Capillary Pumped Loops, Loop Heat Pipe, Canadian Space Agency, Spacecraft Thermal Control.

INTRODUCTION

With continued drive to smaller spacecraft rendered through miniaturization technologies, there is a need to transport an ever-increasing heat flux density of variable heat loads and to offer autonomy in thermal control. Capillary Heat Loop technology (the term "Heat Loop" for identification of Two-Phase Loop with Capillary Pump heat transfer devices was first suggested by Gottschlich [1]) is capable of offering solutions in forms ranging from general thermal control to management of intense thermal loads and heat transport for multiple-payload spacecrafts.

CHLs were invented independently in the USA and the former Soviet Union. In the USA the device was called Capillary Pumped Loop (CPL) and was discovered in 1966 by Stenger from NASA/Lewis [2]. Gerasimov with co-workers from Ural Polytechnic Institute (Ekaterinburg, Russia) published the first article on Loop Heat Pipe (LHP) technology in 1974 [3]. Until the early 1980s CPLs and LHPs were developed in parallel. Both devices are Heat Loops with differences in specific characteristics and principle designs.

Because the use of CHLs as the primary elements of thermal control systems for both space and electronics applications is expected to rise steadily, it is crucial to develop Canada's expertise in this technology. In this context CSA has initiated research of the setting-up of a laboratory prototype of Loop Heat Pipe (LHP) technology. The aim is to demonstrate advantages offerred by LHP technology to Canadian missions and to incorporate them in the existing Canadian Thermal Analysis software TMG. The scope of the CSA LHP development was therefore limited to the engineering tests, analysis of the resulting data, comparison of theoretical, experimental and simulation results, comprehensive understanding, and hence engineering designs and applications for spacecrafts of future Canadian missions.

- Engineering tests: to understand the engineering performance and the key issues of application using LHP;
- Numerical simulation: to construct an industrial tool to simulate the thermal performance of a LHP, to offer LHP modeling capability, at both component and system levels, to the existing Canadian Thermal Analysis Tool (TMG);
- Correlation and verification: to correlate the results from laboratory tests and numerical simulation and hence verify the numerical modeling tool.

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REVIEW OF CAPILLARY HEAT LOOPS SPACE APPLICATIONS

Heat removal will become more important for future space missions as the requirements of power densities of electronics and the temperature control are increased. The design of the heat transport systems for such systems is particularly challenging because earth-based systems that rely on gravity do not often function properly in microgravity.

Today LHPs and CPLs are considered high priority thermal control technologies for aerospace applications. Large number of experimental and operational Heat Loops were successfully tested and used in several spacecrafts [4, 5]. Novel advanced technologies such as miniature LHP for electronic cooling [6] inversion (other names: reversible, and "Push-Pull") LHPs for two-directional heat transfer (Heat Loop is thermal diode by definition) [7, 8], multiple evaporators and condensers [9, 10], and ramified designs [11] for complex thermal control systems are all suggested and being developed at present.

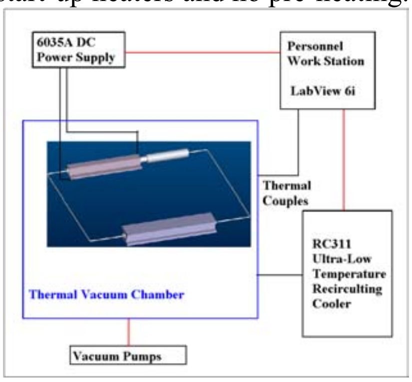
The extended review list of the experiments and applications of the Heat Loops in space can be found in the Appendix. This review is based on an updated version of the table recently presented in [12]. It has to be mentioned that there are at least 5 space missions with Heat Loops as the main thermal control systems which were developed, designed, tested and completely space qualified on the ground but did not operate in orbit due to different reasons: launch failure (Mars-96 (RKA) [13] and STENTOR (ESA) [14]); communications problems with spacecraft (FAISAT-1 [15]); sudden cancellation of the project just prior to flight (CHADOCC experiment with mini LHP and Brazilian mini CPL which were placed onboard the French -Brazilian Micro satellite in 2002 [16]); control computer failure (ESA experiment TPX II) during STS-95 mission in 1998 [17]).

It is clear from the Appendix that the experimental period with single evaporator Heat Loops for the mid range temperature operation (-40 to +70°C) is complete and now single Evaporator LHPs and CPLs successfully operate as a key elements of TCSs in a number of spacecraft. Some critical anomalies were reported for ICESsat (see Appendix No. 20) but this mission is special: there are no redundancy LHPs and the reason of the anomalies is most possibly small fluid leakage due to meteorite hit/penetration, cracked weld, etc. Current research and development efforts are directed in advanced Single (No. 19, Com2Plex) and Multi-evaporator Heat Loop designs and testing in microgravity. Notwithstanding that in the first space CPL (No. 1, 1984) and LHP (No. 3 1989) multi-evaporator designs were realized, this technology is still under qualification. However, recently, the very successful CAPL 3 (No. 15) experiment and ground testing results of novel 3-Evaporator LHP "Zmey Gorinych" (named after the Russian fabulous tri-headed dragon) [10] and 4-Evaporator miniaturized Advanced CPL [18] (authors call it hybrid LHP) hold out hope to accomplish spacecraft TCSs with multi-evaporator Heat Loops in the nearest future.

EXPERIMENTAL INVESTIGATION

An imported non-space qualified LHP from Russia (made by TAIS) was investigated at CSA. This LHP was integrated in a platform for the horizontal tests and installed in a Thermal Vacuum Chamber (TVAC), as shown in Figure 1. The construction of laboratory setting was described in previous work [53, 54]. The following conditions are maintained through the tests:

- Fixed thermal environment: the ambient temperature of 24°C,
- LHP was thermally insulated,
- Fixed sink temperatures,
- Fixed layout of device: horizontal so that the gravitation effects are minimized,
- Fixed pre-conditioning: the condenser is cooled for 90 minutes before start-up attempts,
- No start-up heaters and no pre-heating.



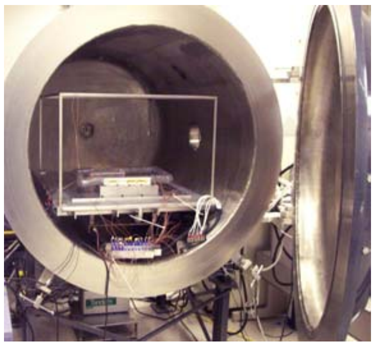


Fig. 1. Laboratory Test System of LHP

The first series of tests were conducted to validate the performance of this LHP by the steady state operations at constant sink temperatures and constant heat powers. The parameters examined were the device overall thermal conductance and the steady state working temperatures versus constant heating loads at fixed sink temperatures. The results were found consistent with the typical LHP devices. Figure 2 is the results at 13°C sink temperature of heating rate from a few Watts up to 400 W. The operational temperature hysteresis was observed in TVAC test for input power range of 5 W to 100 W (Fig 2-B).

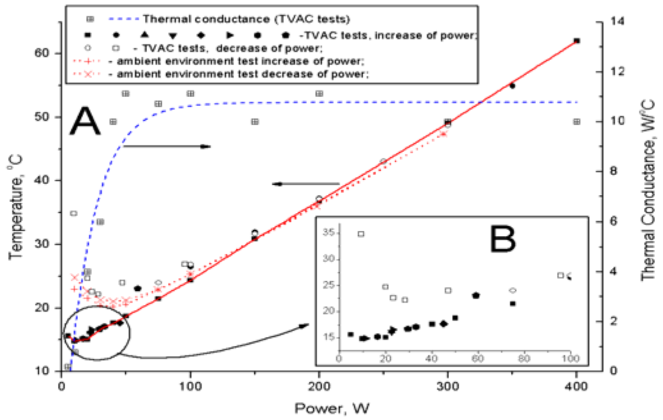
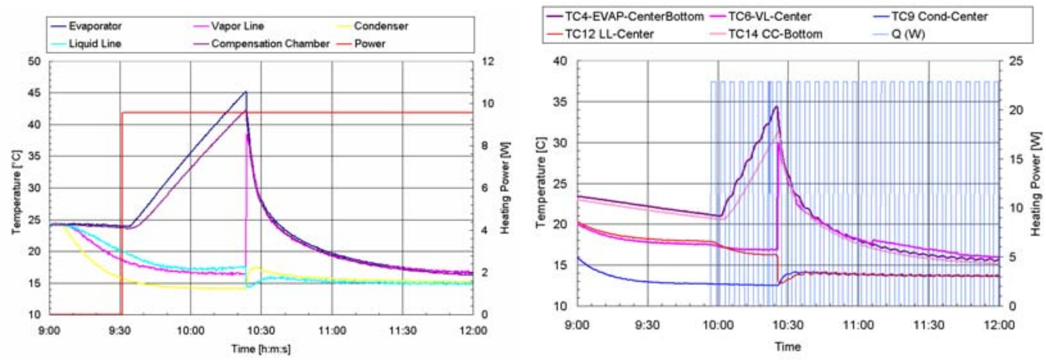


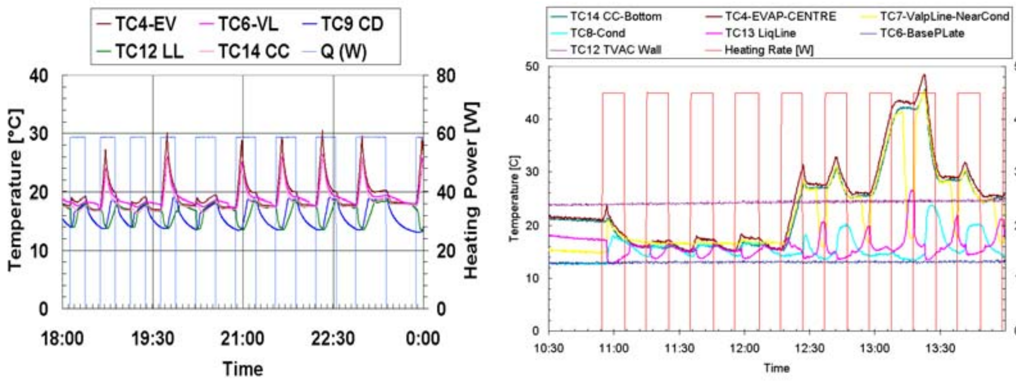
Fig. 2. Steady State Performance of LHP at Constant Heating Powers

Considering the special requirement of spacecraft thermal loads that are typically in short durations and variable rates, sequences of laboratory tests were conducted to examine the LHP performance with periodical heating loads with fully on-off cycles. There are some unconfirmed features found when the periodical heating loads were applied, which are not the same as that of constant heating rates. There were start-ups with varying evaporator temperature overshoots, varying heating cycle times, single or multiple cycles of heating periods. Some of the results were presented previously [54]. Figures 3, 4 and 5 show the performances of several selected cases: comparison of constant heating with periodical heating of small cycle times (Figure 3); steady and non-steady operations at repeating periodical heating cycles (Figure 4); multi-cycle start-ups in vacuum and atmosphere (Figure 5).



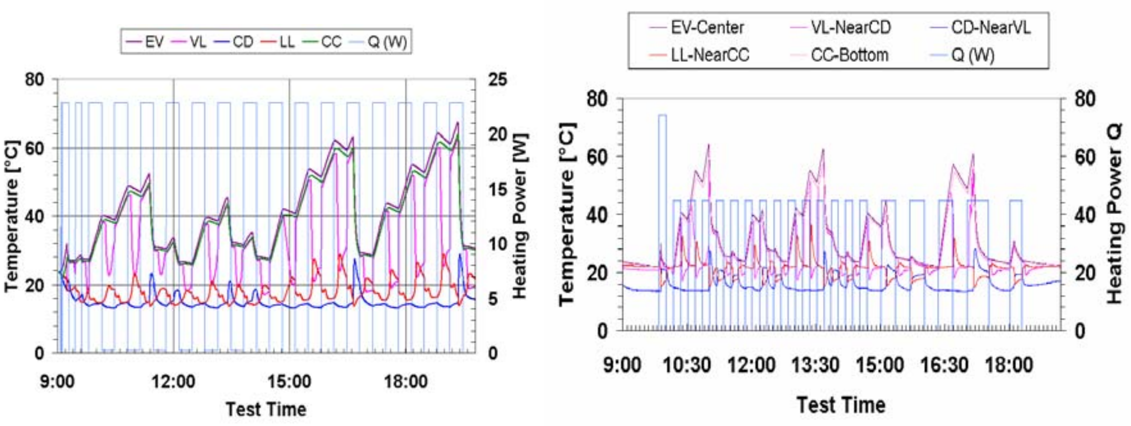
a. Constant Heating Start up b. Small Cycling Time Heating

Fig. 3. Constant Heating versus Small Cycling Time Heating



a. Periodically Steady Operations b. Non-Steady Operations

Fig. 4. Steady State and Non-Steady State Operations



c. Multi-Cycle Start-ups in Vacuum d. Multi-Cycle Start-ups in Atmosphere

Fig. 5. Multi-Cycle Start-ups in Vacuum and Atmosphere

With respect to the engineering application of a Heat Loop in a spacecraft thermal regulation system, it is important to understand the Heat Loop thermal performance with specific payload heating patterns, but pose critical questions, such as:

- Start-ups: Can a Heat Loop be started up reliably without any pre-conditioning techniques? Are the start-up parameters repeatable under the same conditions?
- Low-power hysteresis: Can the low-power phenomena be comprehensively understood and precisely described? Is it practical to have repeatable patterns and to control the performance in the low power regions in which variable conductance feature is shown?
- Feature performance versus specific Heat Loops: Are those unconfirmed performances caused by special test conditions or the features of LHP? Is such phenomenon unique for this LHP, or a certain designs of LHP will show such performance and others not?

Since there has been only one LHP tested at the CSA laboratory, it is difficult to answer these questions. There is a need to find the answers from experiments with other Heat Loops.

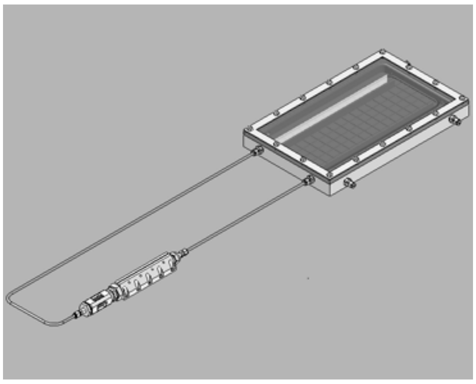


Fig. 6. Schematic Laboratory Setup of CSA LHP

Therefore, CSA is designing a LHP hardware setup for laboratory testing. The setup is to be completed soon with the schematic layout shown in Figure 6. The evaporator will contain a wick tube of 120 mm long, 18 mm diameter. The wick has ~1 μm pore size and 60% porosity. There will be a glass window in the compensation chamber to enable the monitoring of the fluid inside. The condenser will be made from a semi-transparent tube to enable the visualization of two-phase fluid flow.

NUMERICAL MODELING

In the past four decades, the theoretical and experimental explorations of heat pipes and heat loops have been more or less mature. The numerical modeling of multi-phase heat transfer devices in space applications, on the other hand, is generally not as adequate as that of the other thermal regulation technologies. Compared with other two-phase thermal control technologies, CHL technology is of simple design, low mass and passive operation. The numerical simulations of LHP/CPL are, however, neither less complex nor more adequate than that the other two-phase thermal control technologies in the micro-gravity environments.

In general terms, Heat Loops models can be categorized into analytical and numerical, steady-state and transient, structural simplified nodes and geometrically-complex sub-models, physically-simplified and multi-physical-phenomena, home-developed codes for researchers and commercial tools for engineering applications.

The earlier models are mostly analytical tools developed by researchers for their own research works. These models consider the Heat Loop individual elements (compensation chamber, evaporator, liquid and vapor lines, and condenser) as nodes in nodal networks although the condenser may be divided into two-phase and subcooling regions. In a number of articles the evaporator is modeled as the only main component with complexity [flat evaporator: 55, 56, 57; cylindrical evaporator: 58] and a global model links and unites all the Heat Loop elements. The loop elements are presented as undivided control volumes (nodes) while the entire Heat Loop behavior is simulated in the global models. These models are usually simple in physics and geometry and can be solved analytically without using any numerical methods. The results of the predictions are hence less informative with very limited accuracy and, in general, cannot meet the requirement of engineering applications. For example, with the models based on the pressure balance only the maximum heat transfer rate due to capillary limit can be predicted [for instance, see 59].

There have been very few published analytical models that can predict both the hydraulic and thermal performance of the entire capillary heat loops. The first LHP steady-state analytical model was published by Dolgirev et al in 1978 [60], which was based on the one-dimensional (cylindrical geometry, radial direction) heat transfer equation for capillary wick with a pseudo convective term. A CPL model was developed by Ku et al in 1987 [61]. A steady-state analytical approach for CPL was presented in 1992 by Wolf et al [62] and later developed in 1994 [63]. A distinguishing feature of this CPL model is the application of an annexed energy balance equation for the axial variation of liquid bulk temperature in the wick central core. This model standouts from the others by its capability of evaluating not only the CPL thermal resistance, heat load range, operational temperature, but also the CPL deprime at low power levels. An analytical steady state LHP off-design modeling concept for space applications was recently published in 2003 by Furukawa [64]. An analytical transient lumped-heat capacity CPL model developed in 1990 [65] allows prediction of the CPL operational temperature response on head load changes. To our knowledge, it is currently the only analytical approach to the transient operation of CHL in literature published.

In the last 20 years, numerical models have been developed for LHP/CPL to handle the physical and mathematical complexities, number of physical properties of working fluids, application of empirical coefficients and parameters, correlations with experimental data, etc. it is the rapid development of computer technology which enables more advanced and sophistical modeling of CHL heat transfer by numerical simulations. For the practical applications of numerical modeling, some compromises must be achieved regarding the model sophistication in forecasting capability of LHP/CPL performances, the handling of geometric complexity, the engineering conveniences of applications, the speed of computational data generation, and the interfacial compatibility with environment and the other devices in the thermal network. With respect to these requirements, the present existing commercial Heat Loop codes are not sophistical.

Among a number of steady-state numerical simulations, the work of Chuang et al [66] made progress in elaborating a one-dimensional LHP model. This work is the development of the model originally formulated in [67], which was used for the analysis of the influence of different parameters on LHP operational performance [68]. The detailed studies were contributed by the effects of sink and ambient temperatures, elevation, external thermal conductance of condenser, two-phase heat transfer and pressure drop correlations, heat leak, and insulation, on the LHP performance.

The Nodal Parameter Method has been adopted by the majority of numerical transient Heat Loop simulation tools, with which the physical system is divided in a finite number of isothermal regions (nodes). This methodology was first adopted by Sasin et al in 1990 for LHP modeling [69]. Based on this work TAIS (Russia) developed an in-house LHP software and later a commercial computer code EASY [70]. This tool is capable of simulating LHP start-up under certain initial conditions, evaluating temperature control regimes, and predicting the thermal behavior of multi-LHPs TCS [10]. The OHB-System of a German company upgraded the EASY code and developed a commercial software ALGOCAP [71]. ALGOCAP was designed to incorporate the LHP modules into ESATAN at system level.

The first CPL numerical modeler was developed in 1987 in form of a group of subroutines inside SINDA (today SINDA/FLUINT) [72]. Later C&R Technologies, Inc. created the LHP module for SINDA/FLUINT in 2000 [73] with special features of modeling the effects of non-condensable gas attached to the evaporator mass, the adverse tilt effects on the start-up of LHP, and the stochastic nature of the LHP start-up process at low heat loads [74]. A new Excel-based user-friendly interface for modeling of LHPs in SINDA/FLUINT was published by Baumann et al earlier this year [75], in which the module developers declare that the full FloCAD/SINDA/FLUINT program has no limitations on number of evaporators and condensers.

The TTH research (Hoang et al) designed a detailed transient LHP model in 2003 [76] and the outstanding correlation was reported between prediction and experimental data [77]. For instance, the model predicted three types of observed startup temperature patterns with an accuracy of ±1°C. An important advance reported by the same authors in earlier 2005 was the development capable of simulating LHP with up to 5 parallel evaporators and condensers [78].

Efforts of Spanish company IberEspaco in LHP modeling for Ecosimpro software package [79] deserve special attention with the most recent presented (July 2005) first version of the LHP library. Currently this model simulates steady-state and transient performances of one-evaporator LHP. Although there exist some assumptions and limitations in this edition, the development of different configurations of Heat Loops (LHP, CPL, Advanced LHP, multi-evaporator, and condenser etc.) with various additional components (such as isolator modules, back pressure regulators, pressure regulating valves, etc.) is enabled by the modular nature of Ecosimpro code and therefore to be expected coming soon.

Many companies and laboratories are developing their own numerical transient LHP models for device specific designs and operation conditions. There exist potentials for those in-house hand-tools to be developed into generic engineering tools. The examples of such models are:

- MELCO (Japan): Reservoir embedded LHP [80];
- ASTRIUM-UK (former MMS Space Systems LTD): LHP for ESA deployable radiator, the module for ESATAN [14];
- Alcatel Space (France): in-house thermal software CORATHERM developed for modeling of STENTOR LHP deployable radiator [81]; Later in cooperation with EADS Astrium this LHP software was upgraded and implemented to ESATAN [82].
- National Institute for Space Research (Brazil): CPL with flat evaporator and with porous element in flat condenser. Unique feature of the model is account of bubble formation in the evaporator that can lead to the Heat Loop deprime [83].

For describing of a specific Heat Loop behavior such as CPL deprime due to too large power step down, incorporating the low level submodels into a more global Heat Loop model is required. Such an approach demonstrated in [84] where dynamic behavior of two-phase interfaces in condenser and evaporator were taken into account. The presented CPL transient numerical model in this work provides a satisfactory simulation of the CPL response after step up and down of the applied power.

In summary, a significant progress has been made in the Heat Loop modeling in the last two decades. There are still some difficulties with prediction of the actual transient and Start-Up Performances for Heat Loops with satisfactory accuracy. Among the problems which remain to be solved, the following points are identified as the most important:

- Development of models which will be capable of accurately simulating several phenomena including HL temperature hysteresis, pressure and temperature oscillations, possible influence of wick fit, non-condensed gas generation, working fluid leakage, etc.
- Development of general models, which will include single- and multi-evaporator and condenser LHPs, CPLs, & other Heat Loops as Thermal Control System elements;
- Methods of different thermal solutions evolution;
- Heat Loop optimization methods and procedures.

Heat Loop operation is not easily predicted because it is heavily dependant on not only the interfacial parameters between CHLs and other systems as well as the environments, but also internal CHL conditions such as vapor and liquid phases distribution and properties in different parts of CHL.

CSA has initiated collaborations with universities and industries to develop the techniques of LHP numerical modeling. Four Versions of technical models were defined with respect to the development and applications:

- OS-dependent Basic models (version 1): The models are constructed based on the design of one specific loop heat pipe using library functions. These models are to test and validate the numerical techniques being developed. The resulting models will be similar to the other in-house hand-tools, being OS-dependent and device-dependent, and hence not generic applicable in any respects.
- OS-dependent Generic Models (version 2): version 1 models will be modified and tested to match, at limited level, the generic designs of LHP of different types of evaporators and condensers. The

applications of these models will be generic. All the models must produce simulation results with acceptable precisions and the results must match with each other.

- Stand-alone Generic Model (version 3): All the models of version 2 will be further modified to use OS-independent library functions so that a Stand-Alone Generic Model can be obtained which can serve for LHP designers and users. This version will be the engineering model of LHP.
- TMG-imbedded Generic model (version 4): The Stand-Alone Generic Model will be imbedded in the Canadian thermal simulation software, named TMG (Thermal Model Generator), and become an industrial model. This will enable the industrial design LHP in the same way as the other thermal controls by spacecraft thermal designers. Seamless interfaces and computational modules will be designed to couple the LHP model within the thermal network.

CONCLUSIONS AND FUTURE WORK

It is foreseen that the capillary heat loop technologies will become more popular thermal control tools for the thermal controls of future missions of both spacecraft platforms and payloads. In this work, a detailed survey and analysis of space missions using the capillary heat loop technologies were presented. A survey of the available CHL models was provided. The experimental investigations were reported regarding the steady state performance and application of periodical heating-cooling cycles. Development of numerical modeling technology of LHP has been initiated at the Canadian space agency. Due to the complexity of the physical phenomena occurring inside the two-phase capillary pumped devices, it is still a challenge to generate the mathematical models with satisfactory level of precisions. More advanced mathematical modeling technologies are needed to improve the current understanding of LHP devices and improve their performance predictions.

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ACRONYMS

BAT – Burst Alert Telescope
CC – Compensation Chamber
CCPL – Cryogenic Capillary Pumped Loop
CD - Condenser
CPL – Capillary Pumped Loop
CSA – Canadian Space Agency
EOS – Earth Observation System
ESA – European Space Agency
EV – Evaporator
Exp – Experiment
F – Failure
GLAS – Geoscience Laser Altimeter System
GSFC – Goddard Space Flight Center
HP – heat pipe
HST – Hubble Space Telescope
ICESat – Cloud and land Elevation Satellite
ITP – Institute of Thermal Physics Ural Branch of Russian Academy of Sciences (Ekaterinburg)
LL – Liquid Line
NASA – National Aero Space Agency (USA)
NICMOS – Near Infrared Camera and Multi-Object Spectrometer
NLR – National Aerospace Laboratory (Netherlands)
NRL – Naval Research Laboratory (USA)
OD – Outer Diameter
OS – Operating System
PD – Pore Diameter
PE – Polyethylene
RKA – Russian Space Agency
S – Success
SAST – Shanghai Academy of Spaceflight Technology
Ser – service
SS – Stainless Steel
STS – Space Transportation System
T – Temperature
TCS – Thermal Control System
TEC – Thermal Environment Conditions
TES - Tropospheric Emission Spectrometer
VCHP – Variable Conductance Heat Pipe
VL – Vapor Line
VRG – Vapor Removing Grooves
μg – Microgravity

Appendix

Table 1. Chronology of Two-Phase Loops with Capillary Pump Applications and Experiments in Space

No. /Year /Ref	Name/ Purpose /Mission	Organ ization	TCS Objectives/ Duration of functioning	TCS Type /No. of EVs /EV OD, mm /Wick /PD, μm /Fluid /Q_{min}, W /Q_{max}, W	Description and thermal environment conditions (TEC)	Result	Space Test Anomalies	Comments and Conclusions	Recommendations
1. /1985 /[19]	CPL-GAS G-471 /Exp /STS-51G	NASA: GSFC	To check the CPL capabilities in μg- to transport heat in a smooth and continues way; to operate in different heat loads: power step down profile; to shear heat load between 2 EVs; to reliably startup and shut-down; to adjust and maintain set-point T / 120 hours	CPL /2 /31.8 /PE /15 /NH_3 /50 / 200	2 EVs were in parallel, After startup (100 W per EV, 30 min) CPL operated ~ hour followed by non-operating cooldown period (~10 hours). Total 13 cycles were run. Tests included heat shearing, power step down, low power and induced deprime. Set-point T was 29°C for all tests. Environment Ts are varied from –60 to 30°C but min CPL T for cold start check was-20°C	S	No anomalies were observed. All power profiles worked, even low power cycle (25 W per EV) that wouldn't work on the ground	During the cold start ground testing in vacuum the originally planned startup power profile (25 W step increase to 100 W at the end of 45 min) always produced the deprime of EVs. The new power profile called "100 W zapp" was suggested: the EVs are given their maximum power level (100 W) immediately. Low-power cold startup is the wick point of CPL technology	1. To avoid low power CPL startup from cold state 2. To enhance CPL TCS robustness the startup has to be provided by special techniques: procedures and devices
2. /1986 /[20]	CPL-Hitchhiker /Exp /STS-61C	NASA: GSFC,	- To exam CPL performance at higher power levels through extended power profile test program, to verify CPL-GAS experiment data /120 hours	CPL /2 /31.8 /PE /15 /NH_3 /178 / 560	EVs were same as in CPL-GAS experiment, but condenser modified to reject more heat Total 38 power cycles were run. Tests included heat shearing/natural priming, power step up/down, low power, variable set point T induced deprime, sub-cooling limit.	S	Two of three starting power tests at 25 W and two tests at 50 W resulted in EV deprime but the results are consistent with ground testing. The long-time stability test at 142 W per EV did not finished due to increase condenser sink temperature.	Lowest power level at which nominal CPL operation was observed is 89 W High power limit was 560 W (two EVs) and 367 W for single pump operation. No significant difference between μg and 1-g CPL performance were identified	Special techniques are required to eliminate reservoir cold shock during low power startup of CPL
3. /1989 - 1991 /[21, 22]	TPL CP /Exp /Gorizont No.30. 31,32	RKA NPO Applied Mechanics, ITF	To test multi-LHP TCS in mg conditions: startup, low and high power operation. There were 3 same missions with different amount of fluid inventory/ ?	LHP /3 /22 /Ti / ~5 /Freon-11 /40 /120	3 LHP EVs were connected in parallel and had common heater. 8 thermocouples and 2 pressure sensors were used for telemetry. Range of environment T variations was from –70 to +30°C	F	The results of all 3 experiments were negative.	The LHP in μg is much more sensitive to amount of fluid inventory than in terrestrial conditions. The LHP operated unstable and vapor phase were presented in LL and EV core.	The method of LHP fluid inventory precise determination has to be developed for mg applications

4. /1989 /[23, 24]	ALYONA /Exp /GRANAT	RKA Lavochkin Association, ITF	LHP long term operation test /1.12.1989-15.06.2001	LHP /1 /12.4 /Ni /? / Propylene /5 / 100	LHP transferred heat on distance 4 m between opposite two sides of spacecraft ("hot", sun-oriented and "cold", space-oriented) Thermal switch was installed between LHP condenser and "cold" radiator. All LHP elements were covered by MLI. Deviation of solar rays inclination angle to "hot" radiator was in the range $\pm 30°$	S	No anomalies were observed	Only three T detectors were installed, the time between telemetry communications were several hours (days). Even basing on such limited data it was demonstrated that no monotonous tendency in regard LHP thermal resistance change and no crisis LHP phenomena were observed during years of operation.	The unique experiment of more than 10 years stabile onboard operation of the LHP allowed to recommend this technology for extensive application in flight spacecraft TCSs.
5. /1994 /[25]	LHP TCS /Ser /OBZOR	RKA: Polyot, Lavochkin Association, ITF	To provide T control of OBZOR optical instruments and refractive star sensor /2.08.1994-?	LHP /1 /?/?/? /Propylene, NH_3 /5 /50, 100	3 LHP TCSs (radiator, optical instruments and refractive star sensor) were installed in satellite	S	No anomalies were reported	TCSs had no telemetry sensors. In-orbit successful operation is conformed by payload perfect functioning and high quality of downlinked images.	
6. /1994 /[26, 27]	CAPL /Exp /STS-60	NASA: GSFC,	CPL was designed as prototype of EOS instrument TCS to demonstrate CPL capabilities in μg: to transport heat in a smooth and continues way; to operate in different heat loads; to shear heat load between 4 EVs; to reliably startup with help of capillary starter pump and special procedure; to adjust and maintain set-point T /3.02-11.02. 1994	CPL /4 /12.7 /PE /15 / NH_3 /? (Ground test 50 W) /? (Ground test 1200 W)	4 EVs were in parallel & placed on 2 plates (2 EVs on each), Large Diameter Capillary Starter Pump was used for SI. TEC during μg tests were different than ground tests: liquid T was much lower prior to startup procedure	F	20 attempts to start were unsuccessful, only in attempt No.6 one plate (2 EVs) is started and after prolonged operation second plate was successfully restarted. This is only the start allowed to conduct tests with the entire TCS. Attempts to use a mechanical pump to reprime CPLs were unsuccessful	1. Clearing only the vapor lines is not sufficient to ensure the successful startup; wick VRG have to be empty of liquid prior to start. 2. In μg startup procedure were failed to clear VRG due to mismatch in Effective diameters of VRG & VL 3. Reservoir cold thermal shock during start up can lead to undesirable pre-existing bubbles grow and creation of new ones (cavitation)	1. Inclusion in VL capillary vapor flow valve (Back Pressure Regulator) – capillary barrier with pore diameter smaller than that of VRG but larger than wick PD 2. Special Reservoir design to avoid T set-point defection during starting cold shock
7. /1994 /[28]	TPX I /Exp /STS-60	ESA: NLR	To demonstrate CPL capabilities in μg: to transport heat in a smooth and continues way; to operate at different heat loads; to shear heat load between 2 EVs; to prime EV by reservoir fluid content control; to startup from low T; to adjust and maintain set-point T / 43 hours	CPL /2 /?(flat & cyl) /PE /30 /NH_3 /20 /190 (Ground test 555 W)	2 parallel EVs : flat and cylindrical configuration; Reservoir was controlled by Pelletier Element; Two one-way valves were placed on LL with reservoir connection between them. TEC during μg tests were different than ground tests: sink T was considerably higher	S	No anomalies were observed.	Part of experiments was not fully completed because of T equilibrium reached after first 14 hours was much higher than expected. The use of the reservoir for CPL EVs priming, re-priming and T-control has been successfully demonstrated. 2 EVs in parallel operated properly in all regimes including heat load sharing.	1. Re-positioning of the reservoir in the Loop (upstream of the sub-cooler) can minimize the possibility of EV deprime 2. Additional μg tests of less down-scaled loops with realistic heat sources and sinks are required

8. /1995 /[29, 30]	CAPL-2 /Exp /STS 69	NASA, GSFC	Single pump CPL was designed as full scale prototype of EOS-AM instruments TCSs to demonstrate its functionality in μg; to validate new cold plate and EV design changes; to verify TCS operation pertinent to EOS applications; to investigate CPL performance limits; Test plan: startups with special procedures, power cycling, EOS asymmetric power inputs, T-set-point change, high &low power, induced deprime and reprime /112 hours	CPL /1 /25.4 /PE /15 /NH_3 /33 /809	CPL had 1 EV. Reservoir & LL were connected directly into EV core through bayonet tube (three-port design). So any liquid displaced from VL during startup must flow through the pump before entering to the Reservoir. Two grooved HPs were attached to EV (cold plate design). HP heat exchanger was used as condenser radiator. VL consisted of 2 sections, total length 4.2 m; LL consisted of 3 sections, total length 6.2 m.	S	No anomalies were observed. All preplanned tests were completed in time and performance was stellar. Some unusual (high superheat), different from ground tests, behavior during several startups was observed.	Six different startup procedures for different initial & environment conditions (including cases of cold conditions and restarting after forced EV deprime) and several power cycles were performed. All 11 startups were successful. But longer time was required to clear liquid from VRGs in μg prior to startup There were no significant difference in CPL performance between μg and 1-g. Spacecraft maneuvers had minor influence on LHP operation	Single (Start) Pump CPL is very robust Two-Phase Technology for TCS and can be recommended for space applications.
9. /1997 /[31]	LHPFX /Exp /STS-87	NASA, Dynatherm	- To qualify the US made LHP (the technology was transferred from Russia) for use in the US, - to verify technology readiness for spacecraft applications - to characterize LHP technology performance in μg /213 hours	LHP /1 /25 /Ni /2.2 /NH_3 /12.5 /400	LHP had 4.5 m long VL & LL and 3.7 m long condenser Test program included startups from low (-55°C to high (+35°C) T, power cycling/stepping at different T, steady state operation at 25 & 200 W and T-control test at 40°C. Environment Ts were higher than expected	S	No anomalies were observed. Although complete absence of subcooling can be considered as anomaly.	LHP functioned flawlessly through the mission. All startups were successful. As reported in [32] no apparent subcooling of liquid returning to condenser observed during 49-hour steady state test at 220 W. The low temperature startup test was not performed because minimal radiator T was -34°C	LHP technology was recommended for TCS applications in US Space programs
10. /1997 /[33]	ALPHA /Exp /STS-83, STS-94	NASA, Swales Aerospace	- to verify operation American LHP in μg : Startup at hot and cold conditions, heated LL, various start powers; 300 W transport capacity, Power cycling; Low power; - to demonstrate control capability and recovery capability from induced deprime /STS-83: 6 hours, STS-94: 50 hours	LHP /1 /19 /Ti /5.9 /NH_3 /22 /290	LHP had wire mesh secondary wick and counter flow condenser with 15 μm PE wick Test program included startups, power cycling, low and high power steady state operation and T-control tests. Sink T were not controllable (depended on Shuttle orientation and other experiments) and varied in range from 0 to 30°C	S	No anomalies were observed.	All test were successful, including: 8 startups at various powers (22, 46, 290 W) and after induced deprimes; 3 induced deprime/recovery tests (LHP self adjusts to loss of subcooling caused by deprime heater on LL);-High (290 W) and low 22 W power tests;-Power cycling (22-290-22-290W). Test results were similar between 0-g and μg	LHP technology was recommended for TCS applications in US Space programs
11. /1997 /[34]	TPF /Exp /STS-85	NASA: GSFC, TRW	to demonstrate and characterize : CPL TCS flight operation with advanced features and components; CPL TCS reliability in μg while 4 EVs are parallel; capability of Back Pressure Regulator to clean EV VRGs prior to startup; operation of advanced heat exchanger/condenser; operation of VCHPs combined with CPL to compare startup and low power limits for small and large OD EVs /176 hours	CPL /4 /28, 28, 16, 16 /PE /10, 10 15, 16 /NH_3 /51 /242	4 EVs were in parallel & had different designs: 2 EVs (1 large & 1 small) had HP installed in central wick core. 1 large EV had additional circumferential VRGs. All EVs had capillary isolators in its inlet LLs. There was Back Pressure Regulator in the VL (see CAPL). 2 Condensers were identical to small EV (no HP) but operated in reverse. Experiment profile: startup; low, high power tests; power and saturation T cycling. Total 61 test cycle was performed	S	The very first startup failure connected with mismatch of starting procedure The second unexpected startup failure happened after previous unsuccessful startup by small EV. During 10 days of the mission one small EV did not operate reliably. There was 1 deprime of large EV during extreme low power test	A total of 14 startup tests were done. 10 were successful, 2 were not successful but expected: small EVs cannot be starting pumps (conformation CAPL results), 2 were not successful and not expected. 31 hours long term CPL TCS operation with power variations and three special procedures to restart deprimed EV without TCS shutting down were demonstrated. The data showed effectiveness of Back Pressure Regulator. Operation standard small-OD EV was marginal	1. The small-OD EV operation problems are connected with presence of long-lived vapor/gas bubbles in the core. The addition of HP into EV core did appear to increase bubble tolerance 2. Dedicated starter pump has to be incorporated in TCS to allow startup of all operational EVs with clear VRGs

12. /1998 [35, 36]	CRYO TSU CCPL /Exp /STS-95	NASA: GSFC	to determine whether μg environment would have any adverse impact on CCPL performance at startup & steady state operation, and on operational limits & diode action shutdown /70 hours	CPL /1 /14 /SS /2 /N_2 /0.25 /2.3 (Ground test: 13 W)	Two elements: liquid cooled shield and "hot reservoir" were added in CCPL design if compare with CPL. EV-to-CON transport length was 0.25 m. CCPL had 6 test cycles including 6 startups, 6 power cycling, 5 low power (0.5 W), 1 long duration, 1 sink T cycling, and 1 reservoir set point T change. The flight cooler capacity was considerably less than laboratory one	S	No anomalies were reported	Only tests 5 & 6 were fully performed as planned: during tests 1-3 some difficulties with software for heaters controllers and during tests 1-4 the vacuum problems were presented. But the unit started successfully in all of its 6 12-hours test cycles. Due to flight cooler low capacity magnitude of power variations was significantly reduced. It was reported that the μg environment had no discernible impact on CCPL operation.	Basing on success of the experiment authors concluded that CCPL technology is ready for implementation in actual space cryogenic applications
13. /1998 [37]	HOST /Exp /STS-95	NASA: GSFC	HST Orbital System Test (HOST) was conducted for final μg examination of new equipment before installation on the telescope /29.10-7.11.1998	CPL /1 /25.4 /PE /15 /NH_3 /15 /460	Starter Pump CPL (see CAPL-2) are using for the thermal control of cryocooler. Flexible part of VL and LL is property of this design. Two intentional deprime-reprime cycles were performed. TEC were warmer than expected	S	Transient cooldown was much slower than expected and CPL had self-startup when Payload Bay doors were opened	CPL performance was 100% successful.	
14. /1999 [5, 38]	CPL TCS /Ser /EOS-AM (TERRA)	NASA, Lockheed Martin	To provide T control of TERRA scientific instruments /18.12.1999-up to now	CPL /1 /25.4 /PE /15 /NH_3 /25 /264	6 Starter Pump CPLs (see CAPL-2) are using for the thermal control of 3 instruments (2 per each: one is redundant). 6 operational procedures for changing TCS operational modes (Normal, Safe Hold, Survival) were developed: Set Reservoir, Standard Startup, Contingency Startup, Ready to Operational, Operational to Ready, and Shutdown.	S	TCS of one of three instruments had problems: after first start CPLs were deprimed in 2-3 days. Contingency starting procedure was successfully applied. After 1-month operation this CPL again deprimed and again re-started. Last deprime was forced by the unfavorable spacecraft engine burn	The CPLs demonstrated an on-orbit capability to maintain T control within ± 0.1°C. Additional EV heaters were used for stabilization CPL operation. During the mission CPL the set points T were lowered by 3-5 °C due to increased instruments power consumption. This operation extends instrument's life. In 5 years all operating CPLs have provided stable T under all modes of satellite operation, heat loads and sink conditions	Spacecraft maneuvers have to be analyzed from point of possible CPL deprime due to unfavorable acceleration.
15. /2001 /[39]	CAPL-3 /Exp /STS-108	NASA: GSFC, NRL	Objectives was to demonstrate CPL reliable capabilities in μg: - to transport heat in a smooth and continues way; to operate in different heat loads; to shear heat load between 4 EVs; to startup with help of capillary starter pump and special procedure; to adjust and maintain set-point T; to work in variable and fixed conductance modes /5.12-17.12. 2001	CPL /4 /25.4 /PE /15 /NH_3 /100 /1447	4 EVs were in parallel; 2 – placed on one plate, 1 EV connected with heat sink through VCHP. All EVs had special high deprime resistance design [40]. Back pressure regulator on VL and novel reservoir design facilitated to reliable startup (assisted by Capillary Starter Pump) and to stabile transient operation. Startups were performed at 5, 20 and 30°C after special CPL "warming" and VL & VRG "cleaning" starting procedure.	S	After successful Variable/Constant Conductance tests one EV (No.4) always deprimed in subsequent test. During low power tests three times EV No.4 deprimed immediately following a shuttle maneuver	1. All Startups were successful and it conforms chosen concept of starting procedure but the procedure is complex and takes several hours. 2. The CPL operated stabile in all regimes: during heat load sharing (one EV worked as condenser); variable load profiles (power varied among EVs from 0 to 300W); high (1447 W, 756 W for one EV) and low (25 W) power operation; standby mode (forced EV deprime/ reprime); variable/constant conductance modes transition	1 The use in TCSs of variable/constant conductance mode transitions, & heat load full sharing among EVs is possible but require special designs to guarantee reliability 2. Influence of spacecraft maneuvers on CPL TCS operation is critical and special techniques are required to eliminate it.

16. /2002 /[41]	HST SM-3B /Ser /STS-109	NASA GSFC	To cool NICMOS cryocooler, provide tight T control and reactivate NICMOS sensor /03.2002 –up to now	CPL /1 /25.4 /PE /15 /NH_3 /400 W	see HOST-2	S	No anomalies were observed	TCS employs a sophisticated control algorithm to continually change CPL parameters in response of thermal load and thermal sink conditions	
17. /1999 2002 /[42, 43]	LHP TCS /Ser FY1 2 satellites	SAST, TAIS	Thermal control of nickel cadmium batteries / FY1-C: 10.05.99-up to now; FY1-D: 15.05.02-up to now	LHP /1 /7.1 /Ni /? /NH_3 /? /30	Satellite has 6 LHP installed on 6 batteries. 5W Pelletier elements on the reservoir provide T control and LHP shutdown. LHPs operate only if cooling Pelletier element works because VL and LL mounted together and have perfect thermal link.	S	No anomalies were observed	During the flight batteries T controlled in range 4-10°C. The μg data well correlate with ground thermal vacuum tests. LHP TCS demonstrated 10 years (5 in-orbit) stable performance.	
18. /2003 /[44]	LHP TCS /Ser /Yamal-2000, 2 satellites	RKA: RSC "Energia", TAIS	Thermal control of nickel hydrogen battery /24.11.2003 - up to now	LHP /1 /14 /? /? /Propylene /? /125	4 LHPs were installed on each satellite. Each LHP has pressure regulator on VL (main T control element) and 10 W heater & Pelletier element on the reservoir (startup and transient operations management, LHP shutdown, extra T control)	S	No anomalies were observed	All LHPs are working stabile and operational T=5°C is maintained by passive pressure regulator only with accuracy $\pm$3°C. The flight data have good capability with model and ground tests.	
19. /2003 /[45]	COM2 PLEX /Exp /STS-107	ESA: Astrium, EHD, TAIS-OHB System	In-orbit qualification of ESA advanced LHPs /	LHP /1 /?, ?, 12 /Teflon,Ni,Ti /4, 2, 8, /all -NH_3, / ?, ?, 1 /70, 120, 80	3 European LHPs manufactured by different companies were tested. Special features of designs: 2m long VL & LL connected with Swagelok junctions (Astrium); VL & LL with flexible SS portions (Sabca); 3-way valve on VL (TAIS-OHB)	S	TAIS-OHB LHP data: Thermal resistance at low power level was unrealistic. Possible reasons are the leakage of pressure transducer membrane and parasitic heat leaks to the reservoir.	TAIS-OHB LHP data: In general LHP operated as expected; 2 methods to control the evaporator T were successfully tested: (1) active Heating of the reservoir and (2) passive regulating by bypass valve; easy frequent start-up from zero to different power levels demonstrated.	1. All components of LHP need to be carefully insulated in order to minimize parasitic heat leaks 2. Use of differential pressure transducer is risky due to apparent low reliability.
20. /2003 /[46, 47]	GLAS TCS /Ser /ICESat	NASA GSFC	To provide thermal control of onboard electronics and lasers /12.01.2003 – up to now	LHP /1 /25.4 /Ni /1.2 /Propylene /? /125	GLAS has 2 LHPs: Component (CLHP) and Laser system (LLHP). Ordinary HP network was used as thermal link between dissipative elements (lasers, electronics) and LHP EVs. Large range of angles between the orbit plane and the sun, spacecraft yaw angles; solar intensity cyclical variation; increasing absorbing solar heating results in very wide range of mission TECs	S	CLHP unexpectedly deprimed after 7 months of stable operation. That resulted in emergency shutdown of the GLAS. First attempt to restart LHP was not successful. Only second restart procedure recovered CLHP operation. The cause of this anomaly was and remains unclear.	At the beginning LHPs started easily and operated smoothly in space before and after anomaly. There is no significant difference between ground and flight operation. Possible causes of the anomaly are: yaw maneuvers, non-condensed gas, and slow fluid leak. To "fix" this problem additional heater power was applied to EV and T set point was lowered.	The possible influence of yaw maneuvers, non-condensed gas, and slow fluid leak on LHP/CPL TCS operation have to be investigated and taken into account prior to flight mission.
21. /1998 - 2004 /[48, 49]	ALPHA /Ser /10 Commercial communications satellites	Swales Aerospace	To provide thermal control of onboard electronics	LHP /1 /? /? /? /NH_3 /? /~600 (single LHP)	16 LHPs are used in TCS with 4 deployable radiators. Every radiator has 4 LHPs (2 are redundant) and heat rejection capacity of 1250 W. Special patented flexible section connects a payload structure with LHP EVs to the deployable structure (LHP condenser)	S	No anomalies were reported	No data available	

22. /2004 /[50]	TES TCS /Ser /AURA	NASA GSFC	To provide thermal control of TES instrument /15.07.2004 – up to now	LHP /1 /24.2 /Ni /1.2 /Propylene /~20 /80-150	Design of LHPs based on GLAS TCS (see pos.20). 5 LHPs were installed for TES instrument (340 W power consumption) thermal control. Multi-LHP design allowed much better packaging. Every Ev length is 15 cm. Start-up heaters on EVs and Control heaters on Reservoir were used with redundancy.	S	No anomalies were reported	TES is working as planned. Mission is successful and all LHP are functioning satisfactorily.	
23. /2004 /[51, 52]	BAT TCS /Ser /SWIFT	NASA GSFC	To provide thermal control of BAT instrument /20.11.2004 – up to now	LHP /1 /? /? /? /Propylene /? /~260 W	BAT TCS consist of HP array with headers attached to 2 LHPs (one is redundant) at each end. LHPs have flexible line to two parallel condensers/radiators with associated flow regulators. VCHP arrangement moderates LHP liquid return subcooling. Start-up, control and survival heaters are placed on LHP EVs and reservoirs with redundancy. TEC are very complex and change constantly but BAT temperature uniformity has to be in range ±1°C.	S	Some LHP T instability observed after LHP start-up during BAT turn-on. It is suggested VCHP did not work properly in μg. Problem was resolved by enabling LHP redundant heater controller. Large unexpected temperature excursion of LHP#1 EV caused shutdown this LHP in 130 days after lunch. Same excursion happened again during LHP priming (day 137). It was identified LHP#1 primary heater controller failure was reason of the anomaly. Redundant controller is now operates.	In flight the temperatures of all BAT Instrument elements were within nominal range. TCS provided stabile and successful operation of BAT. But if LHP#1 is the only LHP and the LHP CC primary heater controller is the only heater controller, Swift would have suffered a mission failure. LHP#1 shutdown had no effect on detecting gamma ray burst due to redundancy. Also despite that Swift slews constantly, the acceleration forces and mixing in LHP reservoirs have no thermal influence on two-phase devices functioning.	The possible influence of microgravity on LHP temperature control capacity (ΔT between the Block housing and LHP control heater was ~5°C large then in ground test) have to be investigated. In designing TCS it is very important to include redundancy of all components.
24. /2005 /[53]	Mini-LHP /Exp /FOTON M2	ESA: EADS Astrium	In-orbit qualification of mini-LHP heat transport and thermal control capacities/ June, 2005, ~100 hours	LHP /1 /26 /Plastic /? /? /<0.5W /30 W	Mini-LHP (80g total mass) with 40 g Stainless steel "tablet" type EV (19 mm thickness) and thermal resistance ~0.8 W/K was tested. T of LHP was controlled by heater on the reservoir. The experiment consisted of 1 mini-LHP and 2 mini HP.	S	No anomalies were reported	The experiment was completely successful	