DOCUMENT CONTROL SHEET

	ORIGINATOR'S REF.		SECURITY CLASS.
	NLR-TP-2003-231		Unclassified

ORGINATOR

National Aerospace Laboratory NLR, Amsterdam, The Netherlands

TITLE

Development of Different Novel Loop Heat Pipes within the ISTC-1360 Project

PRESENTED AT

As paper SAE-2003-01-2383 in the Tow-Phase Technology Session at the 33rd International Conference on Environmental Systems, Vancouver, Canada, 7-10 July 2003

PERMISSION

AUTHORS	DATE	PP	REF
A.A.M. Delil, Yu. F. Maydanik and C. Gerhart	May 2003	12	1

DESCRIPTORS

HEAT TRANSFER	LOOP HEAT PIPE	MINIATURE LOOP HEAT PIPE
RAMIFIED LOOP HEAT PIPE	REVERSABLE LOOP HEAT PIPE	SPACECRAFT THERMAL CONTROL
TWO-PHASE FLOW	TWO-PHASE TECHNOLOGY	

ABSTRACT

The International Science and Technology Center (ISTC) Project 1360 was carried out by the Russian Institute of Thermal Physics, in collaboration with the National Aerospace Laboratory NLR in the Netherlands, the US Air Force Research Laboratory, and the Korean Aerospace Institute (KARI). The main project task was to demonstrate the possibilities of a variety of Loop Heat Pipe (LHP) design configurations, to considerably extend LHP application ranges both in 0-g environment (space equipment) and in 1-g conditions at different orientations with respect to the gravity vector. The development concerns two miniature LHPs, a reversible LHP and a ramified (multiple-evaporator-condenser) LHP.

Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR-TP-2003-231

Development of Different Novel Loop Heat Pipes within the ISTC-1360 Project

A.A.M. Delil, Yu. F. Maydanik and C. Gerhart

This report contains the paper SAE-2003-01-2383, presented in the Two-Phase Technology Session at the 33rd International Conference on Environmental Systems, Vancouver, Canada, 7-10 July 2003.

This report may be cited on condition that full credit is given to NLR and the authors.

Customer:	National Aerospace Laboratory NLR
Working Plan number:	R.1.C.2
Owner:	National Aerospace Laboratory NLR
Division:	Space
Distribution:	Unlimited
Classification title:	Unclassified
	May 2003

Approved by author:	Approved by project manager:	Approved by project managing department:

Contents

(12 pages in total)

SAE-2003-01-2383

Development of Different Novel Loop Heat Pipes within the ISTC-1360 Project

A. A.M. Delil
National Aerospace Laboratory NLR, Netherlands

Yu. F. Maydanik
Institute of Thermal Physics, Ural Branch of Russian Academy of Sciences, Russia

C. Gerhart
Air Force Research Laboratory, Kirtland AFB, USA

Copyright © 2003 SAE International

ABSTRACT

The International Science and Technology Center (ISTC) Project 1360 was carried out by the Russian Institute of Thermal Physics, in collaboration with the National Aerospace Laboratory NLR in the Netherlands, the US Air Force Research Laboratory, and the Korean Aerospace Institute (KARI). The main project task was to demonstrate the possibilities of a variety of Loop Heat Pipe (LHP) design configurations, to considerably extend LHP application ranges both in 0-g environment (space equipment) and in 1-g conditions at different orientations with respect to the gravity vector. The development concerns two miniature LHPs, a reversible LHP and a ramified (multiple-evaporator-condenser) LHP.

INTRODUCTION

The International Science and Technology Center project 1360 was carried out by the Russian Institute of Thermal Physics, supported by three international collaborators. The main ISTC-1360 objective was the development of improved, high-efficient two-phase heat-transfer devices, with capillary pumping of a working fluid, for the thermal control of modern spacecraft systems: Loop Heat Pipes (LHPs) and their components. The development is discussed of four different, novel LHPs, i.e.

- A miniature (858 mm long, with 2 mm diameter tubing) ammonia LHP with a 40 mm long, 8 mm diameter cylindrical titanium wick evaporator and a 720 mm long flat coil condenser.
- A miniature (865 mm long, with 2 mm diameter tubing) ammonia LHP with a 120 Bar proof flat evaporator, with a nickel-titanium layered wick and a bi-porous thermal contact wall layer, and a 720 mm long flat coil condenser.
- A 900 W reversible 2 m long LHP with two identical 24 mm diameter, 104 mm long nickel wick evaporators, which have to proof to be able to properly act as condensers (in the reversed mode).
- A (ramified) multiple-evaporator-condenser LHP with two cylindrical evaporators (24 mm in diameter with an active zone length of 150 mm) and two condensers (length 200 mm, diameter 24 mm), made as pipe-in-pipe heat exchangers.

Many experimental results are given and discussed.

MINIATURE LOOP HEAT PIPES

The task to build miniature Loop Heat Pipes (MLHPs) with two different types of evaporators was initiated to determine the limits of miniaturisation while employing traditional LHP operational characteristics. Limiting factors, to guarantee MLHP thermal resistances of 0.01-0.1 K/W, are the active-zone area in the miniature evaporator and the constraint condensation conditions in the miniature condenser. The transport lines and the direct condenser designs were held constant in both designs. The evaporator heat load interface was also maintained as a flat surface to represent typical loads such as electronic components. The dimensions of the evaporator, heat transport capacity, and fluid charge were variables that would be determined by the specific evaporator design and could be used to compare the two solutions.

There were two evaporator designs that have been demonstrated in this effort. One consisted of a more traditional cylindrical evaporator and compensation chamber, that was then soldered into a rectangular aluminium block to provide the heat input interface. The second design employed a flat disk with one side as the heat load interface and the opposite side contained the compensation chamber. The characteristics of the two systems are summarised in Table 1. The Figures 1 and 2 illustrate the overall dimensions of the MLHPs.

Table 1. MLHP characteristics.

	Cylindrical MLHP	Flat Disk MLHP
Evaporator active area	955 mm^2, 8mm OD, 38mm long	6080 mm^2, 28mm diameter
Interface surface mount	Aluminium saddle, 40x40x10mm	Bolt circle outside active diameter
Working Fluid	Ammonia	Ammonia
Charge mass	1.9g	3.0g
Vapour line volume	970mm^3, 1.2mm ID, 858mm long	970mm^3, 1.2mm ID, 858mm long
Liquid line volume	970mm^3, 1.2mm ID, 858mm long	970mm^3, 1.2mm ID, 858mm long
Condenser volume	871mm^3, 1.2mm ID, 770mm long	871mm^3, 1.2mm ID, 770mm long
Condenser plate area	13095 mm^2, 97mmx135mm	13095 mm^2, 97mmx135mm
Operational temperature range	-20 to +60°C	-20 to +60 °C
Capacity (horizontal)	20 W	110 W

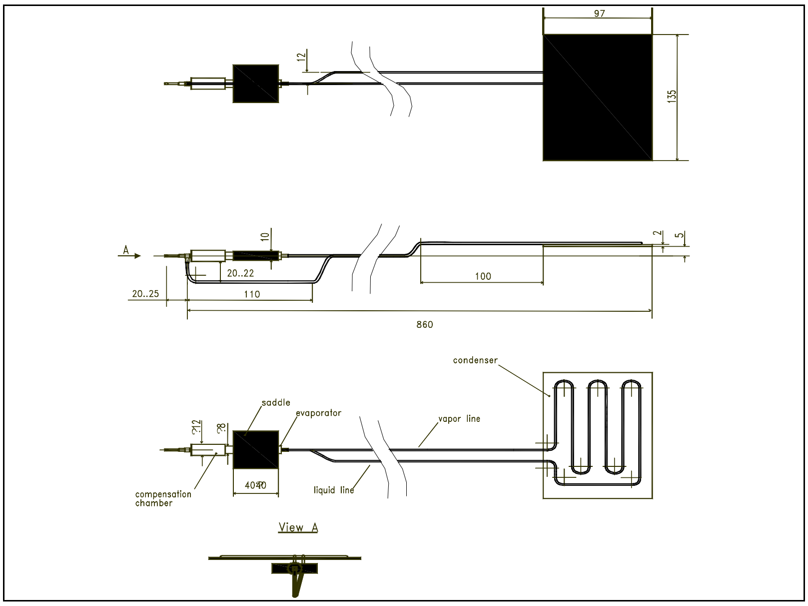

Figure 1. Cylindrical MLHP overall dimensions.

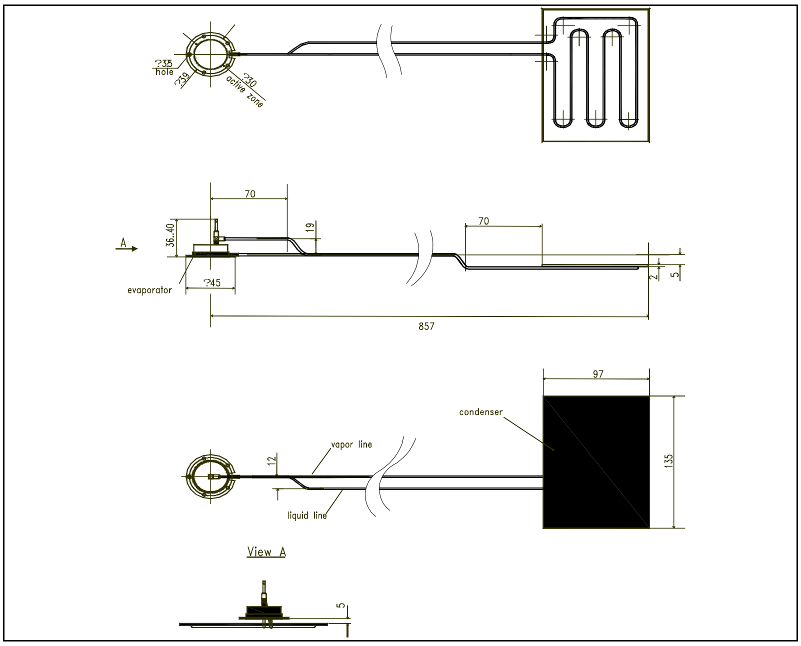

Figure 2. Flat MLHP overall dimensions.

The MLHPs were tested at ITP in Ekaterinburg prior to delivery to the Air Force Research Laboratory. Upon delivery to the US the MLHPs were taken to NASA GSFC to undergo extensive characterisation testing. Both sets of test results will be presented. Testing at ITP was somewhat limited due to the delivery schedule. Both loops were tested horizontally, and vertical in the evaporator above configuration. The condenser was set at –20 °C, 0 °C, or +20 °C.

The cylindrical MLHP had a vapour temperature variation of 10 °C for all the horizontal tests up to 20 W. Gravity effects were apparent when the cylindrical MLHP was operated vertically and the loop appeared to change from the variable conductance mode when testing horizontally, to a constant conductance mode when tested vertically. The test results are shown in Figure 3. The filled symbols reflect tests in the horizontal configuration and the open symbols are for the vertical tests.

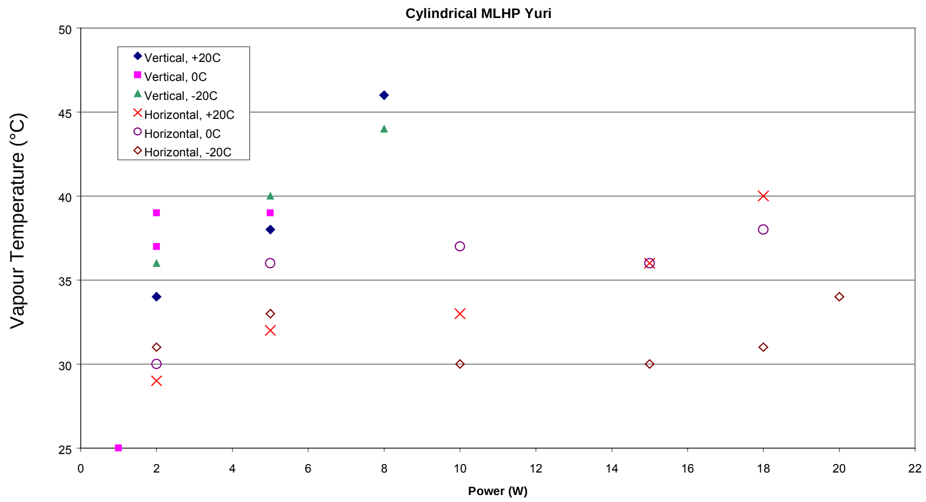

Figure 3. Cylindrical MLHP test results at ITP.

The flat disk MLHP exhibited the more traditional check shaped curves associated with LHPs both in the horizontal and vertical configurations. The MLHP vapour temperature is generally roughly 5 °C cooler in the horizontal orientation than in the vertical, at powers above 10 W. The experimental results are shown in Figure 4. The filled symbols reflect tests in the horizontal configuration and the open symbols are for the vertical tests. Testing at NASA-GSFC included not only the repetition of the tests conducted at ITP, but also a more detailed study of power cycling, condenser cycling, more power settings, and other configurations such as reflux. This level of testing was available because there was much more time available for testing after delivery. There were no significant differences in the test results between NASA and Russian testing. The test data is shown in the Figures 5 to 7, which also include the ITP test data (marked “Yuri”) for easier reference.

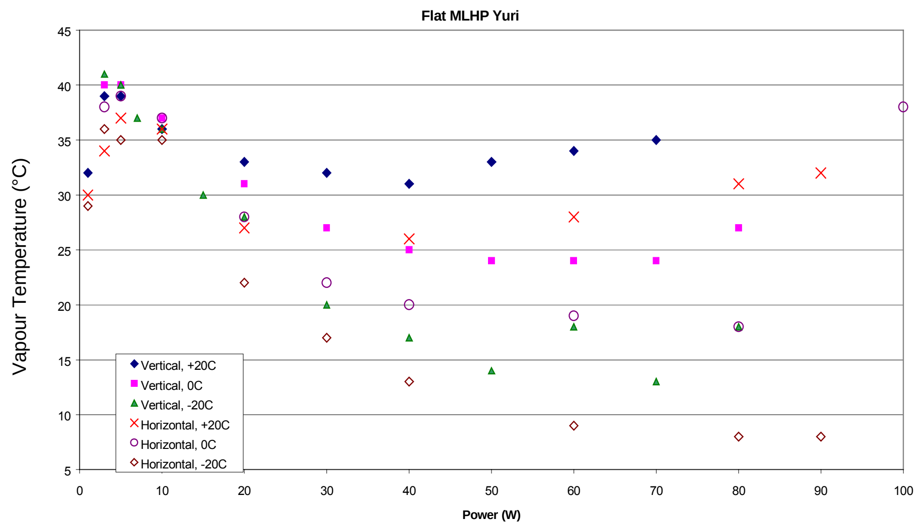

Figure 4. Flat evaporator MLHP test results at ITP.

The flat plate evaporator capacity was confirmed to be impressive: 100 W (1.6 W/cm^2) at –20 and 0 °C. The results indicate that there is little or no gravity effect on LHP operation. The characteristic curves are typical for traditional LHP designs. Figure 6 shows a close up of the test data for 15 W and below, for the ease of comparison to the cylindrical MLHP.

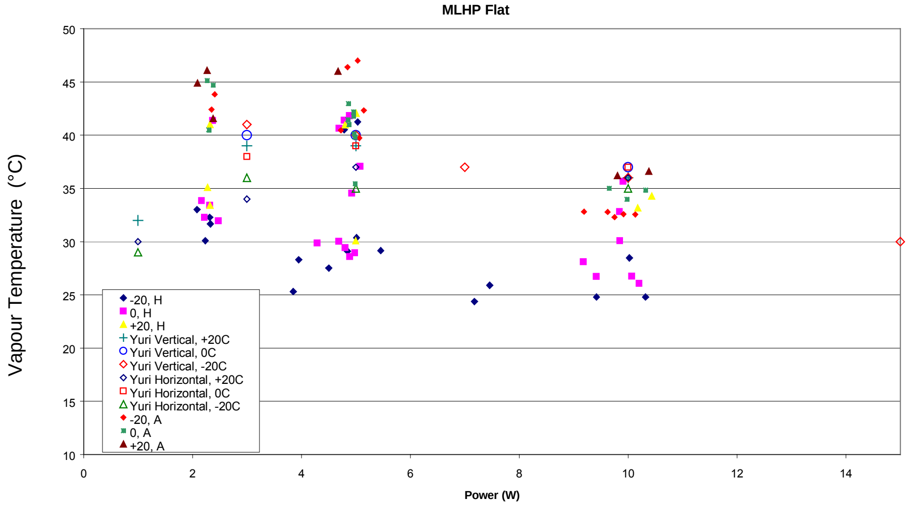

Figure 5. Flat evaporator MLHP test results at NASA-GSFC.

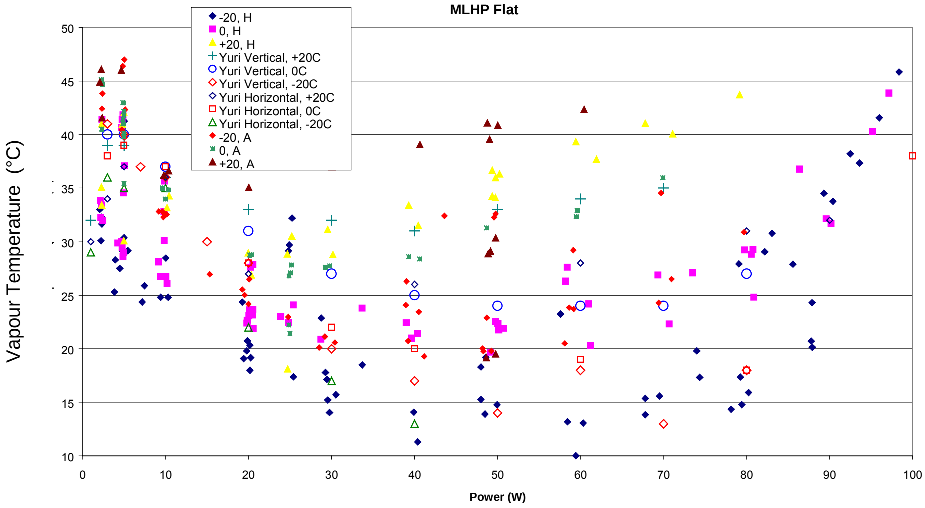

Figure 6. Flat disk MLHP low power test results at NASA-GSFC.

As already shown, the cylindrical evaporator design had a significantly lower heat load capacity, as predicted when initially designed. This LHP shows significant variability in operating temperature, but little or no effect of orientation or condenser temperature. The data are shown in Figure 7.

The results are not really surprising considering the dominance of ambient heat exchange and minuscule mass flow rate of ammonia through the loop during operation. At 1 W the mass flow rate is 0.05 g/minute and at 10 W it is 0.51 g/ minute. Converting this to the speed of the fluid in the lines results in the liquid travelling at 1.3 mm/s for 1 W and 13 mm/s at 10 W, and the vapour travelling at 88 mm/s at 1W and 887mm/s at 10W. At these speeds it is little wonder that all the sub-cooling of the liquid return is gone by the time the fluid reaches the evaporator. Operation of the flat disk MLHP also shows that the condenser is significantly over designed for these heat loads. Comparison of the flat disk MLHP to the cylindrical MLHP at the same power levels shows that the loops actually perform somewhat similarly in this range. However, the cylindrical MLHP cannot be operated at higher powers primarily because of the inherently thin wick thickness dictated by the packaging dimensions.

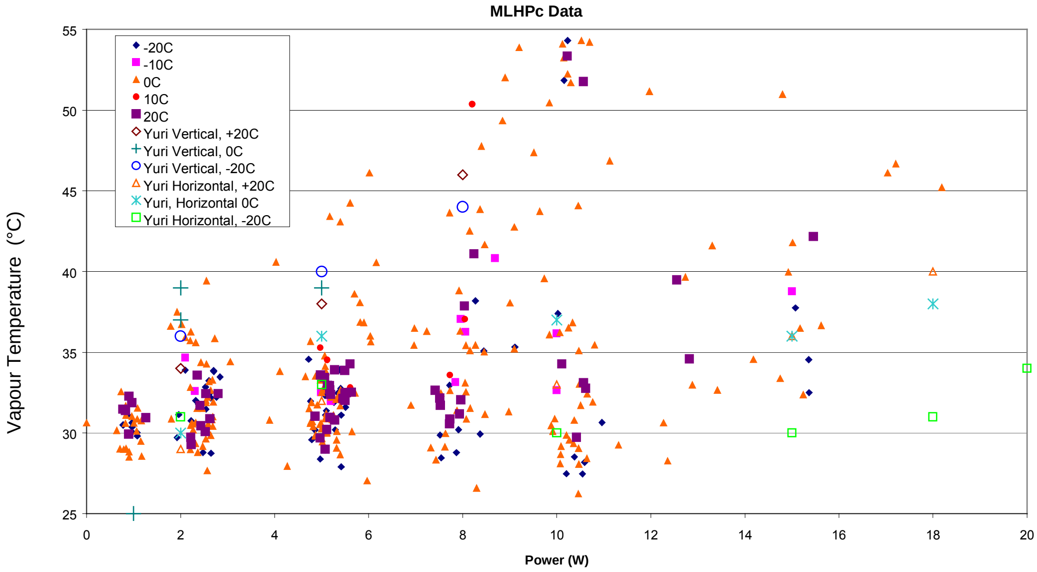

Figure 7. Cylindrical MLHP test results at NASA-GSFC.

Overall the MLHPs have operated as expected. The limitations of the cylindrical MLHP clearly illustrate the inherent geometrical limitations of conventional LHP design miniaturisation. If further miniaturisation is required, design and operational changes are required.

The plan is to fly both of these MLHPs on an upcoming Space Shuttle mission in a Hitch-Hiker experiment canister. Significant effort was expended in this particular effort to design and test the components to meet the NASA Space Shuttle safety standards, and to date all these requirements have been met or exceeded. More GSFC for each MLHP will be published in subsequent papers

REVERSIBLE LOOP HEAT PIPE

An LHP is, unlike an ordinary heat pipe, a "natural" thermal diode. Heat is well transferred from the evaporator to the condenser and is practically not transferred from condenser to evaporator. At the same time there are practical problems, including those in space engineering, when the heat source and the heat sink periodically change place, and an ordinary heat pipe cannot be used for one reason or another. In this case a problem is the creation of a reversible LHP (RLHP) capable of transferring heat equally well in the forward and in the opposite direction. The challenge here is to create an evaporator capable to act sufficiently well as a condenser during a heat-flow reversal. Table 2 presents the main design features of an RLHP. Figure 7 depicts the schematic of such a device, equipped with two identical evaporators located at its opposite ends.

Several experiments were done to determine:

- The efficiency of using an evaporator as a condenser
- The effect of the second evaporator on the thermal resistance and the capacity of the device.

The problem was expected to lie in the fact that the second evaporator, connected with the circulation loop in series with the first evaporator, creates an additional hydraulic resistance as it contains the same fine-pored wick. It was also assumed that it could create an additional thermal resistance.

Table 2. Design characteristics of a reversible LHP

Specifications	Value
Total length	2000 mm
Length of the evaporator active zone	104 mm
Diameter of evaporator active zone	24 mm
Vapour line diameter	6 mm/5 mm
Liquid line diameter	4 mm/3 mm
Body material	stainless steel
Wick material	nickel
Working fluid	ammonia

However, tests have shown that the evaporator fulfils the functions of a condenser very well. Vapour enters the longitudinal channels at the surface of the wick, which usually serve as vapour-removal channels in the evaporator. From these channels the vapour is distributed over small azimuths grooves at the inner surface of the body, where it condenses. The LHP thermal resistance remains practically the same as if an ordinary condenser were used instead of the second evaporator. The device maximum capacity somewhat decreased, but only slightly, as the wick thickness decreased as compared with the usual one.

RLHP test results, for different orientations under normal laboratory conditions and in a vacuum chamber (at a pressure of 0.1mm Hg), are detailed in:

- Figure 9, showing the heat load dependence of the temperature of the RLHP in vacuum, at a cooling temperature of 10°C in vertical orientation (φ = +90°).
- Figure 10, presenting similar curves obtained in a normal laboratory environment.
- Figure 11, depicting the heat-load dependence of the thermal resistance, both for vacuum and normal laboratory conditions.

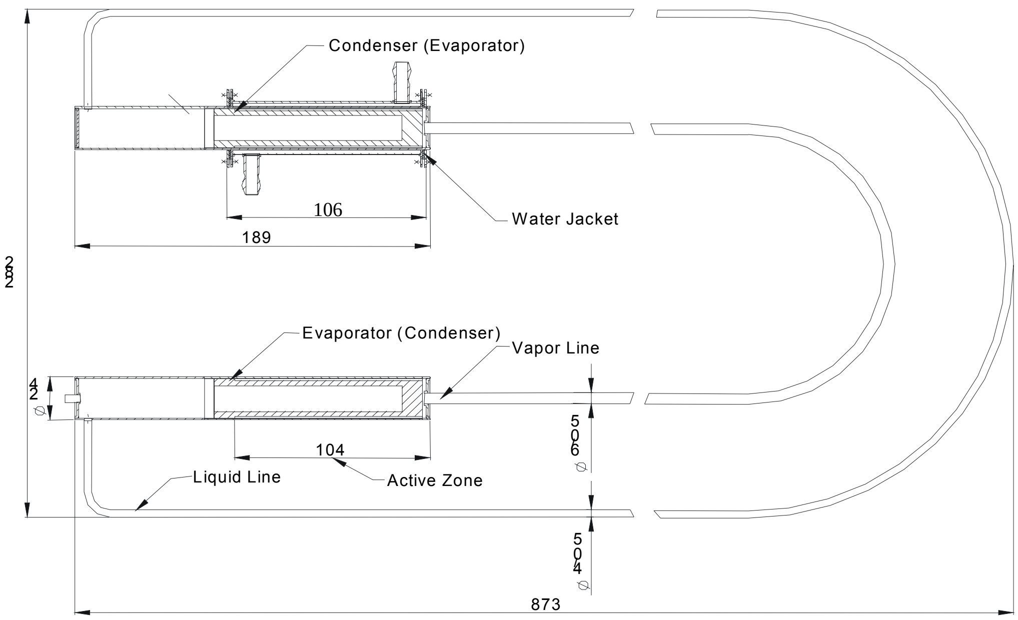

Figure 8. Schematic of RLHP.

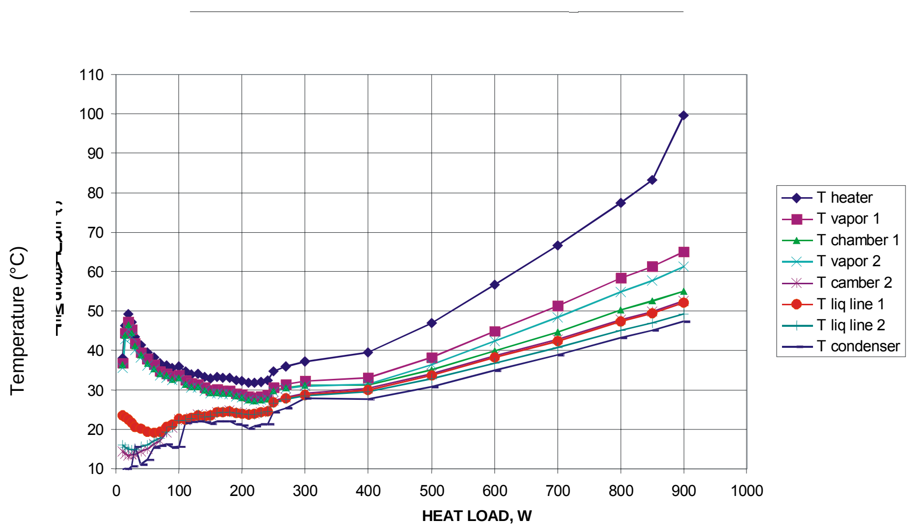

Figure 9. Heat load dependent temperature distribution, for vertical orientation in vacuum.

During testing the RLHP showed a maximum transport capability of 800 W at φ=90°, and of 900W at φ=0°. The minimum thermal RLHP resistance was almost the same, 0.03K/W, which is characteristic of ordinary LHPs with similar design parameters. The minimum start-up heat load, 20W, is larger than in ordinary heat pipes, as the thickness of the wick, separating the absorbing wick from the evaporating surface, is smaller than usual.

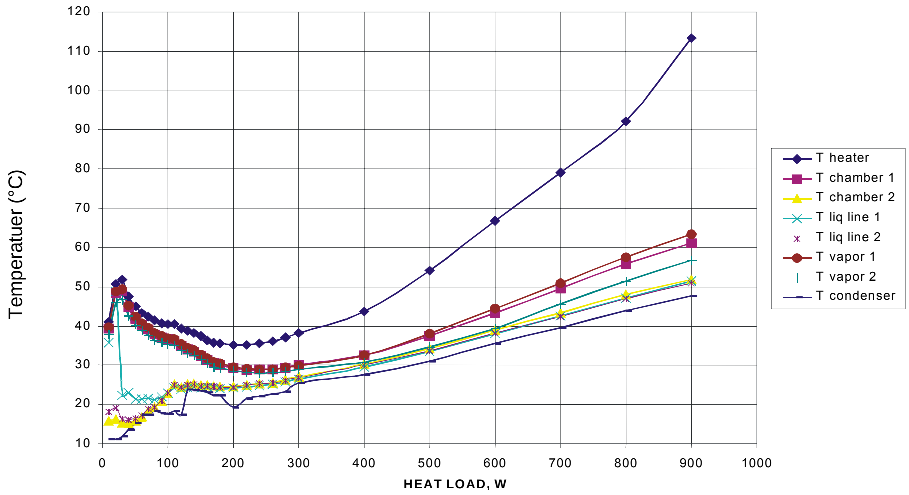

Figure 10. Heat load dependent temperature distribution, for vertical orientation under laboratory conditions.

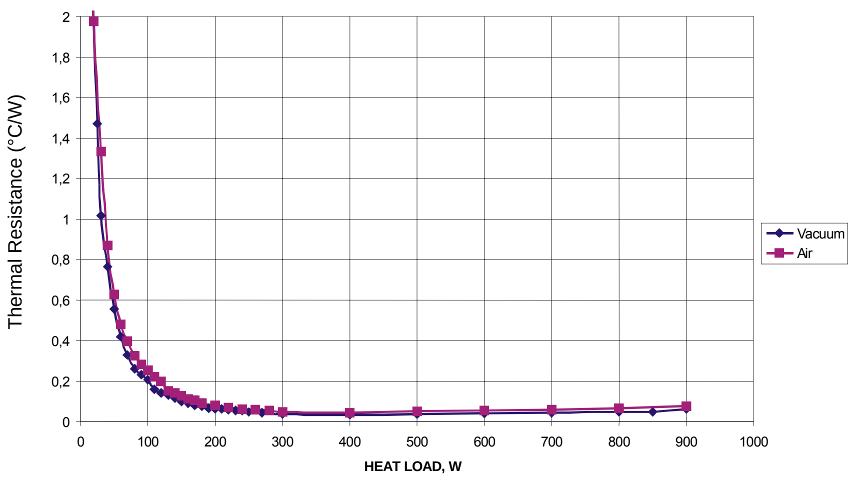

Figure 11. Heat load dependent thermal resistance, both for vacuum and normal laboratory conditions.

RAMIFIED LOOP HEAT PIPE

Ramified LHPs or multi-evaporator-condenser LHPs (MECLHPs) are quite promising heat-transfer devices for applications in spacecraft thermal control systems. They make it possible to reduce the mass of such systems and make them compact. The most typical cases when MECLHPs can prove to be useful are considered next:

- The heat-load source has a large thermal contact surface and/or capacity. In this case the MECLHP evaporators have, as a rule, the same dimensions, are arranged in parallel at a relatively small distance from each other, and are joined to a common “cold plate”, on which the heat-load source is located.
- The heat-load sources are located at a relatively large distance from each other and have the same or different capacity. In this case the number of evaporators should correspond to the number of heat-load sources with which they are in thermal contact. The evaporators may have different dimensions and be located at a different distance both from each other and from the heat sink.
- There are two or more heat sinks remote from each other. In this case the MECLHP is provided with the corresponding number of condensers, each of which has its own heat sink.

Different combinations of the above variants are also probable. The most complicated of them should envisage the possibility of different distribution of the heat load between the evaporators and/or different operating temperatures of thermally controlled objects, and also different conditions of cooling the condensers, including heat sink temperature and cooling intensity.

Reference [1] presents an overview of the development and testing of ramified LHP's. But despite the fact that certain success has been achieved in this field, the information accumulated is not sufficient for predicting with confidence the results of using MECLHPs for many conditions. The reported research is an attempt to make one more step in investigating ramified LHP. It concerns an ammonia-filled MECLHP with two parallel evaporators & two parallel condensers (Fig.12).

The device is made of stainless steel, contains two cylindrical evaporators and two condensers made in the form of "pipe-in-pipe" heat exchangers. The evaporators are provided with nickel wicks with a breakdown pore radius of 1.1 microns and a porosity of 67%. The compensation chambers have the same diameter and are located in the same body with the evaporators. The condensers are equipped with jackets for pumping the cooling liquid. The evaporators and the condensers are positioned parallel to each other and are symmetrical about the main vapour and liquid lines. The working fluid is ammonia. The main design characteristics of MECLHP are given in Table 3.

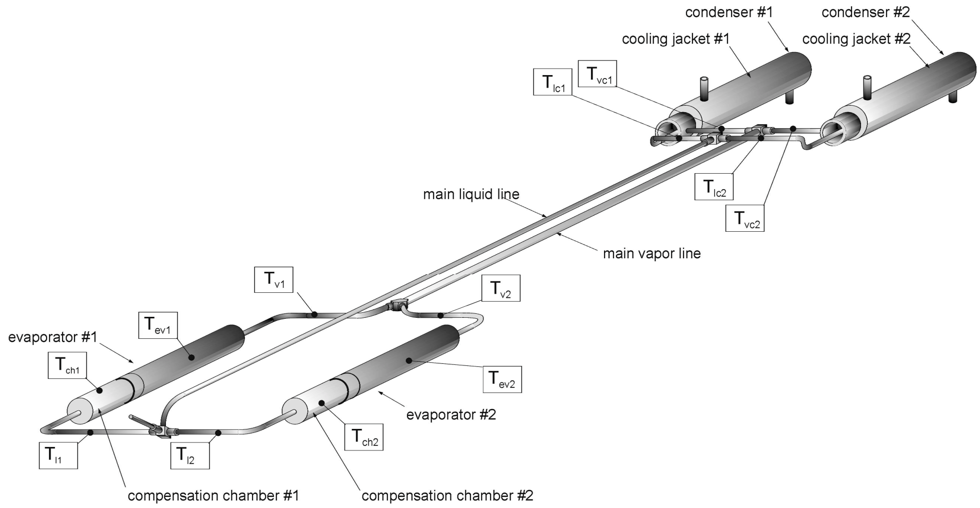

Figure 12. General view of the MECLHP.

Table 3. Main MECLHP design characteristics.

Characteristics	Value
Total Length	1000 mm
Evaporator Diameter	24 mm
Evaporator Active Zone Length	150 mm
Condenser Diameter	24 mm
Condenser Length	200 mm
Outside/Inside Diameter of the Main Vapour Line	6 mm/4 mm
Outside/Inside Diameter of Main Liquid Line	4.mm/2 mm
Outside/Inside Diameter of Main Vapour and Liquid Collectors	4 mm/3 mm

The main object of the tests was to obtain information on the thermal MECLHP characteristics for several conditions. The test conditions included variations of the orientation in the gravity field at 1-g, different heat load distributions between the evaporators, and different cooling of the condensers. The measured thermal characteristics were the MECLHP temperature at 12 points, the heat load on each evaporator, and also the temperature of the cooling liquid. The device orientation was characterised by the slope φ with respect to horizontal. The heat load distribution between the evaporators was symmetrical and a-symmetrical. The condensers were cooled by running water with a temperature 10 ± 2 °C. Also special tests were done with a-symmetrical condenser cooling. In some cases only one of the condensers was cooled actively, in other cases the cooling temperature of one of the condensers varied in the range from 20 to 70°C. The device start-up was realised, as a rule, with a heat load of 10 W on each evaporator. Besides, special tests were successfully conducted with 5 W during the start-up. The transition to a higher heat load was realised when a stationary vapour temperature was achieved. The heat load was defined as maximum if with its further increase a stationary state was not achieved. The main test conditions of MECLHP are presented in Table 4.

Table 4. Test Conditions of MECLHP.

Orientation (φ)	Heat-load distribution (Q)	Condensers Cooling
φ = 0° horizontal position, evaporators and condensers at the same level	$Q_1 = Q_2$, variable	$C_1 = C_2$, constant
	$Q_1 = 0$, Q_2 variable	$C_1 = C_2$, constant
	$Q_1 = Q_2$, variable	$C_1 = 0$, C_2 constant
	$Q_1 = Q_2$, constant	C_1 constant, C_2 variable
φ = 90° vertical position, evaporators are above the condensers	$Q_1 = Q_2$, variable	$C_1 = C_2$, constant
	Q_1 variable, $Q_2 = 0$	$C_1 = C_2$, constant
	$Q_1 = 0$, Q_2 variable	$C_1 = C_2$, constant
	$Q_1 = Q_2$, constant	C_1 constant, $C_2 = 0$
φ = 0°* horizontal position, evaporators and condensers are located in the vertical plane	$Q_1 = Q_2$, variable	$C_1 = C_2$, constant

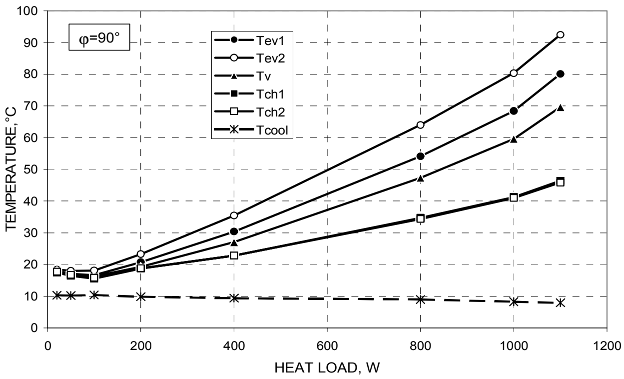

Figure 13. Test with heat load variations (Q_1=Q_2, (C_1=C_2 , constant).

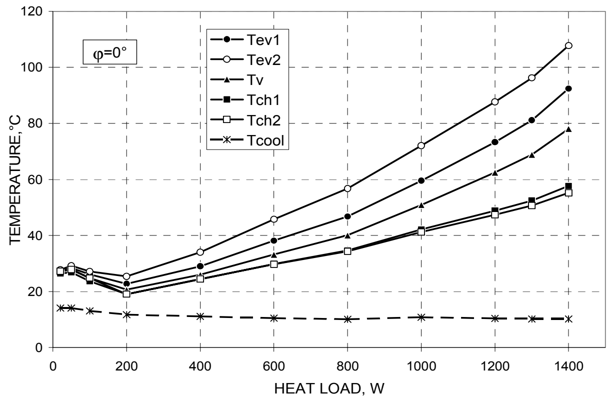

Figure 14. Test with heat load variations (Q_1=Q_2, C_1=C_2 , constant).

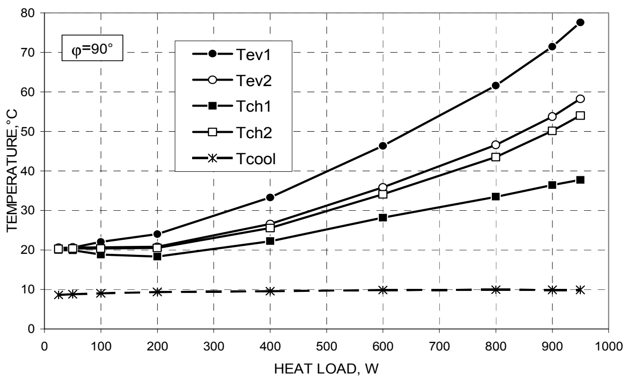

Figure 15. Test with heat load variations (Q_1 , variable, Q_2=0, C_1=C_2 , constant).

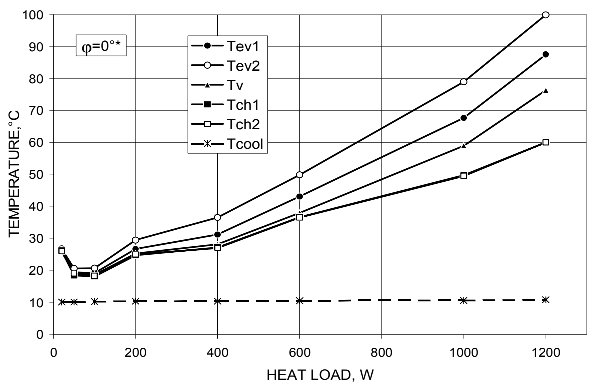

Figure 16. Test With Heat Load Variations (Q_1=Q_2, C_1=C_2 , constant).

Figures 13 to 16 show the operating temperature versus heat load for three different orientations, at the same condensers cooling. Analysis of the results proves that:

- Under all the changes in the device orientation the total value of the maximum capacity varies in the range from 1100 W to 1400 W. The maximum heat load on one evaporator, without powering the other evaporator reaches in these conditions values of 950 W-1100 W. The weak dependence of the maximum capacity on the device orientation in 1-g is ensured by the high capillary pressure created by fine-pored wicks of evaporators and the device relatively small effective length.
- At heat loads in the range up to 150-200 W the vapour-liquid boundary in the compensation chambers is retained. The device operates in the so-called auto-regulation regime, when its temperature with increasing heat load decreases or changes only slightly. In this case the difference between the temperatures of the compensation chambers T_{Ch1}, T_{Ch2} and the vapour temperature in the vapour line T_V is quite small. When the compensation chambers are filled, which happens with a further heat load increase, this temperature difference increases considerably, and the dependence T = T(Q) gets the character of monotonic rise.

- The temperature difference between the compensation chambers (for equal heat loads on the evaporators) is between 0.1 and 0.5 °C. The temperature difference between the wall of the evaporators (at the maximum heat load) reaches 12-15 °C. The great difference is caused by the design drawback of the electric heaters in use and poorly controlled conditions of locating temperature-sensitive elements underneath.

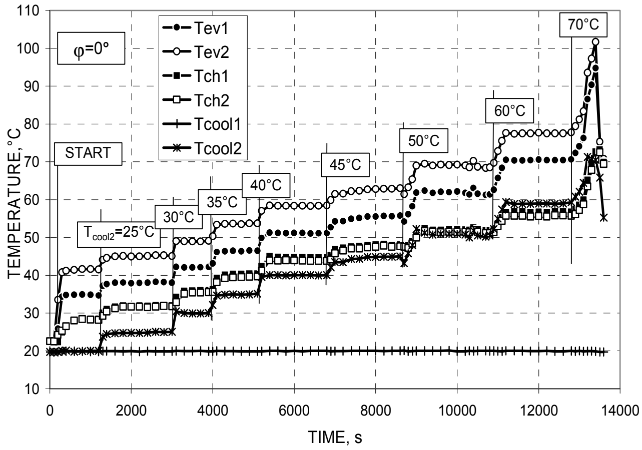

Figure 17. Time diagram with cooling temperature variations (Q_1=Q_2=300 W, $Tcool_1$=20 °C, $Tcool_2$ variable).

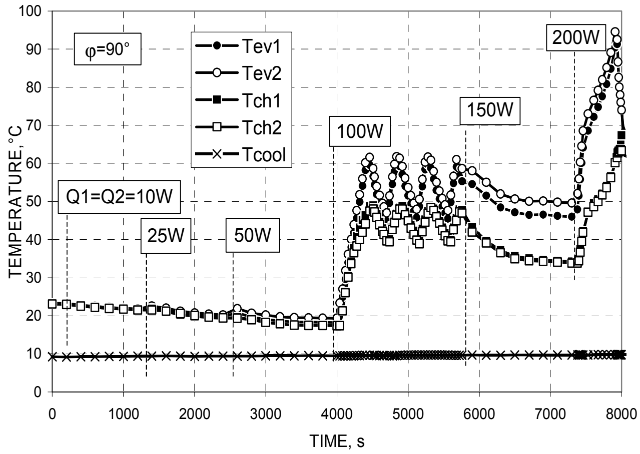

Figure 18. Time diagram with heat load variations. (Q_1=Q_2, C_1 is constant, C_2 = 0).

Figure 17 presents the time diagram of the MECLHP operating temperature at the same heat load on each evaporator (300 W) when the cooling temperature of one of the condensers remains constant at 20 °C, and the cooling temperature of the other increases to 70 °C. These tests have shown that the device operates properly until the difference in the cooling temperatures of the condensers reaches 50°C. After that the temperature of the evaporators increases abruptly, which points to the initiation of a crisis connected with vapour penetration into the liquid line. A similar picture is also observed in the absence of active cooling of one of the condensers, which is illustrated in Figure 18. A crisis of the same nature begins here even at a heat load of 200 W on each evaporator. It is preceded by wide temperature variations arising at a heat load of 100 W. It should be noted that such phenomena are not fatal for MECLHPs. They can be prevented easily by special design improvements of these devices.

In summary it is remarked that:

- Tests of a MECLHP containing two evaporators and two condensers at different orientations in 1-g conditions have shown that its maximum capacity varies moderately remaining in the range from 1100 to 1400 W.
- Different heat-load distribution between the evaporators does not disturb the device operation.
- The vapour-liquid boundaries in the compensation chambers exist (under given test conditions) until the heat load on each evaporator exceeds 150 to 200 W. The results of tests do not allow us to assert that the above-mentioned boundary can exist only in one of the compensation chambers.
- The device operation remains proper at different temperatures of cooling the condensers until the temperature difference reaches a critical value, which depends on the heat load on the evaporators.
- The device maximum capacity decreases abruptly if only one of the condensers is actively cooled. The reason for this phenomenon is the penetration of a great quantity of vapour into the liquid line.

  A hydraulic MECLHP model was developed and described recently [1].

CONCLUDING

The spin-off of the work presented is the potential to design and manufacture a variety of LHPs, between:

- At one side: Miniatures, 0.2 - 0.5 m long, 5 -.8 mm evaporator diameter), for power electronics and computers.
- At the other side: Large ones 10 - 40 m long, 1 - 5 kW, with one or several evaporators and condensers.

REFERENCE

1. Maydanik Yu.F., Pastukhov, V.G., Chernyshova, M.A., Delil, A.A.M., Development and Test Results of Multi-Evaporator Condenser LHP, Conference on Thermophysics in Microgravity, Space Technology and Applications International Forum STAIF-2003, AIP Conf. Proc. 654, Albuquerque, USA, 2003, pp. 42-48.