Variants of vapor removal channels organization in inverted meniscus capillary evaporator

Yakomaskin Alexander Alexeyevich
phone: +7 (916) 856-4719
e-mail: yak40@gmx.com

Zubkov Nikolay Nikolayevich
Bauman Moscow State Technical University, 2nd Baumanskaya Street, 5,
Moscow 105005, Russia
phone: +7 (499) 263-6486
e-mail: zoubkovn@bmstu.ru

ABSTRACT

For further improvement of loop heat pipes (LHP), used in the spacecraft and electronics cooling, it is necessary to pay attention to their compactness, weight and manufacturing cost. Any development of technological and assembly processes, as well as the application of new materials in the LHP attracts interest of designers and researchers. This paper describes an experimental setup for investigation thermal and hydrodynamic processes in a capillary evaporator with microchannels and non-metal wicks. The results of investigations for glass fiber wicks for three variants of the vapor removal channels organization are presented. The glass fiber wick may show its effectiveness if used in the LHP, as it posesses some unique advantages over metal powder wicks. Finned copper plates were used to transfer heat between the heater and the wick. These plates also provided the vapor removal channels. The plates were produced by a deformational cutting technology, that allows producing high aspect ratio channels while keeping manufacturing cost at comparatively low level.

I. INTRODUCTION

At present, significant progress is achieved in the creation of miniature LHP for use in compact electronics cooling. Singh et al. created LHP prototypes with flat thin evaporators with a thickness of 5 mm and 10 mm and discussed the thermal potential of a flat evaporator miniature LHP for Notebook Cooling.[1] Maydanik developed a miniature LHP[2] with a cylindrical evaporator with a thickness of 5 mm. Lin et al. created a copper-water LHP prototype.[3] The device is ready to be installed inside a notebook computer instead of the regular heat pipe cooler. The prototype has a thickness of 3 mm, that is the thinnest miniature LHP among published by the present moment. In recent years, the intensive work is conducted to create copper-water LHPs equipped with flat evaporators with a thickness between 3.2 and 8 mm. The LHPs have a signifcant heat power of up to 900 W.[4,5]

However, a set of solved problems lies behind all these successes, mainly technological problems and problems related to structural features of the LHP. So an LHP in its original concept combines the compensation chamber (CC) and the evaporator in a single enclosure. Such an arrangement allows for continuous feeding of the wick by liquid and unconstrained launch of the device. On the other hand, this makes difficult to provide an adequate thermal barrier, the temperature difference between the evaporator and the CC, which is necessary for the functioning of the device. An LHP evaporator's principle of work is shown in Fig. 1. The left part of the figure depicts the inverted meniscus scheme, when directions of heat flux and the vapor flow are opposite. As described in Ref. 6, 7, the organization of the evaporation by the inverted meniscus scheme may lead to generation of a vapor blanket – the dry zone in the wick at the areas adjacent to the heating surface. The vapor generated at the phase interface has to overcome the resistance of the dry zone of the wick to get to the vapor removal channel. This affects the levels of pressure and temperature in the area of the evaporating menisci. The thermal resistance of the evaporator is raised.

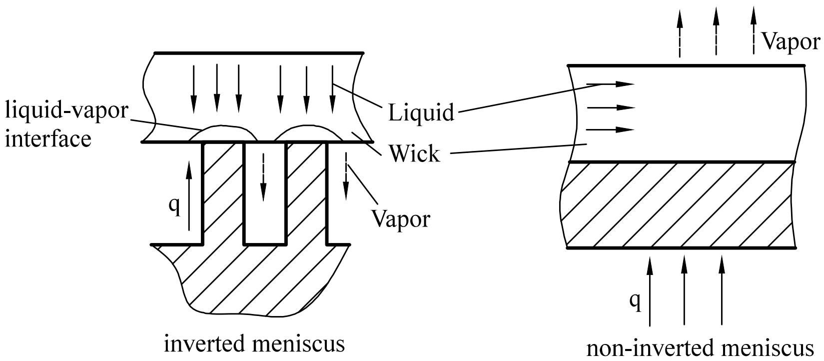

Figure 1. Evaporation mechanisms.

Application of the wick with a high thermal conductivity would reduce the thermal resistance due to the smaller temperature gradient in the dry-out area. On the other hand, such a measure would lead to a substantial increase in heat flow between the evaporator and the compensation chamber over the liquid saturated wick and would prevent the LHP from normal operation. This problem is particularly relevant for the LHP evaporator with a flat configuration, because the contact area of the wick and the CC therein is increased compared with a cylindrical evaporator. Because of the described disadvantages of the evaporator with inverted menisci a number of papers were published aiming to explore the possibilities to improve the effectiveness of the evaporators. Thus, in Ref. 8, the authors experimentally confirmed the effectiveness of biporous structures in comparison with monoporous due to improved structure for removing vapor from the capillary structure due to the presence of large pores on the surface of the wick near the heated wall. Ref. 9 describes a hybrid LHP wick, which is a combination of stainless steel mesh and copper powder structure. The stainless steel wire mesh was used to reduce heat leakage from the evaporation zone to the CC. The described changes in the evaporator resulted in a reduction of its thermal resistance, but they are all added to the complexity of the wick, which is already the most complex and expensive element of the LHP

Because of the drawbacks identified above for the inverted meniscus evaporators, new evaporators have been created by the classical scheme of evaporation used in heat pipes, characterized in that the heat flux and vapor flow are unidirectional.[3,4,5,10,11] The scheme is shown in Fig. 1 (left part). In the evaporators working under this scheme it became possible to ensure the effective thermal barrier for CC and, most importantly, the thermal resistance of the evaporator was significantly less than that of evaporators operating on an inverted meniscus. However, in this case, the designers also can not escape from the technological complexities. In the manufacture of parts, it is necessary to keep the design tolerances on flatness and parallelism for the wick and the enclosure of an evaporator. It is also important to provide sintering of the wick to the enclosure to provide good thermal contact. These requirements may have a significant impact on the cost of LHPs in mass production.

From the analysis of published studies it can be concluded that the LHPs are promising for use as heat transfer devices when working with medium and high thermal loads. Deterrent to their introduction is a technological complexity of manufacturing evaporator.

II. DESCRIPTION OF EXPERIMENTAL SETUP

In this paper, experiments were conducted on the evaporator working with an inverted meniscus scheme. The evaporator is an open thermodynamic system, since the vapor escapes to the environment after leaving the channels. The principle of operating for the evaporator is as following: distilled degassed water at the initial moment fills the internal volume of the evaporator, including the wick, as shown in Fig. 2; thermal load is applied to the microchannel plate; after the water in the channels of the plate and in the wick is heated to the saturation temperature at atmospheric pressure, the evaporation process begins; the produced vapor leaves the evaporator through the vapor removal channels into the atmosphere; on a vacant place of the evaporated liquid the wick pulls water from the compensation chamber, which, in turn, by virtue of the continuity of the liquid pulls the fluid from a reservoir R; liquid in the reservoir is maintained at a constant level relative to the CC by adding it by drops with a necessary flow rate. Thus, during the operation the liquid is supplied to the evaporation zone by the action of capillary forces in the wick. In the described evaporator the same process is realized as in loop heat pipes' evaporators with the inverted meniscus scheme, except that here the liquid flows to the CC due to continuity of the liquid, and not due to the pressure of vapor in the vapor line of LHP. The liquid in the CC is under vacuum conditions, because the reservoir that is connected by a tube to the CC is lower than the liquid level in the CC. According to the law of communicating vessels, the liquid level in the compensation chamber chamber and the reservoir must align. But this is prevented by the fact that the CC is sealed on all sides. The bottom side of the CC is covered by the wick, in which the liquid is held by capillary forces.

A. Wick

Layers of glass fiber filter membranes supported by a copper mesh were used as a wick in this experiment. Parameters of the materials are given in Table 1.

Table 1. Parameters of the wick.

Material	Thickness, mm	Pore size, um	Water flow, sec	Porosity, %
Glass Fiber Grade D Borosilicate	0.5	2.6	5	90 (undeformed)
Copper mesh 200	0.05	76	NA	35

Not many studies have been devoted to LHP with non-metal wicks. In Ref. 12 the authors identified the following features of such wicks: low thermal conductivity, low manufacturing cost, low weight and easy assembly. These features should be described in details. Speaking of the low thermal conductivity of non-metallic wicks the mentioned above design feature of inverted meniscus LHP should be considered. The wick in such LHP design perform the function of a heat barrier. The lower heat conductivity of a wick the thinner design can be achieved. On the other hand, the low thermal conductivity is a disadvantage, because the formation of even a thin vapor layer in the wick will create a significant temperature gradient. Therefore, for non-metallic wicks one should either apply low heat fluxes, or "unload" the menisci by providing more uniform heat input and vapor output. In this work, the wick is composed of a layer of glass fiber membranes adjacent to the compensation chamber, and the copper mesh layer resting on the copper microchannel plate. The copper mesh serves firstly for distributing the heat flux

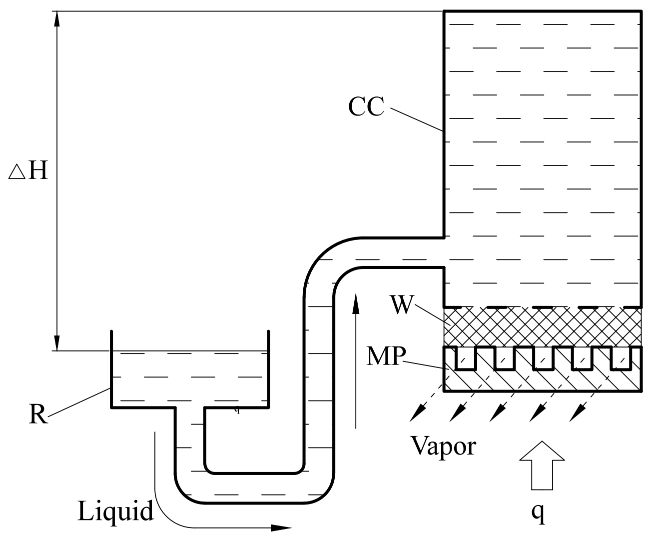

Figure 2. Evaporator.
ΔH – level difference; W – wick; R – reservoir; CC – compensation chamber; MP – microchanel plate.

supplied to the wick, and secondly, it serves as a supporting structure for the glass fiber layer. The glass fiber wick is a soft material, prone to mechanical deformation, so its secure fit and uniform loading is a parameter of the LHP design. In this configuration, the wick rests on a copper mesh, and the top is pressed through the perforated plate. This tendency of the material to deform is a drawback and an advantage at the same time. The disadvantage is that the material properties, such as porosity, permeability will depend on the degree of compression. The positive effect is that the assembly of the evaporator with a soft wick will compensate errors accumulated during the production of component parts of an LHP, i.e. manufacturing tolerances of the parts can be given greater than in the case of rigid metal wicks. The soft wick, like a rubber gasket fills all gaps and ensure good contact. In the described experimental setup the compression ratio of the wick was adjusted geometrically. Clamping flange nuts were tightened up until the perforated plate (item, pressing the wick above) reached a fixed stop. Thus, the degree of compression of the wick in all modes of the experiment was the same.

B. Vapor removal channels

The finned copper surfaces were used as heat distribution elements. Voids between the fins were used as vapor removal channels. The surfaces were produced by the patented deformational cutting method (DCM).[13] The principle of this method is the following: The special form tool undercuts the plain surface layers of the workpiece and raises it to a certain angle by making plastic deformation. The typical cross section of the fins is shown in Figure 2. The pitch of the fins, p, can be varied from 0.08 to 4 mm, while the elevation of the fins for copper may be Hmax=6p. This enables to create channels with high ratio of height to width. It is this effect of high aspect ratio channels is going to be used in conjunction with the non-metal wicks in the evaporator. As stated before, it is necessary to apply the channels of a small pitch to ensure a uniform flow of water to the wick. Doing this one should take into account that the cross sectional area of the channel shouldn't be too small as this may lead to high resistance to the vapor flow. Using of channels with high aspect ratio will prevent such a condition. As a deterrent to the introduction of devices in the industry is the technological complexity of manufacturing evaporator, it is appropriate to clarify the technological advantages of the DCM. First, the DCM produces no chip scrap during the surface treatment, i.e. the method is waste-free. Second, the deformational cutting method is readily adaptable to conventional machine tools, such as lathes, for rounds and sheets, and milling equipment or shaper, for flat surfaces. Sheet finning on a lathe is realized by using a drum for sheet tensioning. And finally, the method does not require lubricant, i.e., secondary cleaning steps are not required.

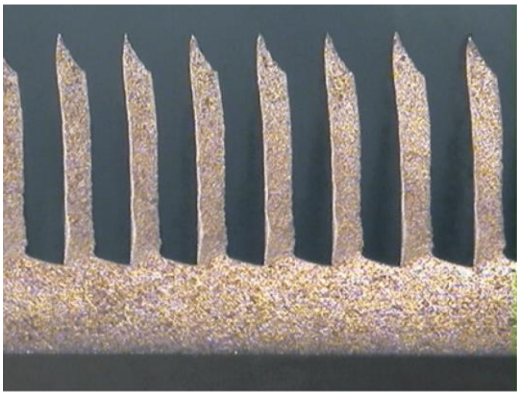

Figure 3. Vapor removal channels produced by DCM.

Table 2. Parameters of the channels

ID	m, mm	h, mm	p, mm
MC 1	0.3	0.7	0.6
MC 2	0.1	0.7	0.2
MC 3	0.1	0.7	0.2

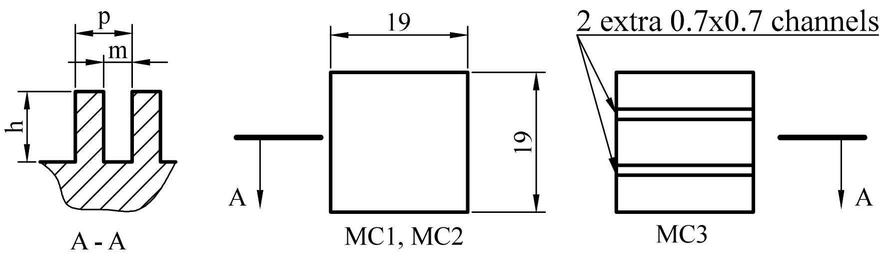

Figure 4. Top view and section view of the channels. Also see Table 2.

Total of three different microchannel surfaces were investigated. The sample MC3 was additionally provided with two transverse channels measuring 0.7 by 0.7 mm to improve the vapor removal process. The parameters of the microchannel plates are shown in Fig. 4 and Table 2.

III. EXPERIMENTAL SETUP ASSEMBLY AND PROCEDURE

Heat input was applied to the microchannel plate through a flat ceramic heater WATLOW measuring 19 mm by 19 mm, a thickness of 2.5 mm. Since the heater is made of ceramic with high thermal conductivity, the heat flow is evenly distributed thereon. The heater was linked via a power meter D5004 (accuracy ± 0.5 W) and a laboratory transformer Solby TDGC2-0.5-B. Because of the small thickness of the heater, and also considering that the heat flow from the heater to the microchannel plate is much higher than to the thermal insulation side, due to the evaporation process with a high heat transfer coefficient implemented on a plate, it is assumed that additional measures to clarify the magnitude of the heat flux are not required. Type-L thermocouples were used to measure the temperature. Thermocouple wires are made of 0.1 mm in diameter and rolled to a thickness of 30 microns at the hot junction. A thermocouple TC1 was soldered to the center of the microchannel plate to a side facing the heater (Fig. 5). Thermocouples TC2 и TC3 were installed in the middle and at the top of the glass fiber wick. Thermocouple TC4 was located just above the perforated plate inside the CC. Data from the thermocouples were acquired using a data acquisition device L-card LTR 27. Experiments on each configuration were conducted at least four times to determine the repeatability of results.

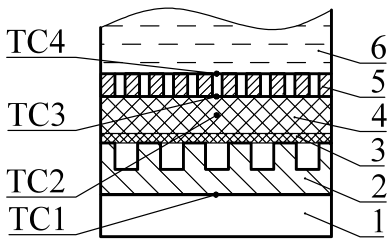

Figure 5. Installation of Thermocouples.
1 – heater; 2 – microchannel plate; 3 – copper mesh; 4 – glass fiber wick; 5 – perforated plate; 6 – compensation chamber.

IV. RESULTS AND DISCUSSION

A. Effect of heat flux supplied

Figure 6 shows the temperature of the plate depending on the heat load for the three samples studied MC1, MC2, MC3. TC1 temperature is determined by the conditions in the area of evaporation. Factors determining these conditions also include the scheme of vapor removal channels selected. The graph shows that the most effective is the scheme MC3, which in addition to narrow longitudinal channels measuring 0.1 mm by 0.7 mm in size has two transverse channels measuring 0.7 mm by 0.7 mm. The transverse channels unloaded the evaporation zone, reducing the vapor path through the narrow channels of high resistance. The schemes MC1 and MC2 face competition in the low heat fluxes, but starting from Q = 60 W, the scheme MC1 with 0.3x0.7 mm channels becomes more efficient. Figure 7 shows the values of the heat transfer coefficient calculated from TC1 temperature and the saturation temperature of water at atmospheric pressure. For comparison, the data obtained by the Mikheyev's equation are also presented.[14] It is seen that for q> 20 W/cm^2 heat transfer coefficient insignificantly increases with increasing heat flux, presumably due to non uniform distribution of liquid over the surface of evaporation. Total cross section of the holes of the perforated plate is about 35% of the surface area of the heater. Also, necessary to consider that wick used is thin, so the liquid may not have time to be uniformly distributed over the volume of the wick, which is especially evident at high heat fluxes, and hence the high liquid flow rates. An indirect confirmation of this is the appearance of the copper mesh, which during the experiment is located between the wick and the microchannel plate plate. The mesh after the experiments had on its surface traces of a circular shape corresponding to the openings of the perforated plate.

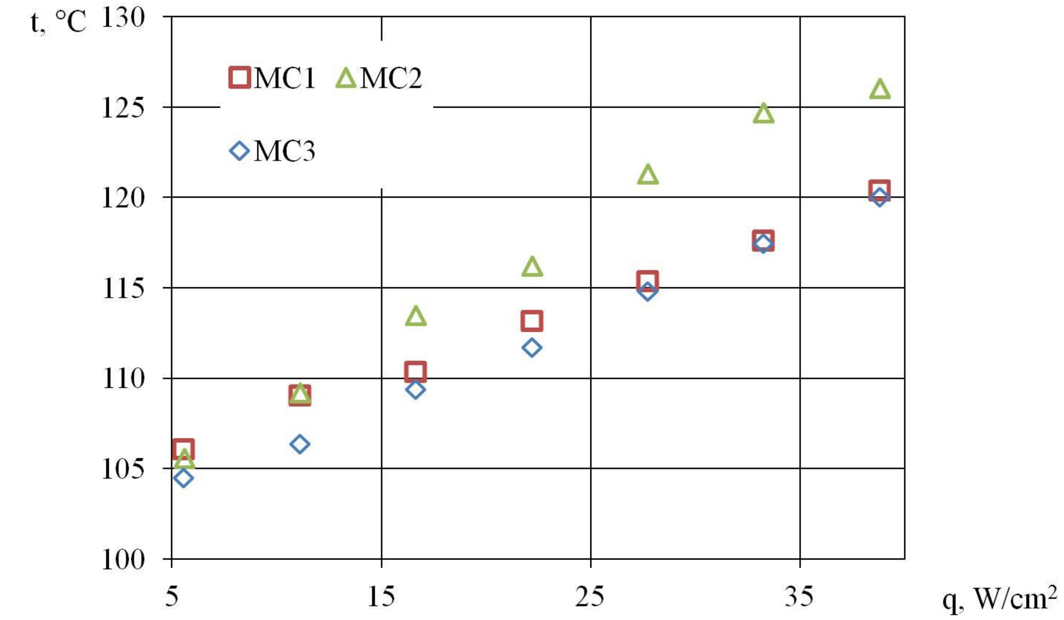

Figure 6. TC1 temperature versus heat load.

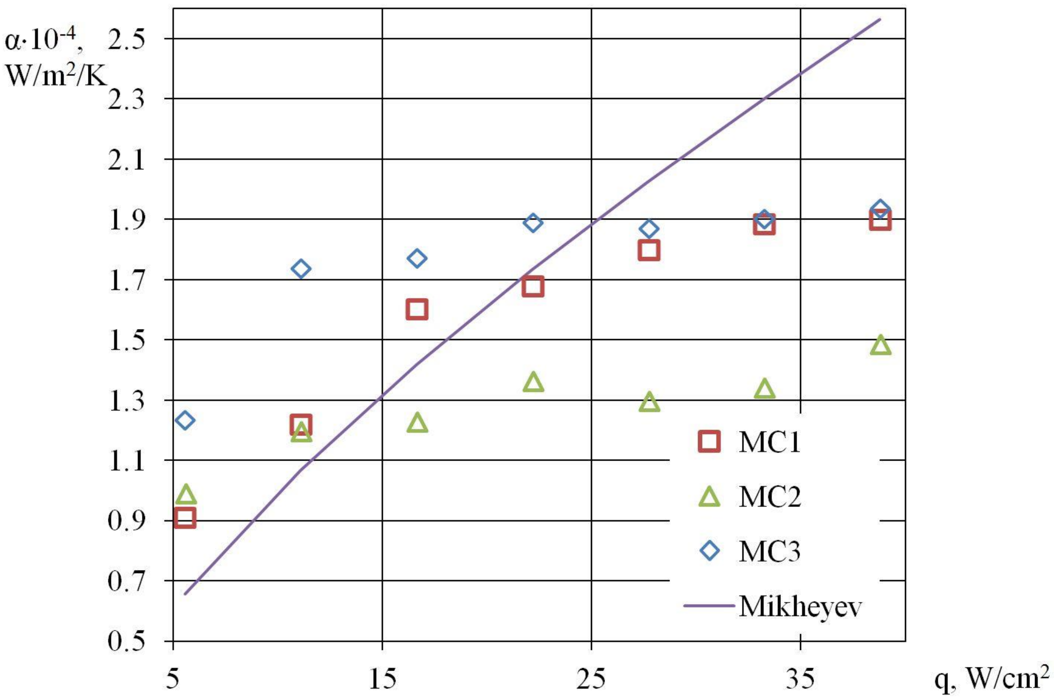

Figure 7. Heat transfer coefficient versus heat load.

B. Influence of the levels difference in the reservoir and CC

To study the effect of different pressure gradients between the absorbing and the evaporating surfaces of the wick on heat transfer, a series of experiments were carried out with a difference in the levels of 0.12, 0.2, 0.4 and 0.6 m, which corresponds to the pressure difference on the opposite sides of the wick ΔP 1.2, 2, 4 и 6 kPa respectively. Figure 8 shows the results for all three samples of the microchannel surfaces. Here the effect of the width of microchannels on heat transfer in the evaporator at different levels difference ΔH is clearly expressed. When ΔH = 0.4 m and 0.6 m readings of the thermocouple TC1 is significantly higher in MC1, as MC1 as a surface provides less uniform thermal load on the wick than MC2 and MC3. Increasing the value of ΔH decreases radii of evaporating menisci, and the liquid flow is disturbed at the the most loaded areas of evaporation especially at large pores, i.e. the wick dries out in these places.

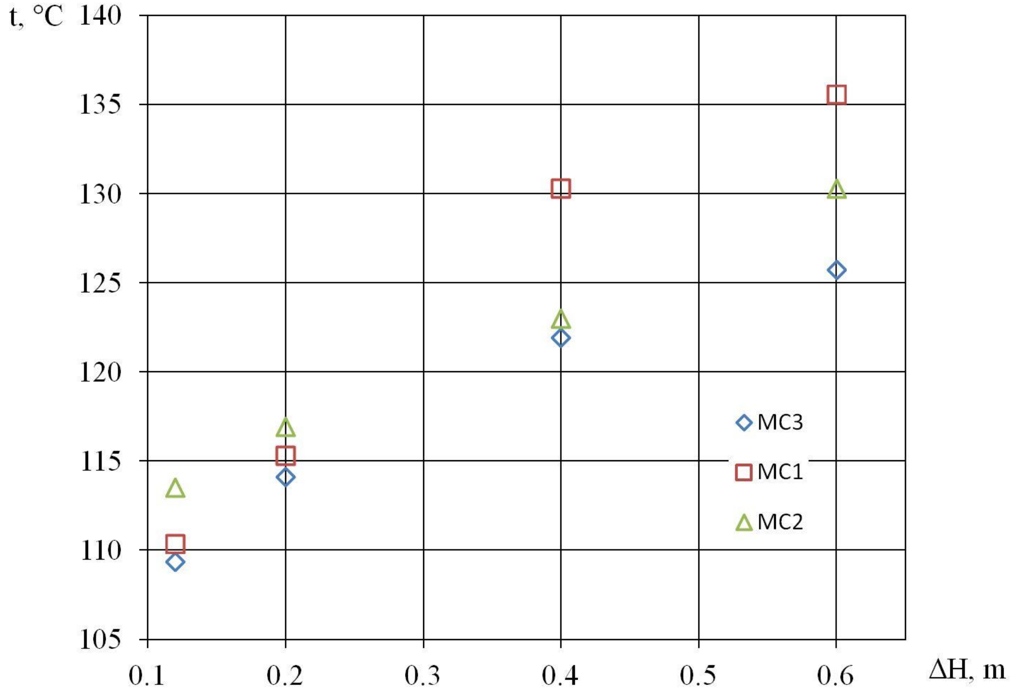

Figure 8. TC1 temperature for different pressure drops.

V. CONCLUSIONS

The experimental setup for the study of the evaporation from a porous material with the inverted meniscus configuration has been created.

The article investigated the glass fiber wicks, which provide a set of functional and technological advantages to an LHP evaporator, as compared with the wicks of metal powders. But the glass fiber wicks and have disadvantages associated with a reduced amount of evaporating menisci owing to the low thermal conductivity of glass. To resolve this problem the paper proposed to provide more uniform heat input to the surface of the glass fiber wick through the use of finned surface with a small step and channels of high aspect ratio obtained by the deformational cutting method.

It was established that even if a microchannel surface with a small step have been created, it is necessary to "unload" the long narrow vapor channels by producing additional transverse vapor removal channels.

It was established that the current configuration of the evaporator has a disadvantage that is the unevenness of the liquid supply to the wick. Total cross section of the holes of the perforated plate comprises only 35% of the wick surface area that is not enough for uniform liquid distribution.

The series of experiments with different levels drop ΔH showed that the configuration of the evaporator with a more uniform supply of heat flux to the wick give greater heat transfer coefficient. In LHP evaporators such a configuration will allow to create a greater external load in the form of pressure drop across the wick, ie this will enable greater length of a transport tube or smaller diameter of tubes.

Technology for assembly of the evaporators having nonrigid wicks will increase tolerances for manufactured parts and the assembly itself, which may affect the manufacturing cost of LHP.

NOMENCLATURE

α	=	heat transfer coefficient
ΔH	=	level difference
ΔP	=	pressure difference
q	=	heat flux
Q	=	heat power

REFERENCES

[1]Singh, R., Akbarzadeh, A., Mochizuki, M., “Thermal Potential of Flat Evaporator Miniature Loop Heat Pipes for Notebook Cooling,” *Components and Packaging Technologies, IEEE Transactions on*, vol. 33, no. 1, March 2010, pp. 32-45.

[2]Maydanik, Yu. F., Vershinin, S. V., “Development and tests of ammonia Miniature Loop Heat Pipes with cylindrical evaporators,” *Applied Thermal Engineering*, Vol. 29, Issues 11–12, August 2009, pp. 2297-2301.

[3]Lin, Z.R., Lin, W.Z., Zhang, L.W., Wang, S.F., “An experimental study on applying miniature loop heat pipes for laptop PC cooling,” *Semiconductor Thermal Measurement and Management Symposium (SEMI-THERM), 2013 29th Annual IEEE*, 17-21 March 2013, pp. 154, 158.

[4]Wang, S., Huo, J., Zhang, X., Lin, Z., “Experimental study on operating parameters of miniature loop heat pipe with flat evaporator,” *Applied Thermal Engineering*, Vol. 40, 2012, p. 318-325.

[5]Chernysheva, M. A., Maydanik, Yu. F., “Simulation of thermal processes in a flat evaporator of a copper–water loop heat pipe under uniform and concentrated heating,” *International Journal of Heat and Mass Transfer*, 55, 2012, pp. 7385-7397.

[6]Khrustalev, D., Faghri, A., “Heat transfer in the inverted meniscus type evaporator at high heat fluxes,” *International Journal of Heat and Mass Transfer*, vol. 38, issue 16, November 1995, pp. 3091-3101.

[7]Raiff, R. J., Wayner, Jr. P.C., “Evaporation from a porous flow control element on a porous heat source,” *International Journal of Heat and Mass Transfer*, vol. 16, issue 10, October 1973, pp. 1919-1929.

[8]Chien-Chih, Y., Chun-Nan, C., Yau-Ming, C., “Heat transfer analysis of a loop heat pipe with biporous wicks,” *International Journal of Heat and Mass Transfer*, volume 52, issues 19–20, September 2009, pp. 4426-4434.

[9]Xiang Jun, Chang, Shyy Woei, Escada, “Thermal Performances of Loop Heat Pipe with Hybrid Wick Structures in Evaporator,” *proceedings of 10th IHPS*, Taipei, Taiwan, Nov. 6-9, 2011.

[10]Maziuk, V. V., Doctarau, V. V., Rak, A. A., “Miniature loop heat pipes with noninverted meniscus concept and treatment,” *International Journal of Low-Carbon Technologies*, 2006, vol 1, is. 3, pp. 228-235.

[11]Maydanik, Yu.F., “Evaporator for heat pipe,” Russian Patent No. 2286526, 2006.

[12]Nagano, H., Ogawa, H., Fukuyoshi, F., and Nagai, H., “Fabrication and Testing of a Small Loop Heat Pipe With a Plastic Wick,” *proceedings of International Conference on Heat Pipes for Space Application*, Moscow, 2009.

[13]Zubkov, N. N., and Ovchinnikov, A. I., European patent for a “Method of Producing a Surface With Alternating Ridges and Depressions and a Tool for Carrying Out the Said Method,” European Patent No. 0,727,269, pub. Date 21 august 1996.

[14]Mikheyev, M.A., Mikheyeva, I.M., *Basics of Heat Transfer*. Moscow, “Energy”, 1973.