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INVESTIGATION OF HEAT TRANSFER IN EVAPORATOR OF MICROCHANNEL LOOP HEAT PIPE

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ABSTRACT

Loop heat pipes (LHP) are closed loop heat transfer devices which use evaporation and condensation of a working fluid to transfer heat and use capillary forces to provide fluid circulation. One of the main applications of LHP is cooling of electronics components. Further development in this field is associated with miniaturization. Therefore in electronics cooling there are strict limits imposed upon size of elements of heat transfer devices. One of such elements is evaporator of LHP, its main element. This paper deals with LHP evaporator and aims to find ways of reducing its thickness. An open loop experimental setup was created to investigate heat transfer phenomena in evaporator. Experiments were carried out with variety of configurations. Evaporator consists of microchannel plates with groove width 100 and 300 micrometers, wick (metal and non-metal porous materials were used) and compensation chamber (CC). Heat load varied from 20 to 140 W by steps of 20 W. The area of heater was equal to 19 mm x 19 mm. Working fluid – deionised water. Experiments resulted in data on temperature distribution across wick's height, temperature of microchannel's surface and temperature of water in compensation chamber. The results reveal potentials to perform optimization of evaporating zone to produce thinner evaporators.

Keywords: evaporator, loop heat pipe, microchannel.

INTRODUCTION

At present there is a high demand for creating of compact heat transfer systems in the field of electronics cooling. Devices must transfer heat fluxes of value more than 100 W/cm^2. Conventional heat pipes (HP) and loop heat pipes are capable to satisfy the demand. HP have already been widely applied to electronics cooling equipment. Almost every modern laptop or desktop computer is equipped by a heat pipe. Application of LHP lay generally in cooling of spacecrafts' equipment. But LHP can also be used for cooling of compact electronic devices because they possess some unique advantages such as:

- Separate channels for vapor and liquid that are made of tubes with smooth walls and can be easily bent in desired way.
- Capillary structure in LHP is restricted to the evaporator section only.
- Evaporator of LHP has more developed structure in comparing with conventional heat pipes. Heat is applied directly to evaporating meniscus through fins of heating surfaces. But in conventional heat pipes heat need to cross liquid saturated wick in order to get to meniscus.

For successful integration of LHP into compact electronic devices it is necessary to create designs with overall thickness comparable to those of conventional heat pipes and liquid cooled heat sinks. But decreasing of thickness has underside. The thinner evaporator is the higher parasitic heat flow occurs from evaporator to compensation chamber in LHP via the interconnecting liquid saturated wick. Heat leaks from evaporator to CC prevent from achieving necessary temperature difference and corresponding pressure difference between evaporator and CC.

Authors of [1] developed compact LHP with metal wick for electronics cooling with supplementary cooler for compensation chamber in order to compensate the parasitic heat flow. LHP evaporator developed had cylindrical shape and thickness of 7 mm.

Technologically it is simpler to create LHP with cylindrical shape evaporator, but flat evaporators are more compact and don't require additional connection interfaces such as saddle.

In [2] authors designed compact loop heat pipe with metal wick and flat evaporator thickness of 5 mm. It was stated that LHP have greater value of thermal resistance at low heat loads in comparing with conventional heat pipes and with single phase cooling. Because compensation chamber is combined with evaporator in a single case. Such design allows providing constant wetting of the wick structure by liquid and regulating fluid inventory change in the LHP under all heat loads. However combining CC with evaporator leads to high heat flux towards to CC across the wick saturated by liquid. And it finally raises evaporator's temperature.

One of the ways to decrease the amount of heat leaks from evaporator to CC is using wick made of material with low thermal conductivity. Practically it is impossible to change only thermal conductivity of wick to catch its influence on operation. All other properties of wick such as pore size, permeability, porosity are inevitably are changed as well. The above properties significantly influence on the main functions of the wick in evaporator:

- capillary feed evaporating surface by liquid (pore size, permeability);
- provide hydraulic barrier for vapor i.e. prevent vapor entering into compensation chamber (pore size);
- provide heat barrier i.e. wick must prevent compensation chamber from getting high heat fluxes from evaporation zone (thermal conductivity, porosity).

Most of developed LHP use evaporators with sintered metal powder wicks (nickel, titanium, steel etc.). Much less studies devoted to LHPs with non-metal wicks (ceramic, plastic, fiberglass etc.).

Authors of [4] concluded that wicks with low thermal conductivity work better at low heat loads, and wicks with high thermal conductivity are better when heat loads are high. Wicks of different thermal conductivity were examined and authors stated that capillary limit occurs at the most loaded meniscus that are in contact with heating surface. Also the peculiarity of low conductivity wick is that evaporating meniscus located in thin layer of wick near the heating wall. But wicks made of high conductive material have more uniform distribution of evaporating meniscus. That's why dry-out of low thermal conductive wick occurs earlier and spreads deeper into the wick. This dry-out leads to additional pressure losses that finally influence on vapor temperature raising it. Heat pipe with wicks of low thermal conductivity has lower thermal resistance at low heat loads before dry-out occurs. But when partial dry-out occurs heat pipes with wicks of high thermal conductivity become more effective.

Authors of [5] created cylindrical LHP with plastic wick and described the main advantages of non-metal wick materials:

(1) low thermal conductivity;
(2) low cost;
(3) high processability;
(4) low weight;
(5) easy assembling.

However authors also mentioned disadvantages:

(1) temperature limit;
(2) compatibility;
(3) shrinkage;
(4) low durability.

In [6] a loop heat pipe with polypropylene wick was developed. It was able to transport thermal load of 80W at horizontal position, while maintaining the vapor temperature (i.e., operating temperature) less than 80°C.

Authors of [7] presented a miniature LHP for laboratory tests with filter paper wick. The results of the experiments showed the working efficiency of described design of LPH with microchannels and paper wick. LHP kept constant temperature under given heat loads up to 70 W.

Another essential part of evaporator is heating surface with fins machined on it. This surface with fins and grooves performs double function: conducts heat through fins to evaporating meniscus and provides channels for vapor removal.

An optimization of evaporation zone consists of choosing wick and vapor removal channels configuration and finding pair that has the best thermal performance in given heat loads range. Such work was performed by Kiseev [3]. He investigated different configurations of vapor removal channels and their influence on heat transfer characteristics of evaporator. Experiments showed effectiveness of developed system of radial and circumferential channels. Author concluded that the less step size of microchannels is created the better efficiency of evaporator. It was noted that machining microchannels of sizes less than 500 micrometers is technologically difficult. Also author investigated wick materials of different thickness. All materials were made of metal. He reported that there was optimal thickness of wick material that depends on configuration of particular LHP and lays in the limits of 4 to 7 mm.

In the current paper authors investigate heat transfer processes in flat evaporator with microchannels. Different wick materials are used. Thickness of wick is varied from 0.4 mm to 2.5 mm. Influence of vapor removal channels' size is also subject of current research.

DEFORMATIONAL CUTTING TECHNOLOGY

The microchannels on investigated samples were made by patented deformational cutting method (DCM) [8]. The principle of this method is shown in Annex A on Fig. A1. The tool 2 undercuts the workpiece's 1 surface layers and plastically deforms them to make uniform finned structure 3. Any ductile metal with elongation more than 18% may be used as work material such as copper, titanium, steel, stainless steel etc. or polymers like polyethylene terephthalate, polyethylene, polyvinylchloride, rubber, Teflon and others. Initially DCM was developed for finning of heat exchange tubes (Fig. A2a).

DCM is readily adaptable to conventional machining as lathe for rounds and sheets and milling equipment or shaper for flat surfaces. Sheet finning on lathe realized by using drum for sheet tensioning. The fin thickness a depends on undercut tool angle φ and fin pitch p as $a=p\cdot sin\varphi$ (Fig. A1). The fin height h is a function of φ and depth of cut t: $h=t/sin\varphi$. The groove width $m=p\cdot(sin\varphi_1-sin\varphi)$. The last expression means that for angled finning when $\varphi_1<90^o$ and $\varphi\approx\varphi_1$ there is no any limitation for minimum groove width. It may be m=0. The DCM is non-waste and needn't any lubricant i.e. secondary cleaning steps are not required.

The typical profile of fins is shown on Fig. A2b. The pitch of fins p can vary from 0.08 to 4 mm, maximum fin height $h_{max}=6p$ for soft materials (aluminum, copper) and $h_{max}=4p$ for steels. Surface area after finning for copper increases up to 12 times.

Finning the surface twice in different directions leads to obtaining pin arrays (Fig. A2c). Using special tool [9] it is possible to enhance inner tube surface (Fig. A2d). Channeling metal sheet from opposite sides, DCM is capable of producing fine meshes via the intersection of the angled channel depths (Fig. A2e). The method permits to make up to 400 holes per square millimeter on titanium sheet. Improved DCM [10] is capable of producing special surfaces for boiling (Fig. A2f).

EXPERIMENTAL SETUP

One needs to get over a lot of challenges while assembling the evaporator structure, particularly for miniature LHPs, which require precision machining and proper placement of the internal components. All below factors can worsen characteristics or lead to fail of LHP cycle: improper thermal contact between fins of heating surface and wick structure in evaporation zone due to assembling tolerances and run-out flatness, partial or complete oxidation of the wick during high temperature brazing or soldering of evaporator, internal leaks or bypass of fluid from evaporator to compensation chamber due to improper sealing around wick, sealing issues in the loop due to brazing or soldering defects, machining and cleaning impurities that can clog the wick, and chemical incompatibility between the structure/wick material and working fluid and non-condensable gases [1].

It is necessary to assemble and disassemble LHP many times in order to investigate heat and mass transfer characteristics of different configurations of the device. And every time one will meet the difficulties mentioned above especially when working with vacuumed LHP. Vacuum systems require very clean and careful operations and don't like any dismountable connections.

Taking all these factors into consideration authors created open atmospheric system of evaporator to investigate heat transfer processes and make steps towards to reducing thickness of LHP. This open evaporator allows to perform quick change of wicks and microchannel plates with easy assembling/disassembling. The schemes are given on Fig. 1 and 2.

As it was stated assembling of test setup was not a difficult task. The process was as following (from bottom to top per Fig. 1): ceramic heater 3 with adhesive bonded copper microchannel plate 4 was installed on the base 1. The orientation of microchannels was chosen in that way to prevent hot vapor from contacting with the heater and thermocouples' wires. Microchannel plate performs two functions – it transfers heat load to evaporation surface and allows vapor to evacuate through channels between fins.

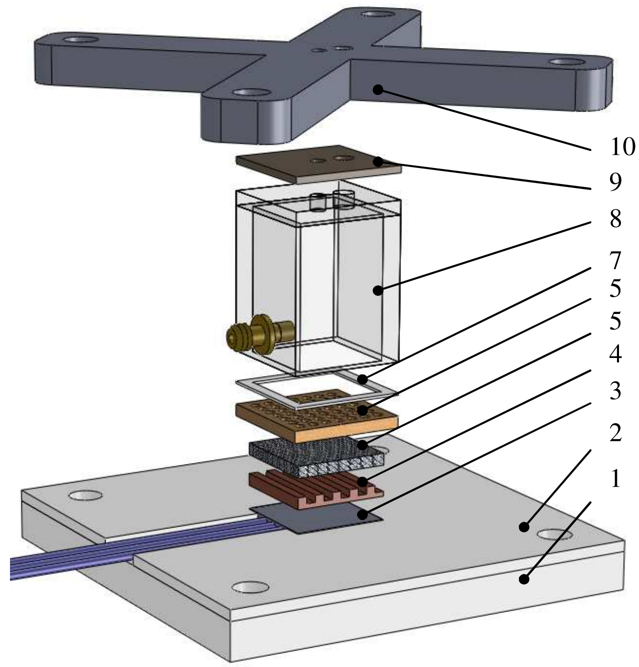

Figure 1. Assembly of evaporator

1 – Base; 2 – insulation plate; 3 – heater; 4 – microchannel plate; 5 – wick; 6 – perforated plate; 7 – paper gasket; 8 – compensation chamber; 9 – vacuum rubber gasket; 10 – cross part.

Then insulation plate 2 made of material of very low thermal conductivity was installed to reduce heat fluxes across sides of the heater. After that the first layer of wick 5 was installed on microchannel plate, then flat 30 micrometers thermocouple was positioned on it with direction perpendicular to vapor microchannels. The next step was installation of remaining layers of the wick. Another thermocouple was attached over the top layer of wick to measure temperature of suction side (Fig. 3). Then perforated plate 6 with diameter of holes 1.5 mm covered the wick. Holes in the plate feed the wick by liquid. After that a gasket 7 made of four filter paper layers was put on perforated plate. Pore size of this gasket material was less than those of wick. Then plexiglass case 8 of compensation chamber was mounted over the gasket. At the top it was pressed by cross-shaped detail using four bolts of 6mm diameter over the gasket made of vacuum rubber. Two holes were drilled in the top of CC for thermocouple TC4 and for tube of pressure transducer and drain valve (Fig. 2).

TESTING PROCEDURES

Experimental setup shown on Fig. 2 is open atmospheric evaporator system. Liquid flows from the upper reservoir to the buffer through the valve V1. Buffer is located on lower level than the compensation chamber. Buffer was used to keep liquid at constant level to provide necessary pressure difference between compensation chamber and environment.

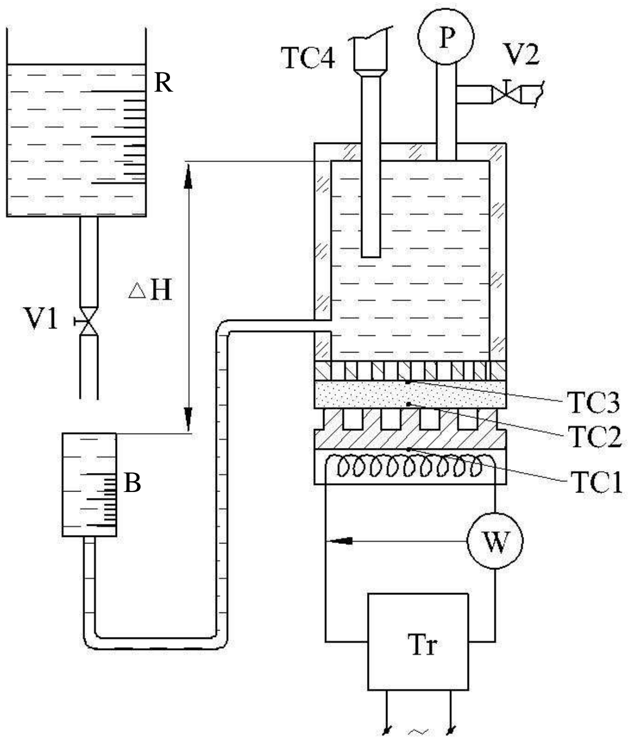

Figure 2. Test scheme

V1, V2 – valves; Tr – transformer; P – pressure transducer; W – powermeter; TC1-TC4 – thermocouples; ΔH – level difference; R – reservoir; B – buffer

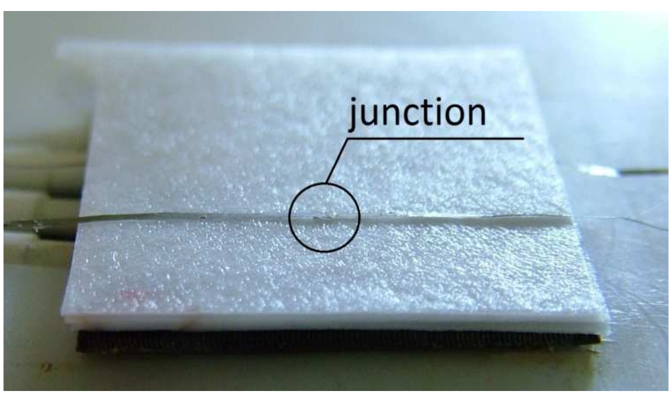

Figure 3. Flat thermocouple TC3 on the top of the wick

Absolute pressure in compensation chamber was measured by pressure transducer P located at the top of CC (Fig. 2). Flow rate was measured using buffer. Liquid was kept on the certain level in the buffer while amount of liquid leaving the reservoir was registered and time passed was measured.

The following wick structures were used in experiments (Table 1).

Table 1. Types of wick material

Material	Pore size, μ	Thickness, b, mm
Filter Paper (FP) GOST 12026-76	10	0.4
Stainless Steel (SS) Powder	10-15	2.5
Glass Fiber (GF)	2.6	0.4; 1.2; 2.4

It was necessary to fill compensation chamber completely and provide necessary pressure difference before starting experiments. When assembly complete the Buffer was installed at level higher than that of drain valve V2. Then CC was filled by deionised degassed water from reservoir. When the compensation chamber was filled water began to leave the evaporator through valve V2. After closing V2 buffer was located at position below the evaporator as shown in fig. 2. The difference in levels was ΔH=150 mm during all experiments. It produced vacuum in CC of approximately 1500 Pa below atmospheric pressure that was registered by vacuum transducer. Such underpressure was necessary to obtain conditions of pressure for wick similar to conditions in closed LHP. As discussed wick's function is to provide hydraulic barrier: high pressure exists at the side turned to heating surface due to evaporation of water in confined space, but on the opposite side of wick – absorbing surface – pressure level is low due to cold liquid entering from condenser.

Heat power was applied via flat ceramic heater that provides uniform heat flux. Thickness of heater was 2.5 mm and dimensions 19 mm x 19 mm. Heater was connected to laboratory transformer. Heat power varied from 20 to 140 W by steps of 20 W. Type L thermocouples were mounted as shown on Fig. 2. Thermocouple TC4 was installed into CC and allowed moving it in vertical direction. TC3 thermocouple shown on Fig. 2 and 3 was located on absorbing side of the wick. It was flat thermocouple with thickness of 30 micrometers. Similar thermocouple TC2 was embedded inside the wick. There was additional thermocouple TC5 that allowed measuring the temperature of vapor leaving the vapor removal channels. During experiment TC5 was moved along the edge of microchannel plate to get temperature distribution. Data from thermocouples and vacuum transducer was acquired using data acquisition device L-card and transferred to computer for processing.

The following types of microchannels were used in experiments (Table 2 and Fig. 4).

It was revealed during experiments that bubble flow occurred in compensation chamber from the bottom of to the top. Amount of bubbles changed for different wick materials. The most frequent bubble generation was captured while carrying out experiments with metal wick. A bit less bubbles occured at evaporator with glass fiber wick of minimum thickness.

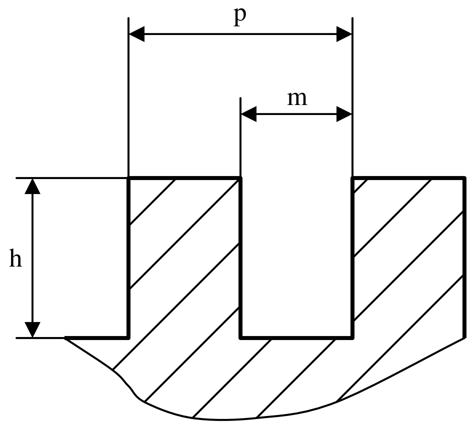

Figure 4. Microchannel's section

Table 2. Parameters of microchannels

№	m, mm	h, mm	p, mm
MC1	0.3	0.8	0.6
MC2	0.1	0.8	0.2

The more layers constructed the glass fiber wick the less amount of bubbles occurred. And finally on glass fiber wick of thickness 2.4 mm no bubbles were registered. Authors consider part of these bubbles to be non-condensable gas that entered CC from atmosphere through the wick. The fact that proved it was existence of bubble inside CC after completing experiments and after system was cooled to the room temperature. The reason for bubble entering the CC is large pores that exist in wick material. Local dry out occurs at the locations of large pores or capillary pressure is insufficient at these locations and bubbles get the way into compensation chamber. Additional prove to this is bubbles' vanishing after increasing the wick's thickness. Authors of paper [11] also stated this.

Using data on temperature the total heat power Q was calculated. The difference between calculated value and value measured by power meter didn't exceed 3-5% for all experiments:

$$Q = Q_w + Q_e + Q_v \quad (1)$$

$$Q_w = \dot{m} C \Delta T_w \quad (2)$$

$$Q_e = \dot{m} r \quad (3)$$

$$Q_v = \dot{m} C_p \Delta T_v \quad (4)$$

$$m^{\cdot} = \rho \Delta V / \tau \quad (5)$$

$Q_{w,e,v}$ – heat applied to water, evaporation and vapor respectively, W; $\dot{m}$ – mass flow rate, kg/sec; C, C_p – specific heat of water and vapor, J/(kg·K); $\Delta T_{w,v}$ – temperature difference for water and vapor, K; r – latent heat of evaporation, J/kg; ΔV – volume, m^3; ρ – density, kg/m^3; τ – time period, sec.

RESULTS AND DISCUSSION

Every experiment of the current study resulted in data on temperature from thermocouples and pressure values from vacuum transducer. Temperature of heating surface measured by thermocouple TC1 versus heat loads is shown on Fig. 5 and 6 for MC1 and MC2 and different wick materials. Filter paper wick could only withstand three regimes 20, 40 and 60 W. At higher heat fluxes temperature began to rise continuously and no stationary temperature was achieved. Authors consider that this type of material has certain maximum temperature level of operating. After exceeding this level behavior of material becomes unstable.

Figures 7 and 8 show temperature of heating surface TC1 for the particular wick for different microchannel plates. Only GF b=0.4 and SS wick are shown but situation is similar for all wick materials and thickness tested.

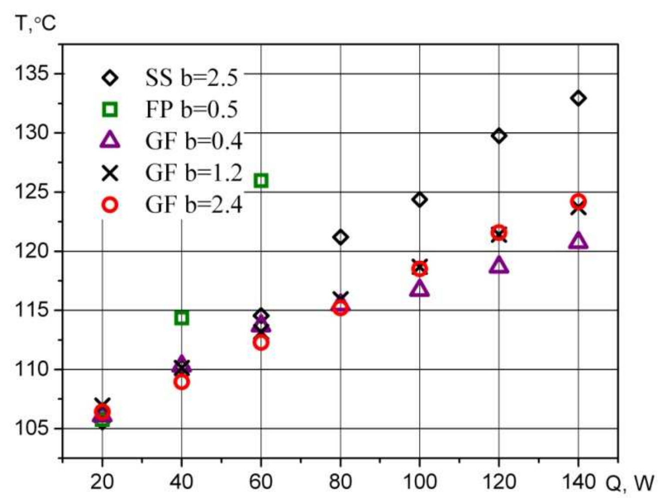

Figure 5. Heater surface temperature TC1 vs heat load for MC1 for different wick materials

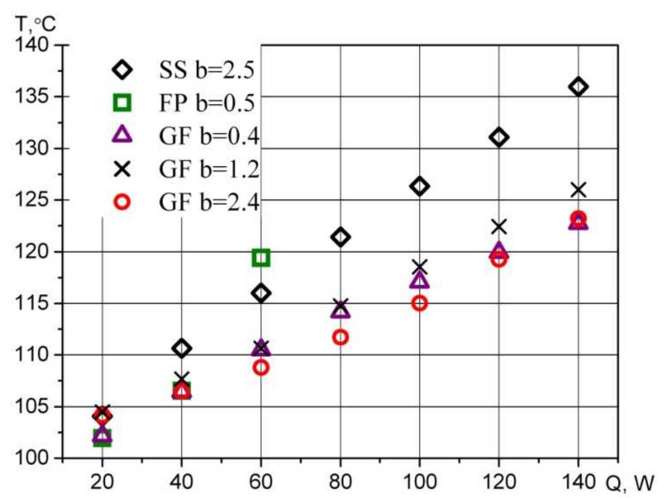

Figure 6. Heater surface temperature TC1 vs heat load for MC2 for different wick materials

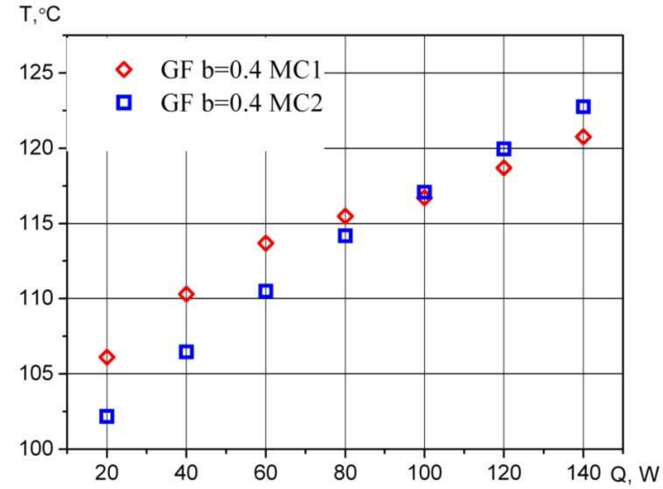

Figure 7. Heater surface temperature TC1 vs heat load for GF b=0.4 for MC1 and MC2

Microchannel plate MC2 with narrow channels works better at low heat fluxes and at high heat fluxes plate with wide channels MC1 become more effective (maintains lower temperature). Narrow fins of MC1 provide more uniform heat input to the wick that result in lower temperature of TC1. But as heat flux grows flow rate increases and pressure losses become significant for narrow vapor removal channels of MC1. In such situation relatively wide vapor removal channels of MC2 provide better solution.

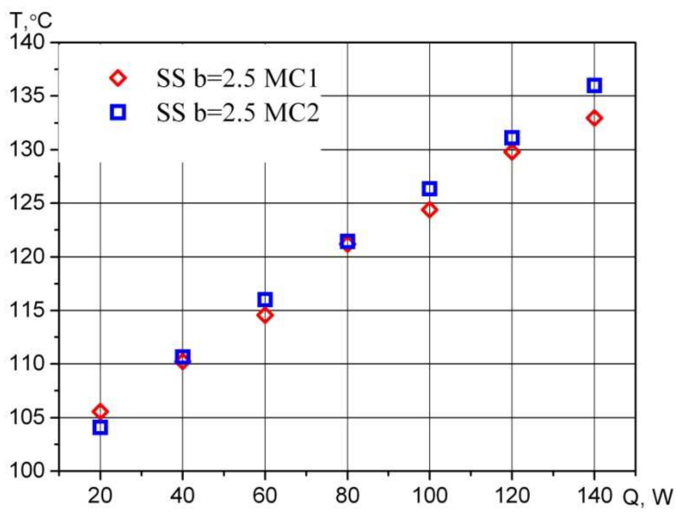

Figure 8. Heater surface temperature vs heat load for SS b=2.5 for MC1 and MC2

Figure 9 shows temperature difference between heater surface and absorbing side of wick under given heat loads for MC1 ($\Delta T=TC1\text{-}TC3$). Graph for MC2 is similar and not shown. Non-metal wicks have temperature difference greater than those of metal stainless steel wick. The only exception is glass fiber wick with thickness of 0.4 mm (it is located close to metal wick points on graph). Temperature difference rises with increasing of thickness as expected. Temperature difference $\Delta T = T_V - T_{CC}$ plays very important role in performance of LHP. This value is a part of equation that formulates the second requirement of LHP efficiency [12]:

$$\left.\frac{dP}{dT}\right|_{T_V} (T_V - T_{CC}) \cong \sum \Delta P_{ext} \quad (6)$$

dP/dT – derivative of saturation line at point $T=T_V$; T_V – temperature of vapor ($T_V \approx TC1$), K; T_{CC} – temperature of water in compensation chamber ($T_{CC}=TC3$), K; ΔP_{ext} – pressure losses in LHP except for wick, Pa.

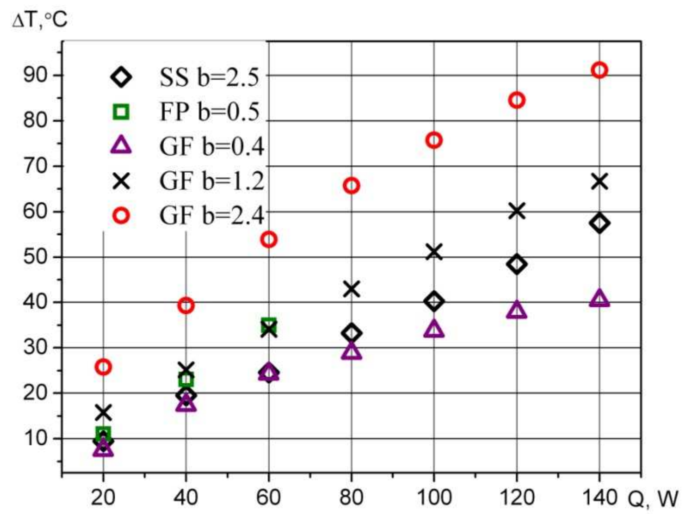

Figure 9. Temperature difference between heater surface and absorbing side of wick vs heat load for MC1 ($\Delta T=TC1\text{-}TC3$)

Having greater ΔT makes possible to create LHP with longer distances of heat transfer (i.e. LHP can work with greater pressure drops). Or under the same sum of pressure drops LHP with greater value of ΔT are capable of operating at lower point of saturation line at lower temperatures for given working fluid.

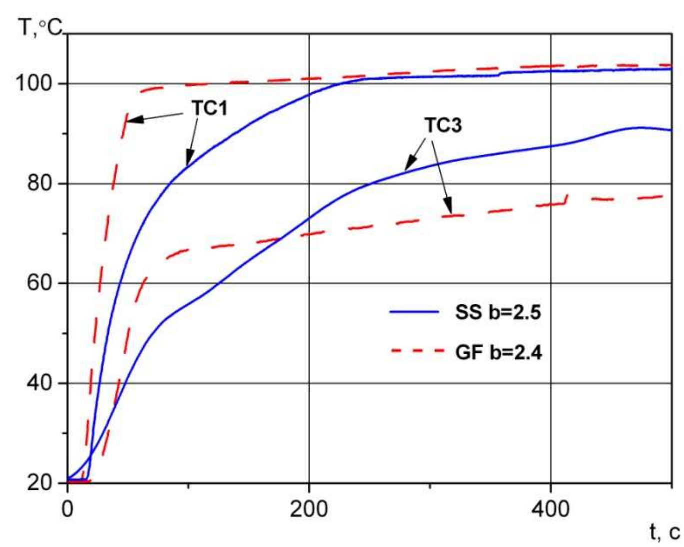

Figure 10. Startup characteristics for MC1 at Q=20 W

Non-stationary processes of heating surface's temperature growing (TC1) and absorbing surface of the wick (TC3) temperature growing are shown on Fig. 10. LHP start-up process is subject of many papers. Especially at low heat loads LHP often cannot start functioning successfully. Because at start moment there is no temperature difference and corresponding pressure difference between evaporator and CC. As shown on Fig. 10 configuration with glass fiber wick has greater slope of growing line. It takes less time for starting evaporation process for glass fiber wick.

CONCLUSIONS

Experimental setup for studying heat transfer characteristics of LHP evaporator was designed, assembled and tested. Experiments were carried out for different wick materials and two configurations of microchannel plates.

Microchannel plate with channels of 0.3 mm in width showed efficiency at high heat fluxes whereas microchannel plate with narrow channels of 0.1 mm were better at low heat fluxes.

Wick materials made of glass fibers having 2.6 micrometers pore size showed better working efficiency (i.e. lower working temperatures) in comparing with metal wick pore size 10 micrometers made of stainless steel powder.

Evaporation began four times faster for glass fiber wick thickness of 2.4 mm than stainless steel wick thickness of 2.5 mm. In closed LHP this fact can influence the startup cycle in the way avoiding the temperature overshoot effect.

Results showed that non-metal wicks have much greater temperature difference between heater surface and absorbing side of wick under given heat loads. This temperature difference represents the key characteristic of the LHP efficiency. Glass fiber wick of 0.4 mm in thickness has almost the same value of $\Delta T = T_V - T_{CC}$ as wick made of stainless steel powder thickness of 2.5 mm. So economy in thickness comprises 2.1 mm. That can greatly decrease the thickness of LHP evaporator.

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ANNEX A

DEFORMATIONAL CUTTING

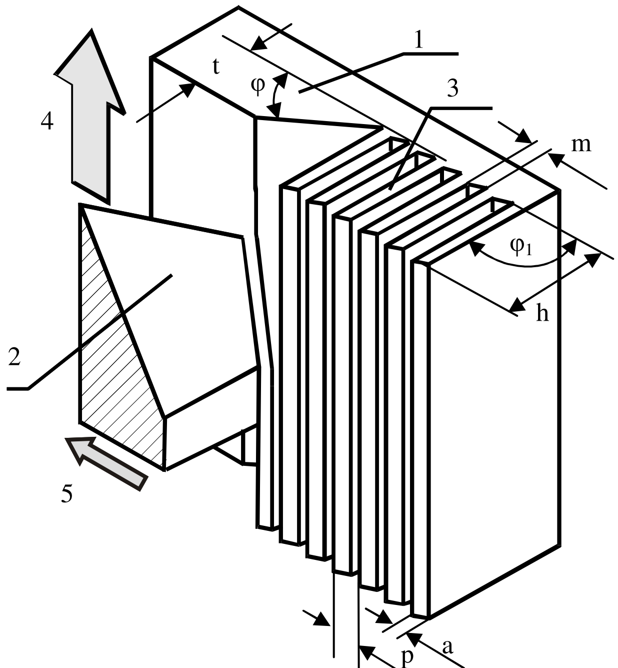

Figure A1. Deformational cutting method
1 – workpiece, 2 – tool, 3 – fins, 4 – primary motion, 5 – feed motion

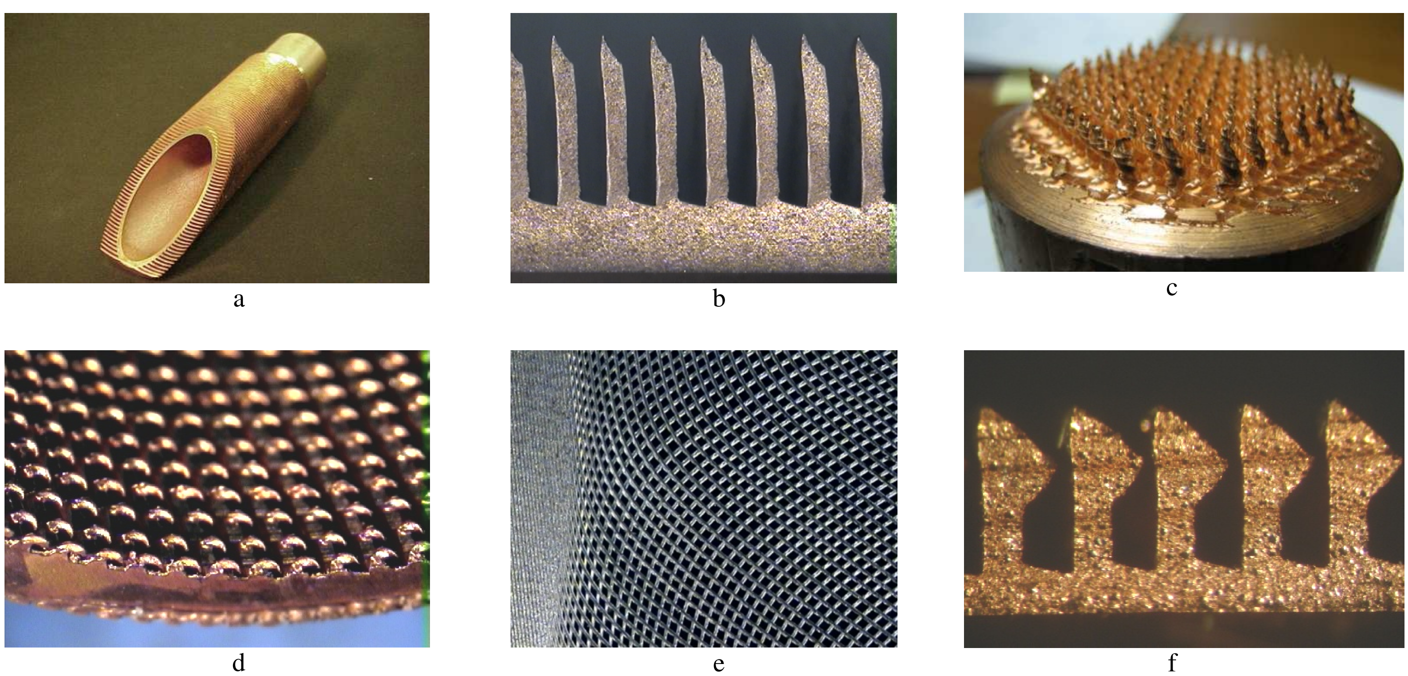

Figure A2. Deformational cutting examples
a- tube finning, b-typical fin frofile, c-pinned surface, d-inside tube enhancement, e-mesh of metal sheet, f- surface for pool boiling