REVIEW OF MICRO-HEAT PIPES: A CONCEPT OF AN EFFICIENT COOLING METHOD

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Abstract. *Micro-heat pipes are passive devices with hydraulic diameter smaller than 1500 μm able to transport a high amount of heat with working fluid's phase change. Direct applications of micro-heat pipes are in cooling compact electronic devices that need an effective refrigeration method to avoid high temperatures on its surfaces. In the last decades, many studies have been carried out focusing on micro-heat pipes development, from different combinations of working fluid type, filling ratio, orientation, material, geometry and size. These parameters must be chosen according to the temperature range between the evaporator and condenser. The objective of this study is to analyse methods of designing micro-heat pipes and the results obtained from different works. The hydraulic diameter observed were between 55 μm to 1500 μm and the most common used geometry was triangular-shape, as many authors state that is better for capillary effect, even though geometries like star grooves and rhombus grooves showed promising results. Substrates as copper and silicon, and working fluids as water, methanol and ethanol are preferred due to their capacity of increasing the effective thermal conductivity, which the highest values observed were between 600 W/m·K and 7574 W/m·K. Other important aspect about micro-heat pipes performance is the orientation relative to gravity, which was considered by a few authors and is a researching point to be further studied in future works. Thus, based on works found in literature, micro-heat pipes can be seen as a promising cooling technique, once it carries out a combination of micro size components with efficient ability of heat transport.*

Keywords*: micro-heat pipe, heat transport, phase change, cooling method*

1. INTRODUCTION

The objective of technology nowadays is mainly to improve devices functionalities in addition to decrease their sizes. The improvement of electronic devices is followed by more energy dissipation in form of heat, which demands an efficient cooling method to keep the surfaces in an operable temperature. A promising solution for electronic industries is the micro-heat pipes. These cooling devices showed to be a promisor cooling method for this case, for being a compact device with high efficiency. According to Vasiliev (2008), small channels have the advantage of a higher heat transfer coefficient and higher heat transfer area per unit volume flow.

The micro-heat pipes consist of devices that transport heat with the constant working fluid's phase change in its interior. Cotter (1984) was the first author to define a concept of micro-heat pipe as a heat pipe reduced in scale linearly in all dimensions and with a noncircular cross section to provide the capillary effect instead of a wick structure. The author considered that, due to the very small dimensions of the micro-heat pipes, the mean curvature of the vapor-liquid interface is comparable in magnitude with the hydraulic radius of the total flow channel. As well as a conventional heat pipe, the micro-heat pipes are also composed by three sections: condenser, adiabatic section and evaporator. The evaporator is in contact with the surface that dissipates heat. The working fluid absorbs this heat and evaporates. The vapor flows through the adiabatic section with a high amount of heat until it reaches the condenser and releases the heat to the outside, normally with a fan. The condensed liquid flows back to the evaporator by capillary effect, provided by the micro-heat pipe's geometry. Thus, there is no need for work injection in the system, differing from others traditional cooling methods.

The thermal analysis of micro-heat pipes are based on different combinations of the substrate that compounds the casing of the device, the working fluid, filling ratio, geometry, size and orientation. A lower thermal resistance and higher effective thermal conductivity measure the performance of these cooling devices. The substrate, the working fluid and filling ratio are closely related to the thermal resistance and conductivity of the micro-heat pipe, and must be chosen depending on the working temperature range, to avoid the fluid flow interruption and dry out. The geometry and size affects the heat conductivity and the capillary effect, in such a way that some geometries transport better the fluid from the condenser to the evaporator. The orientation indicates the micro-heat pipe performance when the gravity is taken into account.

2. EXPERIMENTAL WORKS

This study brings different methods of designing micro-heat pipes, done by other authors, and shows a brief idea about the micro-heat pipes analyses on the last years. A resume about the works are shown in Tab. 1.

The micro-heat pipes studied by Le Berre et al (2003) and Launay et al (2004) were analyzed for two cases: triangular cross-section and triangular plus an artery for liquid transport, as showed in Fig. 1, in order to increase the liquid flow area. This geometry normally is used due to its capacity of improving the capillary effect. Each of them were organized by horizontally arrays with size 20 x 20 mm, which in the first case are 55 parallel channels with a spacing of 130 μm, hydraulic diameter of 120 μm and 20 mm length, and the second case are 25 parallel channels with a spacing of 320 μm, hydraulic diameter of 210 μm and also 20 mm length. For both arrays the condenser length and evaporator length are 5 mm long. The author took the operating temperature range as a reference to choose ethanol and methanol as working fluids, which is up to 125 ºC.

Table 1. Characteristics of micro-heat pipes analyzed.

Author	Substrate	Geometry	Size	Working Fluid	Filling Ratio
Le Berre et al, 2003/ Launay et al, 2004	Silicon	Triangular	230 μm wide - 170 μm depth	Ethanol	0%, 6-66%
Le Berre et al, 2003/ Launay et al, 2004	Silicon	Triangular + artery	500 μm wide - 350 μm depth	Methanol	50%
Li et al, 2015	Silicon	Parallel	150 μm width – 150 depth	Deionized Water	30%, 40% and 50%
Li et al, 2015	Silicon	Nonparallel	230/180 μm width – 150 depth	Deionized Water	30%, 40% and 50%
Kang & Huang, 2002	Silicon	Star grooves	6 corners 340 μm hydraulic diameter	Methanol	0-80%
Kang & Huang, 2002	Silicon	Rhombus grooves	200 μm wide base – 310 μm height	Methanol	0-80%
Moon et al, 2004	Copper	Curved triangular	1.5 mm equivalent diameter	Water	20%
Moon et al, 2004	Copper	Curved rectangular	1.5 mm equivalent diameter	Water	20%

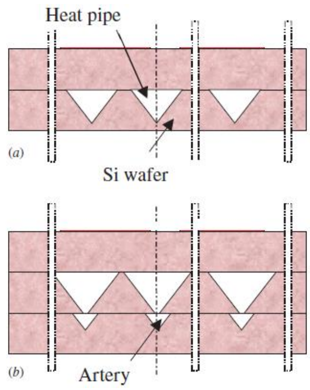

Figure 1. Cross section of (a) triangular micro-heat pipes and (b) triangular micro-heat pipes with arteries (Le Berre et al, 2003; Launay et al, 2004).

Li et al (2015) fabricated the micro-heat pipes with microgrooves on a silicon wafer with 45 mm length, 16 mm length and 0.5 mm thickness, such that the internal channel region has dimensions of 35 mm length, 10 mm width and 0.15 mm thickness. The parallel grooves were made with 150 μm width and the nonparallel grooves were divided in two parts, such that one has 230 μm width and the other has 180 μm width. The space between each channel was determined as 50 μm for parallel channels, 70 μm for nonparallel channels with width 230 μm and 120 μm for nonparallel channels with width 180 μm. The silicon wafers were bonded with a steam chamber of 200 μm height made of Pyrex 7740, which allows the visualization of the process and also improves the vapor flow. The power input of 2 W and 4 W, horizontal direction and different filling ratios were the experimental parameters for analyzing the thermal performance.

The work conducted by Kang & Huang (2002) studied two different kinds of geometry for micro-heat pipes: star grooves and rhombus grooves (Fig. 2). The 31 star grooves were made with 3 silicon wafers on a 25.4 x 25.4 square area, each groove with 24.4 mm of length, 340 μm of hydraulic diameter and spaced 620 μm from each channel. The evaporator section and condenser section have a length of 6 mm each and the adiabatic section is 13.4 mm long. The six corners with small angles were fabricated to improve the capillary effect, acting as arteries for the liquid. The 31 rhombus grooves needed two silicon wafers with the same square area as the first array, grooves with 24.4 mm of length, 55 μm of hydraulic diameter and 620 μm for inter-channel spacing. As the author provided the wall thickness as 370 μm and the silicon wafer thickness as 525 μm, the other dimension of rhombus groove was calculated and obtained as 310 μm.

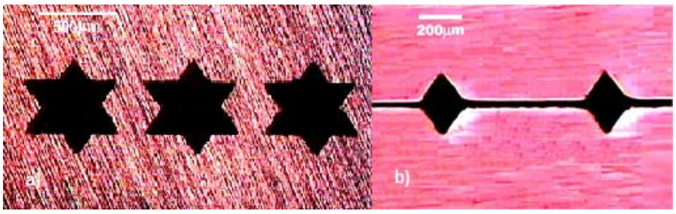

Figure 2. Cross section of (a) star grooves and (b) rhombus grooves micro-heat pipes (Kang & Huang, 2002).

Unlike the other works, Moon et al (2004) utilized copper as a substrate for the micro-heat pipes. Lengths of 50 mm and 100 mm were adopted to run the experiments. For a micro-heat pipe with 50 mm long, the evaporator has 10 mm length, the condenser has 25 mm length and the adiabatic section has 15 mm length. For 100 mm long, the evaporator has 20 mm length, the condenser has 50 mm length and the adiabatic section has 30 mm length. The sharp corners acts to keep the capillary pressure sufficient for liquid flow back to the evaporator. The fill ratio of water was kept constant in 20%, while the power input varied according to the test for operating temperatures of 60, 70, 80 and 90 °C, reaching 10 W as a maximum value. An analysis about the influence of gravity by changing the inclination angle of the micro-heat pipes was carried out. The results are based on heat transfer limit and thermal resistance instead of the effective thermal conductivity that also differs from the other works.

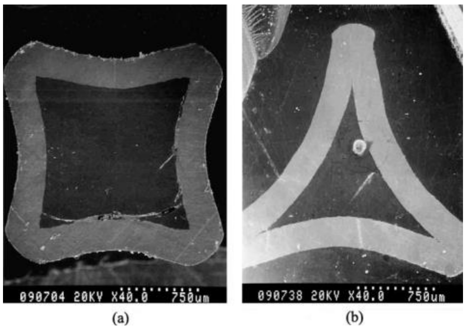

Figure 3. Cross section of (a) curved rectangular and (b) curved triangular micro-heat pipes (Moon et al, 2004).

3. PERFORMANCE ANALYSES

Table 2 shows the best results for each work with effective thermal conductivity and thermal resistance as criteria for evaluation of thermal performance. The ratio between solid area and empty area are also presented and were calculated by the authors according to the interpretation of dimensions given by the works, in order to identify the influence of the wall thickness on the effective thermal conductivity.

Table 2. Results of experimental works based on effective thermal conductivity, thermal resistance and experimental conditions.

Author	Substrate	Geometry	Effective Thermal Conductivity	Thermal Resistance	A_{solid}/A_{empty}	Conditions
Le Berre et al, 2003/ Launay et al, 2004	Silicon	Triangular	142.31 W/m · K	*7.53 K/W	12.02	3 W, 24% FR
Le Berre et al, 2003/ Launay et al, 2004	Silicon	Triangular + artery	600 W/m · K	*1.19 K/W	8.6	2 W, 50% FR
Li et al, 2015	Silicon	Parallel	305 W/m · K	**18.44 K/W	6.11	4 W, 40% FR
Li et al, 2015	Silicon	Nonparallel	380 W/ m · K	**14.8 K/W	7.25	2 W, 40% FR
Kang & Huang, 2002	Silicon	Star grooves	277.9 W/m · K	*1.99 K/W	4.46	10.7 W, 60% FR
Kang & Huang, 2002	Silicon	Rhombus grooves	289.4 W/m · K	*2.51 K/W	18.23	6.3 W, 80% FR
Moon et al, 2004	Copper	Curved triangular	*7574 W/m · K	1.30 K/W	0.8678	10 W, 90 ºC, 20% FR
Moon et al, 2004	Copper	Curved rectangular	*4689 W/m · K	2.1 K/W	0.8678	4.5 W, 20% FR

*Calculated by the authors from this study.
** Effective length considered as total length.

The missing values for thermal resistances and effective thermal conductivity were calculated by Eq. (1) as the equation of thermal resistance for conduction, obtained by Fourier's Law of heat conduction.

$$R = \frac{L_{eff}}{k_{eff} \cdot A} \quad (1)$$

The terms of the equation are thermal resistance R, effective length of the micro-heat pipe L_{eff}, effective thermal conductivity k_{eff} and cross-sectional area A.

$$L_{eff} = L_A + \frac{L_C + L_E}{2} \quad (2)$$

The effective length is calculated knowing the adiabatic section length L_A, condenser length L_C and evaporator length L_E, as shown in Eq. 2.

The triangular micro-heat pipes showed a large difference between the two experimental models. For the first experimental model, the comparison was made with different filling ratios and 3 W of heat input. With a 3D numerical model of the experimental bench to analyze the experimental thermal performance, no significant enhancement in heat transfer was noticed, reaching 7% for effective thermal conductivity enhancement with 24% filling ratio. On the other hand, for the second experimental model, a fixed fill charge of 50% and 2 W of heat input, an effective thermal conductivity of 600 $W \cdot m^{-1} \cdot K^{-1}$ was obtained, which is an increase of 300% of the silicon thermal conductivity. According to the authors, the first array worked with the large thermal conductivity of silicon itself, and is suggested that the array's geometry must be changed for a possible significant improvement in its thermal performance. For the array with artery the improvement was possibly due to the compliance between the thermal conditions and methanol as working fluid.

The parallel and nonparallel micro-heat pipes showed an improvement with a filling ratio of 40%. For a 2 W power input, with 30% of working fluid, the effective thermal conductivity for both arrays was quite the same about 290 W/m·K. At 40% the nonparallel micro-heat pipes showed to be better, reaching 380 W/m·K, while the parallel structure showed no significant changes from the first filling ratio. A 50% filling ratio made the effective thermal conductivity decrease, with both types of structure close to 220 W/m·K. The increasing of power input to 4 W showed better changes for the parallel micro-heat pipes when it comes to a 40% filling ratio, with both reaching 305 W/m·K. For 30%, the nonparallel type has about 13 W/m·K more effective thermal conductivity than the parallel structure. On the other hand, both types dropped to under 220 W/m·K for a 50% fill charge. The worse thermal performance observed for a 50% filling ratio was explained by the authors as an excess of working fluid preventing a portion of vapor and liquid to change phase. The experimental work showed a better thermal performance for the micro-heat pipes with nonparallel structure, because it is favorable for the capillarity and provides a good flow for the working fluid, according to the authors. The thermal resistances for both arrays were calculated based on the total length of the micro-heat pipe, as the authors didn't provide the condenser and evaporator length. The results for the ratio between solid area and empty area were obtained considering rectangular section for both micro-heat pipes and the number of internal channels calculated with the dimensions provided, resulting in 50 channels for parallel and approximately 32 channels for nonparallel micro-heat pipes. As the nonparallel structure is divided in two parts wherein each one has its uniform cross section, the ratio between solid area and empty area was calculated as the average value of the ratios calculated for each cross section type.

Kang & Huang (2002) studied the thermal performance of the micro-heat pipes with different filling ratios (0%, 20%, 40%, 60% and 80%) in a range of power input from 0 to 20 W to star grooves and from 0 to 14 W to rhombus grooves. The unfilled micro-heat pipes showed an increasing of effective thermal conductivity in small values of power input, until 2.5 W for star grooves and until 1.8 W for rhombus grooves, and maintained constant in approximately 150 W/m·K for subsequent values. For the star grooves, the best result observed was for a 60% filling ratio with a power input nearly of 10.7 W, reaching 277.9 W/m·K, which is about 70% higher to the average effective thermal conductivity. An effective thermal conductivity of 289.4 W/m·K was obtained for rhombus grooves with 80% filling ratio and power input about 6.3 W, being in this case an increase of 80% in the average effective thermal conductivity, according to the authors. The ratio between solid area and empty area was calculated considering that the channels occupied 18.3% and 5.2% of the cross sectional area for star grooves structure and rhombus grooves structure, respectively, as it was proposed by the researches.

On the tests carried horizontally, Moon et al (2004) observed 1.30 °C/W as the lowest value of thermal resistance. The operating conditions were operating temperature 90 °C, measured in adiabatic section, and about 10 W of power input for the curved triangular micro-heat pipe with 50 mm long. The analysis of inclination angle changing started from the evaporator position higher than the condenser (-90°) to the evaporator position lower than the condenser (90°). This analysis was made only with curved triangular micro-heat pipe, and has shown a better thermal performance at 90°, with 7 W of heat transfer limit against 4.51 W for -90º. Another test made with the curved triangular micro-heat pipe was the decrease of its length from 100 mm to 50 mm, causing 92% enhancement in the heat transfer coefficient for 3 W power input. The mainly limitation for this experiment was the dryout in the evaporator, interrupting the correct flow of the working fluid. In a not constant operating temperature condition, as it increased according to the power input, the curved triangular micro-heat pipe showed to be more promisor then the curved rectangular micro-heat pipe, with heat transfer limit 1.6 times higher. Due to its sharper corner compared to the curved rectangular, the curved triangular cross-section maintain a sufficient capillary pressure to return the liquid to the evaporator, which is an important feature to explain its better performance. The effective thermal conductivity and the ratio between solid area and empty area from both types of micro-heat pipes were calculated based on a circular cross section of 1.5 mm diameter and wall thickness of 0.275 mm for a single channel.

The works analyzed involved different geometries, working fluids and filling ratios combinations, in order to show different operating conditions and the thermal performance associated. The tendency of most works is the use of silicon as a substrate, due to its high thermal conductivity, but more types of conductive materials should be investigated, once it can reveal good thermal performance in combination with other micro-heat pipes parameters. The preference of horizontal direction avoid the influence of gravity, but it is also unknown the thermal operation of these micro-heat pipes in different inclination angles. It is relevant to investigate different angles and find more operating limitations. The influence of wall thickness in effective thermal conductivity has most influence on rhombus grooves micro-heat pipe studied by Kang and Huang (2002). Most of works evaluated the micro-heat pipes performance by the effective thermal conductivity, but without values for thermal resistance. The missing values were calculated by the authors from this study. The analysis of both parameters is a starting point to optimize some feature of the micro-heat pipe.

4. CONCLUSION

Works about experimental investigation of micro-heat pipes were analyzed. The different combinations of geometry, working fluid and filling ratio showed promising results for the effective thermal conductivity and comparisons can be made. The effective thermal conductivity values varied from 600 W/m · K to 7574 W/m · K and thermal resistance values from 1.30 K/W to 18.44 K/W. A brief idea about the wide range of micro-heat pipes parameters combination is shown. Additional investigations on micro-heat pipes should be done to improve the equivalent thermal conductivity and to better understand the effect of gravity field on the performance. The present study indicates a promising future for these devices in compact electronic cooling methods.

5. REFERENCES

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