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EXPERIMENTAL ANALYSIS OF A
SCREEN-COVERED GROOVE HEAT PIPE

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Abstract. In this research, a heat pipe with screen-covered groove capillary structure was experimentally analyzed. The heat pipe was manufactured from a copper tube with the external diameter of 9.45 mm, inner diameter of 6.20 mm, and a total length of 200 mm. A wire electrical discharge machining, or wire-EDM, was used to manufacture axial microgrooves in the heat pipe. A layer of phosphor bronze mesh #100 completed the capillary structure. Deionized water was the working fluid and the loading filling ratio was 60% of the evaporator volume. The condenser was cooled by air forced convection, the adiabatic section was insulated with fiberglass and the evaporator was heated by an electrical resistor and it was insulated from the environment with aeronautic insulation. The heat pipe was tested in horizontal position, under different heat loads varying from 5 up to 30 W. The experimental results showed that the screen-covered groove worked satisfactorily as a capillary structure.

Keywords: heat pipe, capillary structure, screen-covered groove, experimental analysis.

1. INTRODUCTION

The modern electronic technology lead to the electronic device miniaturization and the higher switching speeds, which created a significant demand for achieving high heat dissipation rates (Nishida *et al.*, 2014). The existing electronic cooling techniques cannot be effective, affecting the performance, cost, and reliability of electronic devices (Ghajar and Darabi, 2014). Hence, according to Çengel and Ghajar (2015), the thermal management of electronic packaging has become a key technique in many applications. The heat pipes are passive devices based on phase change of the working fluid, which can be a good technological solution alternative to the stabilization of microelectronic devices temperature. Major advantages of heat pipes include a very high thermal conductance, no pumping power requirements, no moving parts, and relatively low pressure drops (Faghri, 2014).

According to Groll and Rösler (1992), the heat pipes operate according to the following principle: in the evaporator region, heat is transferred to the heat pipe, vaporizing the working fluid contained inside this region. The steam generated is moved, due to the pressure and density differences, to the cooling regions of the heat pipe (condenser region) where heat transported is rejected to the cold source. In the heat rejection process, the steam condenses, and the condensate returns back to the evaporator closing the cycle. The adiabatic region, which may have variable dimensions (in some cases it is absent) is located between the evaporator and the condenser being insulated from the external environment. The working fluid returns from the condenser to the evaporator due to capillary pumping effect. A schematic diagram of the operating principle of heat pipes is presented in Fig. 1. More details on the principle of the heat pipes can be found in Chi (1976), Peterson (1994), Faghri (2014), and Reay *et al.* (2014).
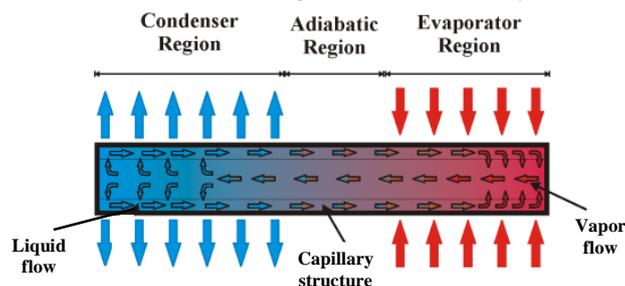

Figure 1. Sketch of the operating principle of a heat pipe

A heat pipe consists essentially of three components: an involucre, a working fluid, and a capillary structure. The capillary structure of heat pipes can be made of screen meshes, grooves, or sintered metal powder. As an alternative to improve the thermal performance of the heat pipes, some composite capillary structures can be developed. The screen-covered groove capillary structure is an example. In this kind of capillary structure, a mesh screen is used to improve the development of a large capillary pumping pressure. Already, the axial grooves ensure low resistance to the liquid flow and the highly conductive groove fins ensure low resistance to heat flow in the radial direction (Reay *et al.*, 2014).

In this context, this research presents a thermal performance experimental analysis of a heat pipe with screen-covered groove capillary structure operating horizontally. Due to the geometric characteristics, the heat pipe can be used in thermal management of electronic equipment.

2. EXPERIMENTAL ANALISYS

The methodology for manufacture (cleaning, assembly, tightness test, evacuation procedure, and filling with the working fluid); test; and analysis of the heat pipe were developed based on Nishida (2016), Krambeck (2016), and Santos *et al.* (2017).

2.1 Description of the Experimental Device

A heat pipe was produced by copper tube ASTM B-75 alloy 122 with an outer diameter of 9.45 mm, an inner diameter of 6.20 mm, and a length of 200 mm. The heat pipe has an evaporator region with 80 mm in length, an adiabatic region of 20 mm in length, and a condensation region with 100 mm in length. The working fluid used was deionized water with a filling ratio of 60% of the evaporator volume. Table 1 shows the main characteristics of the heat pipe analyzed in this research.

Table 1. Heat pipe main characteristics.

Characteristics	Heat Pipe
Inner diameter [mm]	6.20
Outer diameter [mm]	9.45
Evaporator length [mm]	80
Adiabatic section length [mm]	20
Condenser length [mm]	100
Working fluid	Deionized water
Volume of working fluid [mL]	1.60
Filling ratio [%]	60
Capillary structure	Screen-covered microgroove

The internal capillary structure of the heat pipe is composed by a screen-covered microgroove. First of all, the axial microgrooves were fabricated in a straight copper tube by wire electrical discharge machining (wire-EDM). A scheme of microgroove profile is illustrated in Fig. 2a. Figure 2b shows the image in micro-scale of the microgrooves with an average diameter of 220 µm. The image was obtained by Backscattered Electron Detector (BSD) for Scanning Electron Microscope (SEM). Figure 3 presents a schematic diagram of the microgroove geometric configuration and Table 2 shows the dimensions of the microgrooves. In the nomenclature used in this paper, w represents the microgroove width [m], w_f is the microgroove thickness [m], δ is the microgroove depth [m], and ϕ is the wire diameter from the wire-EDM process [m], in this case, $\phi = 25$ µm.

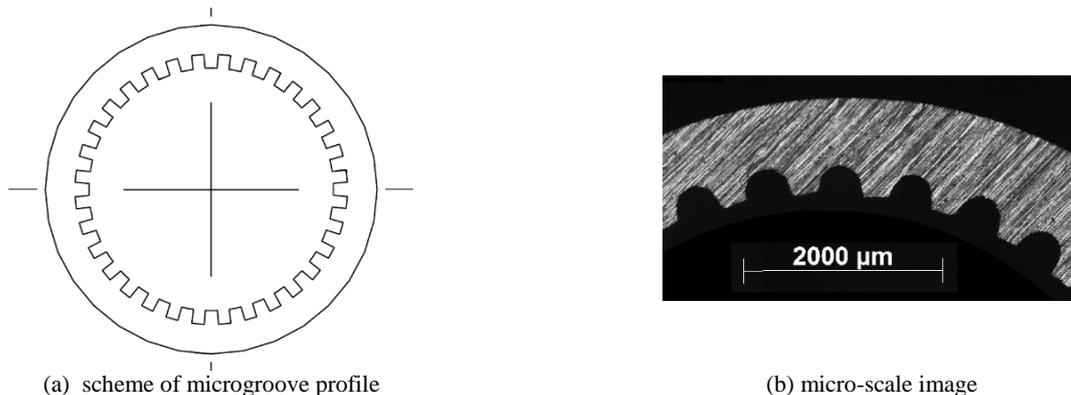(a) scheme of microgroove profile   (b) micro-scale image

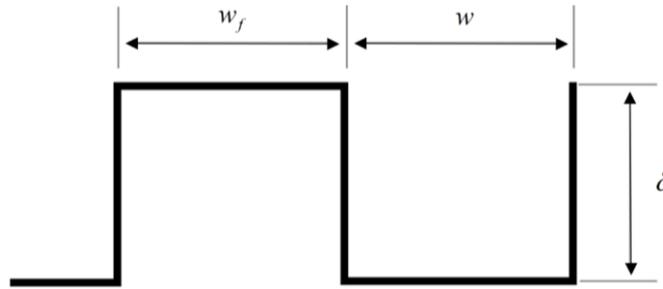Figure 2. Capillary structure of microgrooves
Source: Nishida (2016)

Figure 3. Schematic diagram of the microgroove geometric configuration

Table 2. Characteristics of Microgrooves.

Characteristics	Symbol	Value
Wire diameter from the wire-EDM process [m]	ϕ	25 μ
Microgroove depth [m]	δ	1.2ϕ (30 μ)
Microgroove width [m]	w	1.4ϕ (35 μ)
Groove thickness [m]	w_f	1.4ϕ (35 μ)
Number of microgrooves	N	32

A screen mesh completed the capillary structure. The mesh configuration used was a single layer of phosphor bronze mesh #100. A image of screen mesh #100 is shown in Fig 4. Figure 5 presents the final capillary structure manufactured, the screen-covered groove capillary structure.
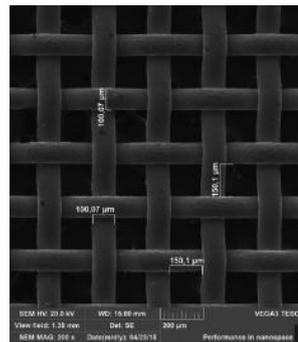
(a) general view   (b) micro-scale image
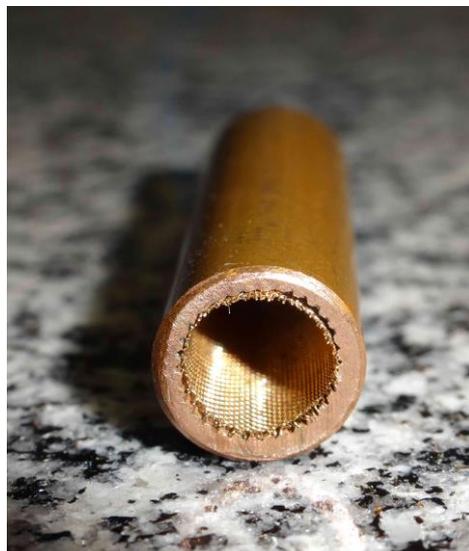
Figure 4. Image of phosphor bronze screen mesh #100

Figure 5. General view of the screen-covered groove capillary structure

2.2 Description of Experimental Apparatus

The test rig used for the experimental tests, shown in Fig. 6, is composed of a power supply unit [$Agilent^{TM}$ U8002A], a data logger [$Agilent^{TM}$ 34970A] with 20 channels, a laptop [$Dell^{TM}$], a universal support, a uninterruptible power supply [NHS^{TM}] and an fan [$Ultrar^{TM}$].
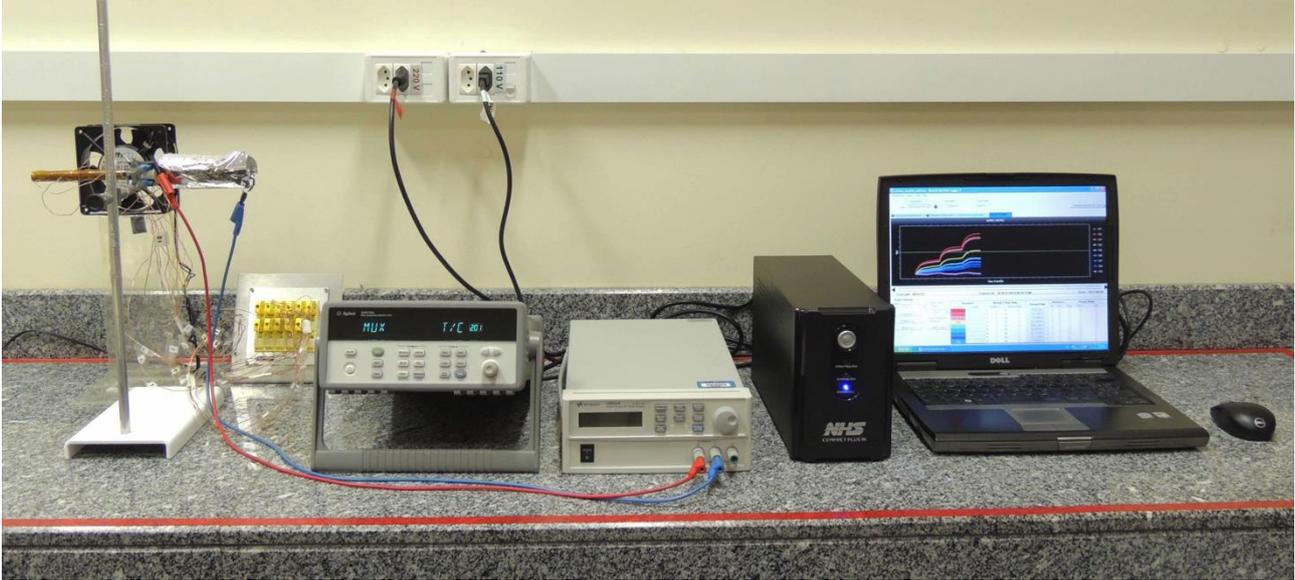

Figure 6. Experimental apparatus

For the evaluation of the thermal performance of the heat pipe, K-type thermocouples [$Omega^{TM}$] were used. They were fixed on the outer surface of heat pipe by a thermosensitive adhesive strip [$Kapton^{TM}$]. As shown in Fig. 7, there were three thermocouples in the evaporator ($T_{evap,1}$, $T_{evap,2}$, and $T_{evap,3}$), one thermocouple in the adiabatic section (T_{adiab}), and four thermocouples in the condenser ($T_{cond,1}$, $T_{cond,2}$, $T_{cond,3}$, and $T_{cond,4}$) of the heat pipe.
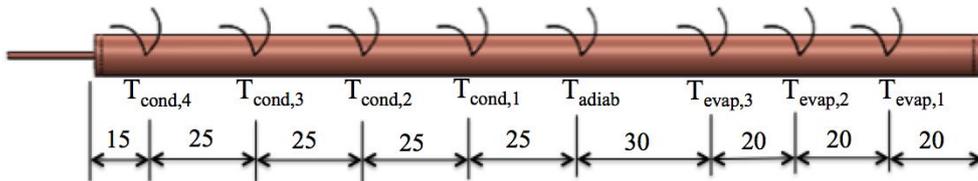

Figure 7. Thermocouple positions [mm]

The heating system of the evaporator was conducted by power dissipation in a nickel-chromium alloy power strip resistor [$Omega^{TM}$]. To ensure that the generated heat by *Joule* effect was transmitted to the evaporator, an aeronautic thermal insulation and a layer of polyethylene were installed in this region. A fiberglass tape was used in adiabatic section as heat insulation between the support and the heat pipe. The cooling system using air forced convection was consisted of a fan in the condenser region.

2.3 Experimental Procedure

To ensure the best results and the repeatability of experimental tests, the ambient temperature was maintained at 20.0 °C ± 1.0 °C by the thermal conditioning system [$York^{TM}$]. The heat pipe was carefully fixed to the universal support with bracket in the adiabatic region at the horizontal position. The fan was turned on, positioned correctly in the condenser region and set at a speed of 5.0 m/s with a combined error of ± 0.2 m/s. The data acquisition system was turned on, and the temperatures measured by the K-type thermocouples. The power supply unit was turned on and adjusted to the dissipation power desired. The initial load was 5W and, after approximately 15 minutes, the thermocouples showed stationary values. The load increment was made until the maximum average temperature of the passive device reached the critical temperature (150 ºC), where the melting of the materials could happen. Data was acquired every 5 s, recorded in the laptop by the software *Agilent^{TM} Benchlink Data Logger* 3. The experimental uncertainties are associated to the K-type thermocouples, the data logger, and the power supply unit. The experimental temperature uncertainty is estimated to be approximately ± 1.0 °C and a thermal load was ± 1%. For the uncertainties determination, the error propagation method described by Holman (2011) was used.

3. RESULTS AND DISCUSSION

The experimental results regarding thermal performance of the heat pipe using deionized water as the working fluid are presented considering the horizontal position. The experimental tests were repeated three times and the errors were compared taking into account the difference between the mean values were less than 0.5 °C. Tests were performed to a heat load varying from 5 to 30 W. Figure 8 shows the temperature distribution as function of time for the heat pipe with screen-covered groove structure.
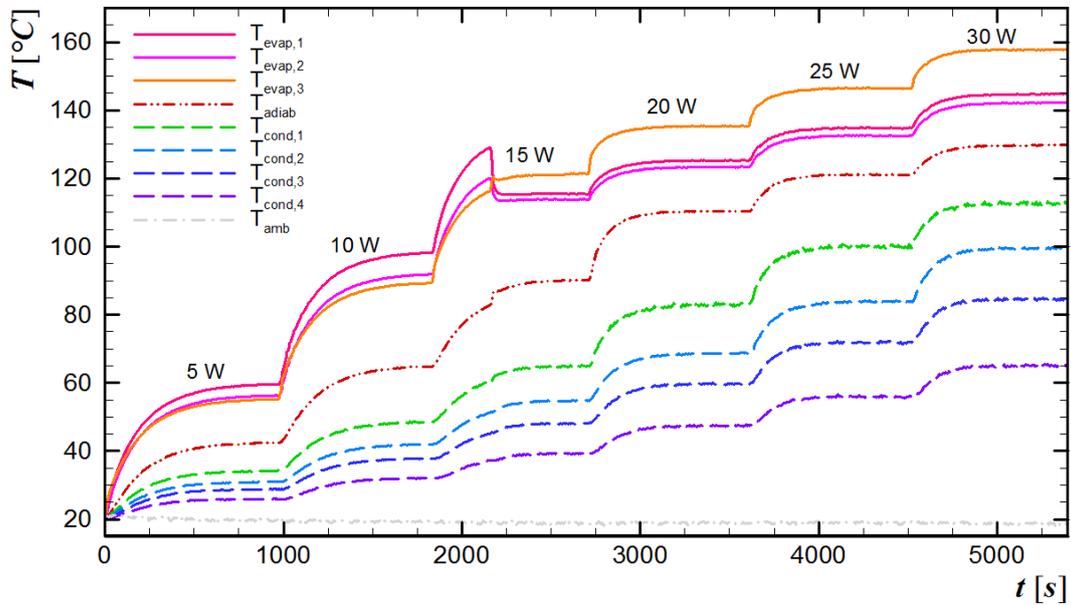

Figure 8. Temperature of the heat pipe *versus* time for different heat loads

To ensure that the capillary structure worked successfully, the experimental results presents a thermal performance comparison between a rod, a thermosyphon and the heat pipe manufactured, with the same geometry and characteristics. The operation temperature in function of the heat load for the three passive devices is shown in Fig. 9. Figure 10 presents the comparison of the thermal resistance versus the heat load. The heat pipe worked satisfactory, since the capillary structure provided to the heat pipe the operation in a higher load and lower thermal resistance.
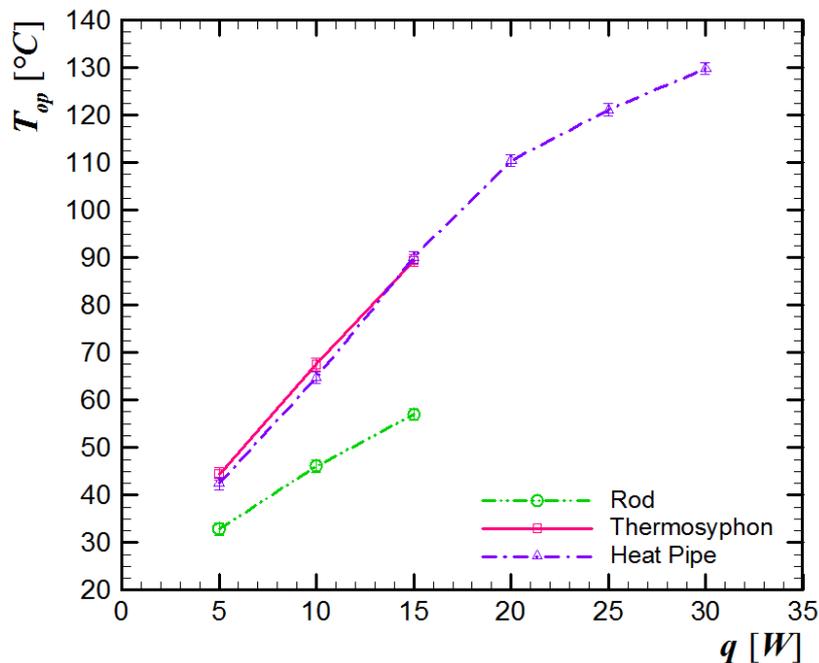

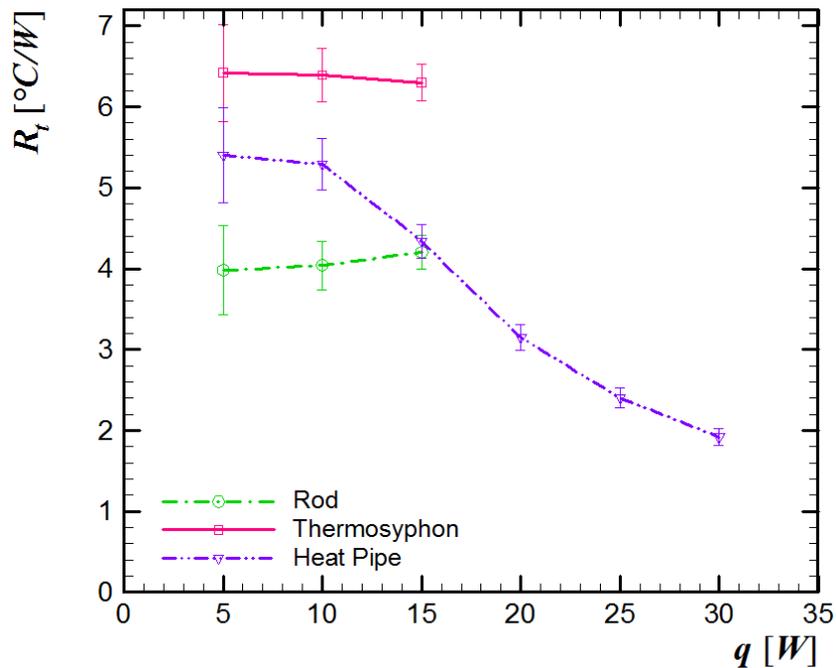Figure 9. Operation temperature *versus* heat load

Figure 10. Thermal resistance *versus* heat load

4. CONCLUSIONS

In this research, a screen-covered groove heat pipe was experimentally analyzed. Due to the shape and size, the heat pipe can be used in thermal management of electronic equipment. The heat pipe was 200 mm long, its inner and outer diameter were 6.20 mm and 9.45 mm, respectively, and the working fluid was deionized water. Tests were performed to a heat load from 5 up to 30W in horizontal position. The experimental results showed that the screen-covered groove worked satisfactorily as a capillary structure.

5. ACKNOWLEDGEMENTS

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