Heat Powered Cycles Conference
Nottingham, UK, June 26-29, 2016

DEVELOPMENT OF COPPER-METHANOL HEAT PIPES: THERMAL PERFORMANCE EVALUATION FOR ELECTRONCIS COOLING

Roger R. Riehl

GamaTech Thermal Solutions,
R. Cordoba 34, São José dos Campos, SP BRAZIL, 12235-390, email: roger.riehl@gtts.com.br

Abstract

Heat pipes are well-known passive thermal control devices used to transport the heat generated from a source to a sink with little temperature differences and high efficiency. They have been developed for many years and applied in several areas, from aerospace to military, as well as industry and laptop computers cooling. There are several other applications for heat pipes and they can be made of many different shapes and forms, however, a great deal of development is necessary for a given thermal design especially when highly concentrated heat is being observed from the source. Applications where a high density of electronics are present generate a great deal of heat that need to be properly managed in order to maintain their operation temperatures according to the project's requirements. For the current investigation, heat pipes have been developed as important components for the thermal management of electronics on printed circuit boards (PCBs) applied to defense/surveillance equipment. Results obtained from the development process indicate that the heat pipes will present a lifetime of at least 13.5 year and their thermal behaviour are compatible with the requirements established for the project, where their overall temperatures are within the accepted operational limits. Thermal tests performed in an environmental chamber show the heat pipes reliable operation with thermal conductances of up to 8 W/^{o}C at the highest operation temperature of 60^{o}C.

Key words: heat pipes, thermal management, life tests, thermal control, electronics cooling.

INTRODUCTION

The continuous development of heat pipe technology has given to this passive thermal control device great interest for new applications where it has not been considered before. It is well known that heat pipes are reliable two-phase passive thermal control devices and their applications have spread out for many fields from aerospace to computer cooling. However, new applications are arising for such device which has called attention from many sensitive fields such as military and surveillance. This is especially important to consider because of new developments of electronic systems devoted to military applications, regarding data and communication hardware. Previous investigations have addressed this issue, where the potential of applying heat pipes and also pulsating heat pipes have been demonstrated (Riehl, 2012; Riehl and Cachuté, 2013; Riehl and Cachuté, 2014; Silva et al, 2015; Riehl, 2015). Concerns related to any new heat pipe development are clearly regarding the chemical compatibility between the housing and working fluid, as well as maximum heat transport and life time for a given application (Faghri, 1995; Chi, 1976; Reay and Kew, 2006).

With the increase on the processing speed demand from electronics, along with the continuous decrease on their sizes, the reject heat rate increases considerably as the heat density is directly related to the component's area. Therefore, heat will be concentrated in a region of the electronic device that might influence other electronic components located nearby. Thus, a proper thermal management design must be performed in order to have a so-called "low thermal inertia" design, in such a way that the heat generated by the component must be promptly removed and dissipated to the environment. Coupled with the proper considerations of thermal resistances and materials, heat pipes are important components used in the current thermal designs applied to surveillance equipment.

Materials' compatibilities, manufacturing procedures, testing and verification of heat pipes designed for this purpose are mandatory steps that need to be taken and results must be carefully evaluated in order to apply this important thermal control device in the application where it is required. Since this device is part of the general thermal design, its use is considered upon several variables evaluation, such as heat concentration, number of electronic components with sensitive use, thermal resistances and couplings. The development and results presented here are part of a complex problem solution and the analysis considers the use of heat pipes to transport the heat from a concentrated source and spread it to other parts of the equipment, so the heat dissipation area can be maximized to improve the heat rejection to the environment. For the current investigation, only the heat pipe development will be considered as the overall project cannot be disclosed due to its application. Steps of the development are presented, regarding the estimates for the heat pipes' life time, test results during accelerated, performance and acceptance tests.

HEAT PIPE DEVELOPMENT AND CONSIDERATIONS

Thermal control management is a complex task and requires the definition of several variables in order to ensure the control of the heat transfer process, especially when dealing with composed electronics cooling and structural definitions. From the thermal investigation, the mechanical design will come naturally as all considerations regarding the minimum heat dissipation characteristics will be defined, as well as thermal resistances, materials, layout, etc.

When defining the application of heat pipes, one should consider their geometry and shape in order to meet the heat management requirements. Considering the fact that many electronic equipment designed for surveillance applications must operate in several environmental conditions, the heat pipe must also be able to work under these conditions, thus its working fluid must comply with the temperature range at which it should be fully operational. Due to the fact that the equipment must operate within the temperature range of -20 and +50 ^{o}C, methanol was selected as the working fluid. In order to meet the requirements related to the thermal management design, the heat pipes were conceived to have 3.0 mm OD, 2.0 mm ID, 1.5 mm of vapor diameter and 170 mm in length, built with copper (oxygen free and high conductivity) and using a wick made from 316L stainless steel #200 screen mesh. For this geometry and application, the working fluid inventory is considerably small, demanding a maximum volume of 0.05 ml of methanol (purity above 99.98%) to be charged in each heat pipe. Therefore, a dedicated charging station was also designed for this project, which required precision instruments to be able to deliver the required fluid inventory.

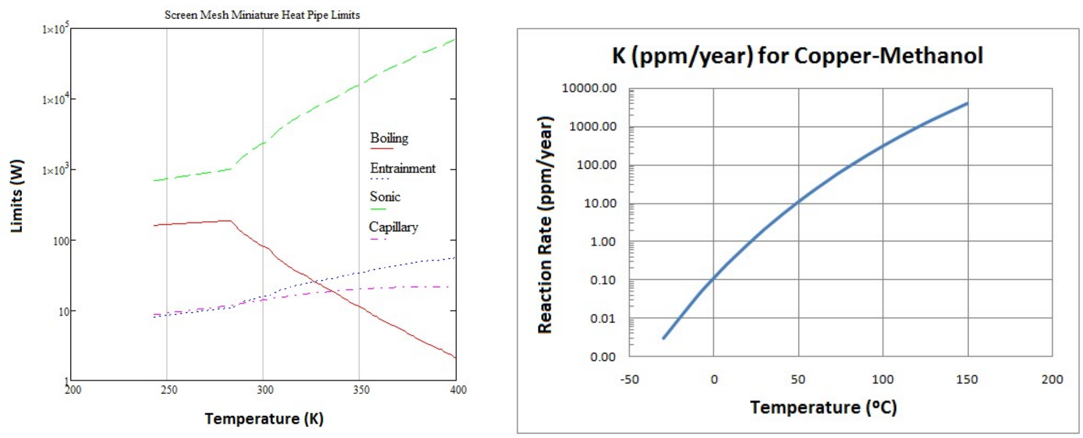
The combination between copper and methanol requires a full investigation in order to evaluate the heat pipe's expected life time based on accelerated life tests. Tests are necessary given the fact that methanol will react with the copper housing along time especially when heat is applied. The Arrhenius model is the most used to perform the life time verification based on the chemical reaction and amount of non-condensable gases (NCGs) generated as the heat pipe is under accelerated tests. Those tests were performed with the heat pipes being operating at higher temperatures than those they will face during real conditions, accelerating the NCG generating. After the accelerated tests were done, final clipping (cold weld) and cutting of the heat pipes were performed in order to remove the volume where the NCG was trapped, giving the heat pipe its final shape and length. After this step was completed, the heat pipes were checked for their thermal performance, which had to be in accordance to their design. Only after completing the development steps as mentioned here, the heat pipe was ready to be integrated to the structure where it should operate and, finally, it would be tested for verification prior to its approval.

Considering the development of the heat pipes, first the design should be verified against the limitations that this device will be subjected to, which are the capillary, boiling, entrainment and sonic limits (viscous limits were not considered due to the working fluid selection and operational temperature range). Therefore, Fig. 1a presents the heat pipe limits considered on the current project. Based on the Arrhenius model, the heat pipe must be able to deliver the 10 W heat transport requirement within the operational temperature range. Figure 1b shows the evaluation of NCGs generation based this statistical model. Accelerated life tests based on the Arrhenius model established that the heat pipes had to undergo the following steps for reaching up to 13.5 years of operation:

- Bake-up time of 0.5 days at a temperature of 150 ºC (non-operational);
- Aging time of 15 days at a temperature of 100 ºC (operational on thermosyphon mode).

The results from this procedure will allow the accumulation of NCGs at the upper end of the heat pipe, which would allow the removal of the volume with the undesired gases. Baking and aging times, as well as the entire manufacturing and test procedures, were determined according to previous developments of heat pipes, based on previous experiences of projects and methodologies applied over the years (Riehl and

Vlassov, 2004). Additional details regarding the aging as well as the performance tests cannot be disclosed at this time due to client's non disclosure agreement.



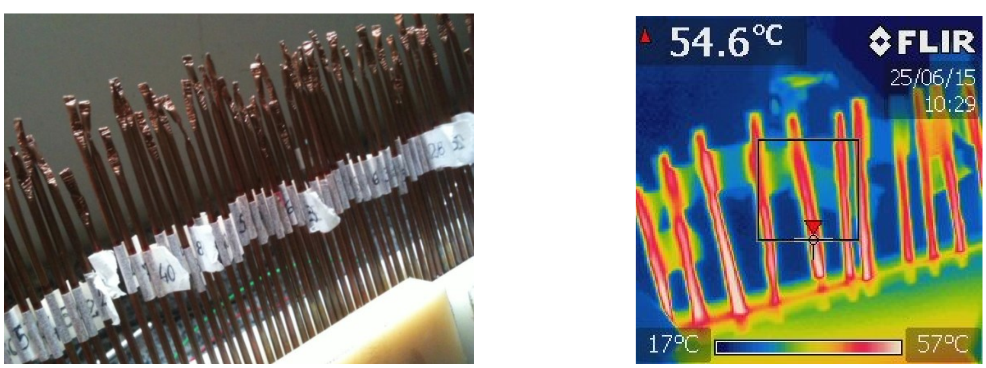
(a) design limits **(b) NCG generation**

Figure 1. Copper-methanol heat pipe considerations.

HEAT PIPES TESTING

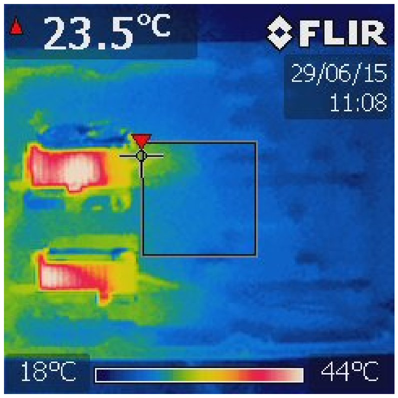
From the current development, the manufactured heat pipes are able to present 13.5 years of life expectancy based on the applied model, following the established processes to have the devices operating according to their design. Figure 2a presents the heat pipes undergoing accelerated life tests, where they were kept operating at a fixed heat load at the temperature of 100 ^{o}C during all the time as described above. Figure 2b presents the infrared photographs for the heat pipes during performance tests, where they were checked against several power level to verify their heat transport capabilities as they had to match the levels predicted on their design. During this step, the heat pipes need to present reliable operation for the temperature range at which they were designed, and heat cycling is a normal procedure applied for this type of testing. This means that each heat pipe shall present a reliable startup at both low and high power within the operational temperature range, without showing any indication of failure. For the current investigation, a set of 100 units of heat pipes were tested and passed all steps without a single failure.

Figure 3 presents the heat pipes being tested for acceptance already integrated in the structure, where it can be seen that they can transport the heat from the source to the other side. Figure 3a presents the startup of the heat pipe using a skin heater to simulate the heat that will be rejected by the electronic component, for the maximum applied power of 12 W. Figure 3b shows the heat pipes fully operation as it can be seen how the heat is transported throughout their entire length. Upon operating as demonstrated, the integrated heat pipes will substantially contribute with the better heat distribution on the surface thus enhancing the overall heat dissipation capability.

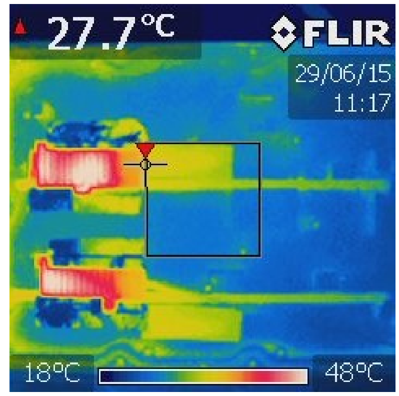


(a) Accelerated life tests rig (b) Performance Tests

Figure 2. Heat pipes under different tests.



(a) Startup



(b) Fully operational

Figure 3. Integrated heat pipes during acceptance tests.

The heat pipes integrated to their structure were tested in an environmental chamber with controlled temperature and humidity, for three levels of temperature: -20, +20 and +60 ºC (this last one to stress the heat pipes to verify their operation at a higher temperature than that established on the project's requirements). Especially for the last test, the objective was to observe the heat pipes temperatures which should not exceed 80 ºC. Figure 4 shows the operation of the heat pipe located at the superior part of the structure, while Fig. 5 shows the operation for the heat pipe located at the inferior part. Both heat pipes were tested at the maximum operating heat load, being 12 W and 8 W for the superior and inferior heat pipes, respectively. The results show reliable startups and transients when the chamber had its temperature set to another level, as well as steady operating until reaching stability.

The thermal conductances were calculated by the relation $G = Q/ (T_e - T_c)$, being Q the heat load applied to the heat pipe (W), T_e and T_c the average evaporator and condenser temperatures (ºC) respectively, with uncertainties of ±8%. One can see that even for such small heat pipes, the thermal conductances are substantially high, for the maximum of 10.6 W/ºC and 4.4 W/ºC for the superior and inferior heat pipes, respectively.

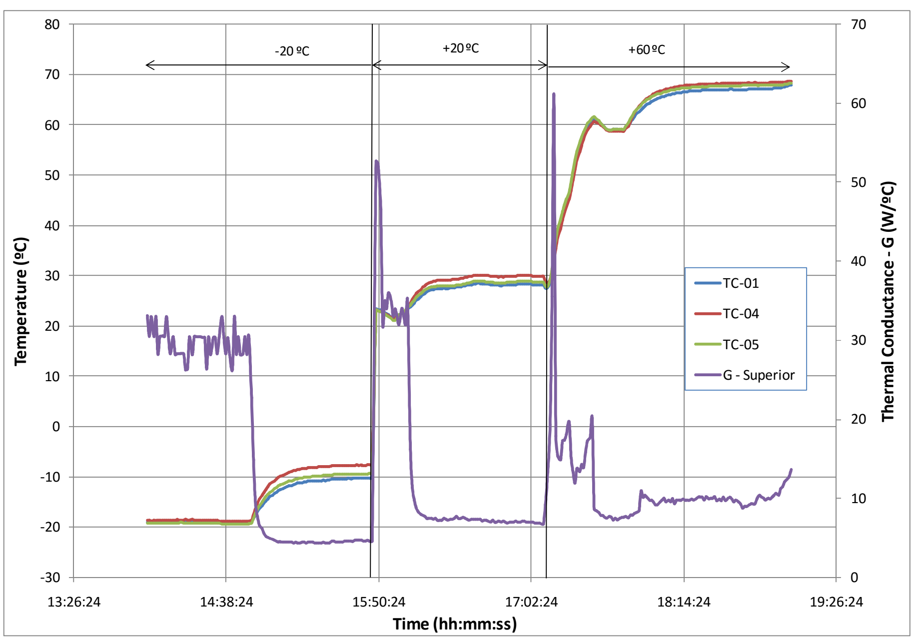


Figure 4. Integrated superior heat pipe tested in the environmental chamber.

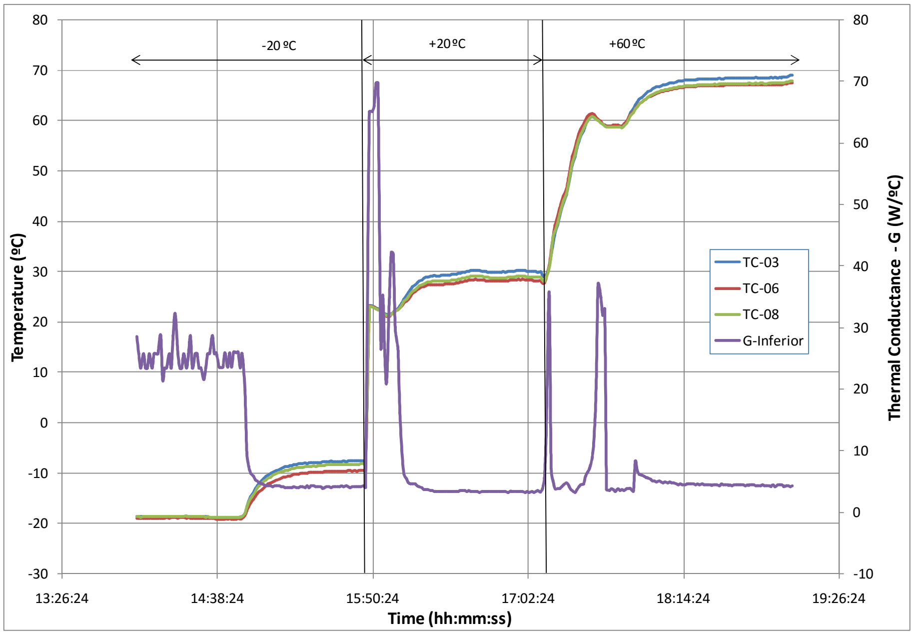


Figure 5. Integrated inferior heat pipe tested in the environmental chamber.

From the presented results, it is possible to verify that the heat pipes were performing according to their design, operating at temperatures below the maximum allowable limit of 80 ºC. Important information can be derived from the entire development results, which are mainly related to the heat pipes potential to present fast startups and transients (when changing from one temperature level to another) as well as considerably high thermal conductances.

CONCLUSIONS

The development of heat pipes for certain applications is still required due to some particularities found from one project to another, and developments are still necessary to meet the operational requirements. The use of copper-methanol heat pipes finds several applications on aerospace and military fields, as the equipment designed for those purposes need to operate within a wide range of temperature which, in several cases, limit the use of water as a working fluid due to its high solidification temperature. Therefore, copper-methanol heat pipes can be applied to several areas, and considering the geometry presented in this investigation, they can be of interest in electronics cooling as well as micro-structures thermal management.

The most important conclusions taken from this investigation are the following:

a. copper-methanol heat pipes show reliable operation and the potentiality of a high life time performing the thermal management of electronics;
b. due to their small diameter, the technological issue was related to the screen mesh wick insertion as well as the guarantee of contact with the container's inner diameter;
c. a precision charging method was also developed since the heat pipes required a small amount o methanol, therefore, a thorough methodology was conceived for this purpose;
d. the performance and acceptance tests showed that the heat pipes present reliable operation for the maximum heat load for which they were designed, presenting maximum operational temperature below the limit established by the project's requirements.

REFERENCES

Riehl, R. R., "Surveillance System Heat Transfer Enhancement Using Single-Phase flow with Nanofluid", *Heat Powered Cycles Conference*, Alkmaar, The Netherlands, Sept 9-12, 2012.

Riehl, R. R.,Cachuté, L. "Thermal Control of Surveillance Systems Using Heat Pipes and Pulsating Heat Pipes", *49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit 11th International Energy Conversion Engineering Conference*, San Jose, CA USA, July 14-17 2013.

Riehl, R. R., Cachuté, L. "Thermal Management of Surveillance Equipments Electronic Components Using Pulsating Heat Pipes", *IEEE-ITherm Conference - Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronics Systems*, Orlando, FL USA, May 27-30, 2014.

Riehl, R. R., Vlassov, V. V., "Proposal of a Universal Production and Test Procedures of Capillary Pumped Loop (CPL), Loop Heat Pipe (LHP) and Heat Pipe (HP)", *National Institute for Space Research (INPE) -* Internal Report of Technological Development, 42 pp, 2004.

Silva, D., Marcelino, E., Riehl, R. R., "Thermal Performance Comparison Between Water-Copper and Water-Stainless Steel Heat Pipes", *50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit 12th International Energy Conversion Engineering Conference*, Orlando, FL USA, July 27-29 2015.

Riehl, R. R., "Passive Thermal Management Systems Using Pulsating Heat Pipes", *IX Minsk International Seminar "Heat Pipes, Heat Pumps, Refrigerators, Power Sources"*, Minsk, Belarus, Sept. 07-10, 2015.

Faghri, A., Heat Pipe Science and Technology, Taylor and Francis, 1995.

Chi, S.W., Heat Pipe Theory and Practice, Hemisphere Publishing Corporation, 1976.

Reay, D. A., Kew, P. A., Heat Pipes-Theory, Design and Applications, 5th Ed., Elsevier's Science & Technology, 2006.