Thermal Management of Surveillance Equipments Electronic Components Using Pulsating Heat Pipes

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ABSTRACT

Surveillance systems have presented to be important applications for high performance thermal control devices, especially passive ones using heat pipe technology. This is usually applied when the heat source is located far from the heat sink and the use of liquid cooling or any other active thermal control system is not possible. Design and application of pulsating heat pipes (PHPs) and heat pipes become an indicated solution especially for restricted areas for integration. This investigation is focused on presenting the thermal control management of electronic components of a surveillance system using an open loop PHP with conventional heat pipes. Despite the relatively high temperature differences observed between the heat source and sink (up to 25 ^oC), the open loop PHP was able to transport the rejected heat (up to 40 W) from the electronic components to a remote heat dissipation area, while keeping their temperatures within the required range (below 80 ^oC) with relatively high thermal conductances (up to 1.6 $W/^oC$). The heat pipe has demonstrated the capability of spreading the heat, positively affecting the PHP operation, as this combined solution has proven to be stable and reliable with promising results.

KEY WORDS: pulsating heat pipe, thermal control, surveillance, electronics cooling.

INTRODUCTION

Pulsating heat pipes (PHPs) are two-phase thermal control devices that consist of a meandering tube bent with several curves forming several parallel channels, without the presence of a wick structure. The channels are formed from capillary tubing and a working fluid is responsible for acquiring the heat from a source and dissipating it in a sink. This kind of device can be considered a special type of heat pipe and was introduced by Akachi [1]. PHPs can be applied in several thermal control problems, such as microelectronics, but recently has gained interest in applications such as those for aerospace and surveillance systems used on the ground.

As PHPs operate by means of slug/plug dynamics [2], several investigations have been performed in order to improve their efficiency, also focusing on working fluids with the presence of solid nanoparticles, which can act on the improvement of this dynamics as well as on the thermal conductivity of the fluid [3]. PHPs have been under investigation in the last years with great development regarding the phenomenon involved in their operation, but further investigations are still required. Delil [4] has presented a survey on pulsating/oscillating devices suitable to be used in space and microgravity environments where important contributions to understand such devices are given. Lin et al. [5] presents an experimental investigation on an open loop PHP, where the maximum heat transport capability was investigated, showing the great perspective of using PHP as a thermal control device. The first investigations regarding the operation of PHPs were important to guide the future studies and applications, focusing on the use of this technology where the big temperature difference between the heat source and sink was not an issue, as this is a characteristic of this device.

Important investigations were performed regarding the operation dynamics in closed loop PHPs in order to understand and predict the thermal behavior of such a device [6]. Applications where open loop PHPs were used have presented important results with promising developments [7]. The operational limits of closed loop PHPs have been investigated by Yang et al [8], indicating that this type of thermal control device can operate at any orientation, even though a loss on its performance can be observed. Recently, Supirattanakul et al. [9] have presented an investigation where a PHP was used on the performance enhancement of air conditioning systems, showing promising results for such application. Investigations regarding the pressure losses presented in closed loops PHPs were performed [10] where it shows that this parameter is the limitation for some applications. Other important investigations regarding the use of PHPs were performed focusing on their improvement upon using the so-called nanofluids [11], as well as the application of magnetic fields when ferrofluid working fluid is used [12] and the analysis of the startup on the PHP overall performance [13], as well as oscillatory phenomena in such an application [14]. Recently, PHPs have gained attention for their capability on performing the thermal control on a satellite payload with reliable operation [15].

Focusing on this important and promising application, this paper is intended to present results related to the application of open loop PHPs designed to meet the requirements for thermal control of electronics components used in surveillance systems, working together with regular heat pipes. Considerations and analyses about the PHPs and heat pipes operational conditions were performed once this application requires the proper heat transport to the heat sink and further heat rejection to the environment (air), in order to keep the electronics within the project's limitations regarding their temperatures.

DESIGN FOR THE SURVEILLANCE SYSTEM THERMAL CONTROL EQUIPMENT

A specific design for the surveillance equipment for defense applications has been conceived to operate in hostile environments where the ambient temperatures range from -20 to +50 °C and humidity levels up to 95%, along with limited mass for the entire equipment to have. In this case, a combined solution has been designed, which presents both the pulsating heat pipe (PHP) and conventional heat pipes, together with a finned surface area that presents the entire thermal control design, rejecting heat to the environment by forced convection promoted by the clockwise rotating movement of the surveillance equipment, ranging from 15 to 60 rpm. A schematic of the arrangement showing a PHPs and heat pipes designed for the thermal control of a so-called “Components-1” setup are presented by Fig. 1.

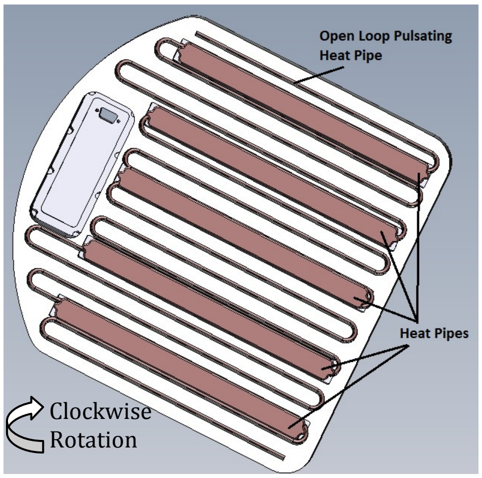

Fig. 1. “Components-1” schematics of the thermal control setup.

The details of the surveillance equipment and its architecture are considered proprietary information and cannot be disclosed at this time. For the sake of the necessary information to perform the adequate analysis, the above presented system’s characteristics are:

- Heat rejection of up to 200 W to the environment;
- The PHP is responsible to reject up to 40 W from the electronic components to the environment, being assembled in an array that is able to handle the entire heat rejection needed;
- Regular heat pipes (screen mesh as wick, total of 5 units, straight configuration) are embedded under the PHP and are responsible to homogenize the temperature along the heat dissipation surface, working together with the PHP;
- Maximum temperature of the electronics shall not exceed 80 ^{o}C.

A second open loop PHP was designed to promote the thermal control of another set of electronics called “Components-2” of the surveillance system, and its architecture is presented by Fig. 2. This PHP was designed to meet the following requirements:

- Heat rejection of up to 50 W to the environment, acquiring heat from the electronics setup and transporting it to the finned surface;
- Ability to operate at adverse conditions (evaporation section above the condensation section), within the required operation temperature range defined for the project
- Maximum temperature of the electronics shall not exceed 80 ^{o}C.

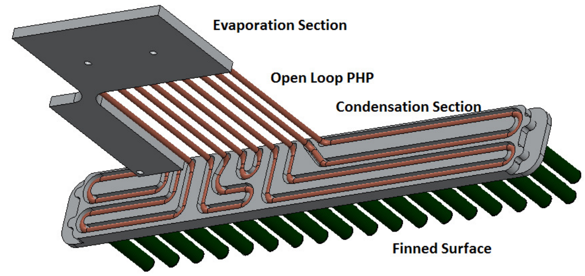

Fig. 2. “Components-2” schematics of the thermal control setup.

The architecture of the thermal control equipment designed for the surveillance system presents a finned surface that rejects the heat to the environment, configured in such a way that high performance heat rejection could be together with low weight for the entire equipment. Heat dissipation is enhanced due to the forced convection of the air across the finned surface, which rotates at 60 rpm. More specific details of this project cannot be disclosed at this time as they are considered sensitive information.

For the “Components-1”, the PHP and the heat pipes were assembled at the inner part of the finned surface (Fig. 1), and the “Components-2” setup was assembled on its dedicated heat sink, being embedded to it using aluminum based thermal compound. The entire surveillance system was made from painted anodized aluminum, which the thermal characteristics of the coating using are also considered proprietary information.

PULSATING HEAT PIPE AND HEAT PIPE DESIGN

The PHPs applied to this project was configured as open loop as it presents better operation at any orientation than the ones configured as closed loops [10,16]. For higher thermal efficiency, copper capillary tubes were used to manufacture the PHPs, presenting an outer diameter of 3 mm and an inner diameter of 1.6 mm, with a total linear length of 3 m. With this configuration, the PHP presents on its final form 100 mm of length for the evaporation, adiabatic and condensation sections. A single open loop PHP is considered to be enough for the “Components-1” application, operating at a maximum temperature of 80°C for a heat dissipation rate of 40 W. Due to the temperature operation range of the surveillance system, methanol (minimum purity of 99.98%) has been selected as the working fluid. The filling ratio applied for this investigation for both PHPs was 80% of the internal volume, in order to select the most appropriate amount of fluid for the highest thermal performance.

For the heat pipes, a total of 5 units were designed and used in order to present a homogeneous temperature distribution along the heat rejection finned surface. The heat pipes were built with aluminum alloy 6063 tubes using 316L stainless steel #200 screen mesh as wick, operating with methanol as working fluid. The heat pipes have an outer diameter of 10 mm, 8.5mm of inner diameter, 300 mm of length and were flattened in order to be embedded to the heat dissipation surface.

For the "Components-1" setup, the PHP and heat pipes have to operate simultaneously to dissipate the heat generated by the electronics installed inside the surveillance system. The PHP shall be directly connected to the electronics dissipating up to 40 W of heat, while the regular heat pipes shall be connected to the rest of the components, being able to transport and dissipate up to 160 W, on a joint maximum heat rejection capability of 200 W. For the "Components-2" setup, the single PHP was able to transport the heat and promote the thermal control of their electronics.

For the tests, each thermal control device was verified for operation independently. Each PHP was instrumented with a total of 20 type-T thermocouples (accuracy of ±0.3°C at 100°C), used to measure the temperatures throughout the PHP. Seven thermocouples were placed on the evaporation and condensation sections of the PHP and 6 were placed at the adiabatic section, which were then connected to a data acquisition system controlled by LabView. Readings were taken at each 5 seconds and recorded in a spreadsheet for further analysis. The PHP heat sink was kept at a constant temperature of 20°C during the acceptance tests in order to better evaluate the devices' thermal capability and their capacity to meet the project's requirements. To simulate the heat source, a kapton skin heater (280 mm X 25 mm, 11.5 Ohms) was attached to the evaporation section to deliver the desired heat load, which was controlled by a DC power supply.

Continuing the thermal control verification, a heat pipe was tested using 20 type-T thermocouples (accuracy of ±0.3°C at 100°C), with 7 thermocouples located at the evaporation and condensation regions and 6 at the adiabatic region, being responsible for the major part of the thermal control process. The condensation area was kept at 0°C in order to better evaluate the devices' thermal capability and its capacity to meet the project's requirements. A skin heater was used as heat source (100 mm x 25 mm, 14.5 Ohms), which was attached to the evaporator directly, controlled by a DC power supply. The instruments were read using LabView at each 5 seconds, and the heat pipe had to be able to transport at least 60 W while keeping the evaporator temperature below 50°C.

RESULTS AND DISCUSSIONS

Both PHPs were tested at horizontal and vertical orientations. A filling ratio of 80% of methanol (purity of 99.98%) was used for this application, which was selected considering the best startup conditions and continuous operation for the PHPs at any orientation [16]. The tests results for both PHPs are very similar regarding their thermal behavior despite their orientation, and the data presented by Fig. 3 is very representative regarding their overall operation.

The PHP presents its operation from the beginning of the administration of heat at its evaporation section. For this condition, low temperatures could be observed during all the test sequence. Intense pulsations were verified due to the generation of vapor plugs, as this is the characteristic of this thermal control device. During the entire test, the evaporator temperature was always kept below the 80 °C requirement, presenting fast responses to the heat load change and reliable operation, despite the temperature oscillations observed, which are a characteristic for this thermal control device. Even though a high temperature difference between the evaporation and condensation sections could be observed during both PHPs tests, this does not represent an issue for the present application.

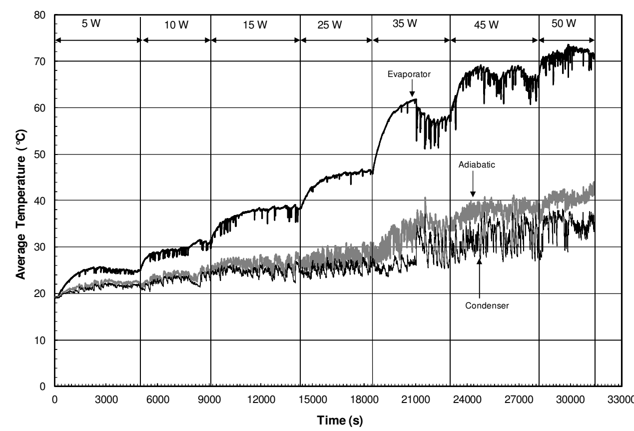

Fig. 3. PHP operation**.**

For the heat pipe, the test condition was performed at horizontal orientation and should be able to transport at least 60 W of heat without presenting a temperature above 50 °C. Thus, a power step test was performed in order to verify the heat pipe capability for the required heat transport.

As presented by Fig. 4, the heat pipe can promote the required heat transport at 60 W while the temperature is below 50 °C, which meets the project's requirements. Stable operation and fast responses to the variations on the heat loads were a characteristic for this thermal control device, showing reliability for the task that has been designed for. Fast transient periods were observed when the heat load was changed, with no temperature overshooting.

The thermal conductance on both PHPs and heat pipes can be verified from the experimental results using the following relation:

$$C_{HP} = Q / \left(T_{evap} - T_{cond} \right), \qquad (1)$$

where C_{HP} is either the heat pipe or PHP thermal conductance (W/°C), Q is the heat load (W), T_{evap} and T_{cond} are the evaporation and condensation sections average temperatures (°C) respectively, with calculated uncertainties below 8%. Figure 5 presents the calculated thermal conductance for the PHP and heat pipe operations, where it is clearly shown that at the highest heat load, the PHP presents thermal conductances around 1.6 W/°C which is considerable high for such an application. This condition directly contributes for a good performance for the PHPs and an efficient heat transport, while keeping the electronics below the maximum required temperature. One should note that this test was performed with the PHP at a stationary condition (without rotation).

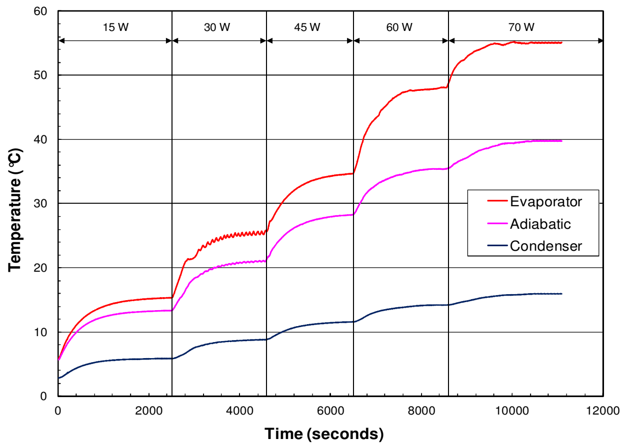

Fig. 4. Heat pipe operation.

Using the same relation presented by Eq. (1), the thermal conductances for the heat pipe are considerably high, with observed maximum values of up to 1.9 W/°C for the operation at 30 W and 1.78 W/°C at 60 W. The relative compatible thermal conductances observed on both PHPs tested for this investigation, as well as the heat pipe, demonstrates a behavior that can lead to a reliable operation for the entire thermal control system in order to meet the project's requirements.

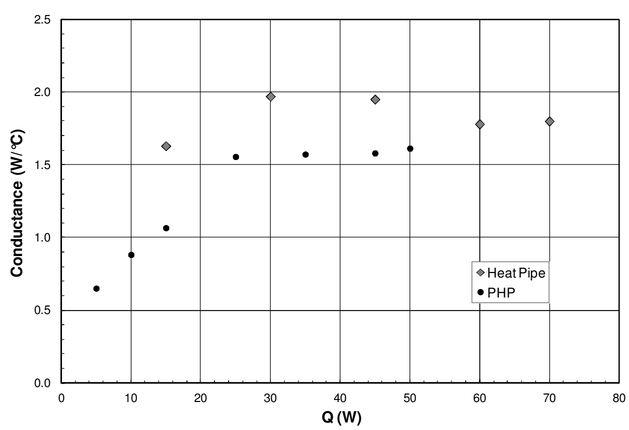

Fig. 5. Thermal conductances for the heat pipe and PHP.

When operating together, the setups composed of PHP and heat pipes for the "Components-1" and the PHP for the "Components-2" were expected to present reliable operation while keeping the surface temperature below the requirements. Preliminary tests were performed, where the surveillance system was operating at its maximum rotation of 60 rpm, which promoted a forced convection across the finned surface. In this case, according to simulations, the heat transfer coefficient should be around 45 W/m^2°C, which was then verified during the tests. Such an angular velocity, along with a finned surface, was enough to reject the heat collected by the PHPs and heat pipes on both setups to the environment resulting in superficial temperatures below the project's requirements. At its minimum rotation of 15 rpm, the forced convection across the finned surface has also shown to be efficient to promote the heat dissipation as needed.

Extensive tests were performed and Figs. 6 and 7 present pictures of the surveillance system fully operational. The temperature concentration observed on the thermal images shown by Fig. 6 indicated where the main heat dissipation is located, with the entire system operating with a rotation of 60 rpm and peak processing rates. Figure 6 shows the temperature distribution along the finned surface for the surveillance equipment on the "Components-1" setup, showing that the PHP and the heat pipes were able to transport the heat and homogenize the temperature distribution on the entire heat source surface, which proves to enhance the heat dissipation process to the environment. It was observed that the temperature distribution is rather homogeneous due to the present of the HPs and PHP, enhancing the heat transfer process to the environment as practically all the finned surface is fully operational, which resulted in low surface temperatures. Tests have been performed with variable rotation of the surveillance equipment and despite the verification of higher temperatures for lower rotation, the PHP and heat pipes have proven to promote the heat dissipation as expected.

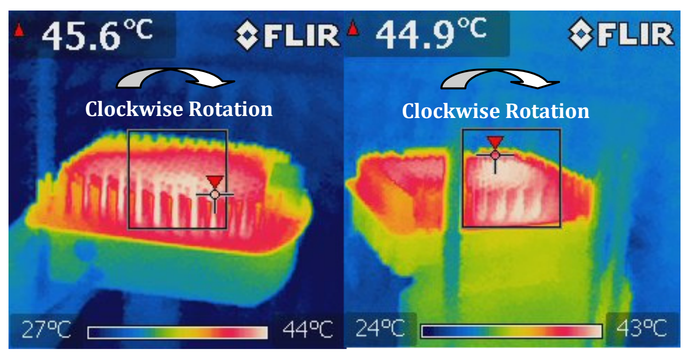

Fig. 6. Thermal image of the surveillance system heat dissipation surface – "Components-1" setup.

Figure 7 presents the thermal image for the "Components-2" setup during operation. It can be observed that the heat could be adequately transferred by the PHP, transferring the heat from the electronics to the finned surface, and thus to the environment. The superficial temperatures were maintained below the required level, showing that the thermal management solution presented is able to transfer and reject the heat generated by the electronic components efficiently. The highest observed temperature at the surveillance system finned surface during all testes was always below 55 °C, showing an effective thermal control promoted by the applied thermal control design.

CONCLUSIONS

The use of a combined solution for the thermal management of electronic components presents to be an important approach for new designs, especially for the growing demand of heat dissipation.

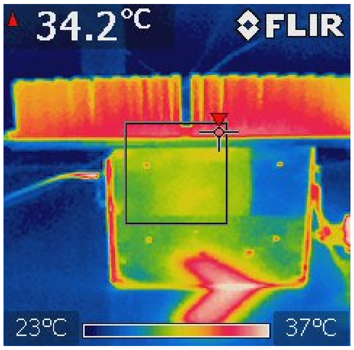

Fig.7. Thermal image of the surveillance system heat dissipation surface – "Components-2" setup.

The use of a PHP coupled with regular heat pipes for the "Components-1" setup and a single PHP for the "Components-2" setup presented in this investigation show an important approach, where the main conclusions that can be derived are as follows:

- Both PHPs presented reliable performance while operating during the tests with variable rotations of the surveillance equipment, and same reliability was observed for the regular heat pipes;
- Both passive thermal control devices presented fast responses to the heat load change, while keeping their evaporation section below the temperature requirement of the project, also showing temperature distributions with acceptable variations;
- The surface temperature of the surveillance system was kept below the requirements during operation, showing that the presented solution is capable of performing the required thermal control, while keeping the electronic components within their operation temperature range;
- The use of a combined solution of PHP and regular heat pipes, along with a finned surface for heat dissipation to the environment, have shown reliable results even when the rotation of the surveillance equipment was varied from 15 to 60 rpm, as expected during simulations;
- The single PHP used to promote the "Components-2" setup thermal control showed reliable operation while keeping the temperatures below the requirements for the project, despite the equipment's rotation;
- The overall thermal design conceived for this operation presents important results regarding the heat dissipation generated by the electronics components of the surveillance system. This indicates that the PHP and heat pipe technologies can be widely applied for ground applications where certain requirements need to be met and conventional thermal control is not possible.

Future projects where a more flexible solution is needed for the thermal control of electronics devices shall consider the presented results. Variations on the presented thermal design have been applied either using only the PHP or the heat pipes for both setups where the thermal control was necessary, in order to promote their heat dissipation and the results will be presented in future reports.

More flexibility on the design of such applications can be reached with the proposed solution, along with more compact equipments also resulting in less weighted devices, presenting reliable operation due to the use of well-known aerospace thermal control solutions. The application of PHPs and heat pipes have gained attention and interest to be used as thermal control and heat dissipation devices for Defense/Military purposes.

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