Solving the Thermal Challenge in Power-Dense CubeSats with Water Heat Pipes

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ABSTRACT

This paper describes the results of a project researching the application of water heat pipes in CubeSats. Heat pipes are proposed to solve for the increase in CubeSat power density, being one of the main thermal challenges appearing in high-performance missions. Commercial off the shelf water heat pipes have been tested and a proof-of-concept design has been made showing the flexibility of heat pipe integration. Thermal tests reflecting a common hot- and cold case experienced in low-Earth orbit, have been carried out. These tests have proven that the water heat pipe is capable of keeping a single component generating a continuous heat dissipation of \(10\,\text{W}\), within a reasonable temperature range and successfully start-up from a frozen state before temperature limits are breached. The outcome of this research has shown that water heat pipes can be the thermal solution for high performance CubeSat missions.

INTRODUCTION

Over the years, the potential of CubeSats has been recognized and acknowledged by industry. The original intent of education and technology demonstration is being surpassed, fueled by the rapid enhancement of available commercial-off-the-shelf components.\(^1\) A shift is occurring where Earth observation and other services are enabled by using advanced CubeSats.\(^2\)

The current mission portfolio at ISIS – Innovative Solutions In Space shows this trend clearly from the increased demands for CubeSats being able to provide Earth observation services or support scientific experiments. In conjunction with this trend, the thereby necessary introduction of deployable solar panels for CubeSats has led to a tremendous increase in CubeSat power density.

This trend leads to two main thermal challenges to be solved; transporting the heat from source to (local) sink and radiating the waste heat towards deep space. While the latter challenge can be solved by using deployable radiators, it is actually the first challenge that has not been researched much yet. So, what exactly is the challenge?

With the increased power density and in particular the shift towards Earth observation and service provisioning, local heat dissipation becomes problematic, creating so-called local thermal hotspots. The creation of these hotspots is mainly driven by the increase in usage of high-performance payloads and RF subsystems. FPGAs, detectors, and MCUs are typical components that consume the most power when looking at EO payloads. With the movement towards service provisioning, duty-cycles need to be as high as possible in order to maximize profit. Furthermore, data generation for the aforementioned type of missions is usually significantly higher than in the early days of CubeSat missions. Downlinking large data volumes can only be realized by high-power transmitters. As only a small portion of the power usage is actually converted into RF power, the majority is dissipated at the power amplifier, leading to a local thermal hotspot. With contact times in the order of 10-15 minutes and a dissipation in the order of 5 to 10W for state of the art...
S-Band transmitters, it is not difficult to realize the problem at hand.

While the local heat dissipation on itself does not need to be a problem it actually the CubeSat standard that adds to the complexity and upcoming challenge; the buildup of CubeSats is such that multiple PCBs are crammed into stacks and through usage of rods and spacers are mounted in the external structure. For any of the aforementioned components (PA, FPGA) it means that their conduction path runs from the component through the PCB to spacer to rib to external structure. Along the way it may also pass through edges of the other PCBs, making the heat transfer from source to sink (external structure) cumbersome.

Requirements on Thermal Control Solution

To get from problem to solution it is important to define the requirements to which the thermal control solution needs to adhere. In the search for this new solution the following requirements have been identified:

Passive/Low power solution – Any powered thermal control solution will only move the problem from one location to the other. Furthermore, active solutions will add complexity and decrease reliability by possible usage of moving parts.

No/Limited impact on CubeSat design – The solution should allow freedom to the CubeSat systems engineer and not pose additional constraints on any parts of the design, including other subsystems.

Able to remove a continuous heat load of up to 10W – Considering the expected power densities and high local heat dissipation the solution should be able to remove a continuous heat dissipation up to 10W while keeping the component within its temperature limits. This is representative for a radio transmission period where the power amplifier is under a considerable load.

Considering these requirements, a short literature study revealed that the prime candidate is the heat pipe. Not only have heat pipes been extensively used for Earth-applications, they are also a common solution used for heat transport in large satellites. They provide design flexibility to the thermal engineer by allowing application of bends and any desired length as in the absence of a gravity-gradient its performance is independent of its length.

HEAT PIPE THEORY

Heat pipe functionality is achieved through a passive liquid-vapor cycle, thereby relying on the capillary pressure force. If one of the ends of the heat pipe is subject to a heat input (evaporator) the present liquid in the wick will vaporize. This, together with wetting of the wick structure leads to a depression and decrease in pressure of the remaining liquid. With evaporation, the local vapor pressure will increase, effectively leading to a movement of the vapor towards the condenser section. By choosing a proper wick structure and material capillary forces will transport liquid from the condenser section towards the evaporator section, completing the heat pipe cycle, as shown in Figure 1.3

![Figure 1: Heat pipe operation principle.](image)

Heat Pipe Limits

The performance of heat pipes is measured by heat transport capacity as a function of heat pipe temperature. This transport capacity is dictated by a multitude of limits, leaving behind an operating space for the heat pipe. The main limit of interest is the capillary limit. The capillary forces generated by the wick structure must overcome the liquid, vapor, and gravitational pressure drop to have a continuous cycle:

$$\Delta p_c \geq \Delta p_l + \Delta p_v + \Delta p_g$$  \hspace{1cm} (1)

Assuming the heat pipe being tested in horizontal position or used in space the gravitational term in equation 1 can be neglected. Furthermore, it can be shown that the vapor pressure drop is negligible compared to the liquid pressure drop. Finally, setting both the capillary pressure force equal to the liquid pressure drop results in the capillary limit of the heat pipe, as shown in equation 3, for axial grooves.

$$\Delta p_c = \Delta p_l$$  \hspace{1cm} (2)

$$\frac{2\sigma_l \cos \theta}{r_c} = \frac{8\mu_l m}{\rho_l NA_N r_h}$$  \hspace{1cm} (3)

where $\sigma_l$ = liquid surface tension; $r_c$ = capillary radius; $\theta$ = contact angle liquid at wick; and $\mu_l$ = liquid viscosity; $l_{eff}$ = effective heat pipe length; $m$ = mass flow; $\rho_l$ = liquid density; $N$ = number of grooves; $A_w$ = wick groove area; $r_h$ = hydraulic radius.

For heat pipes with a porous wick structure, such as sintered or meshed (see also Figure 5), the liquid...
The pressure drop is given by the Darcy-Weisbach Equation:

\[
\Delta p_l = \frac{\mu_l V_m}{\rho_l K A_w} \tag{4}
\]

where \( K \) = the wick permeability, given by equation 5.

\[
K = \frac{8\sigma_{lj}}{f D \text{Re}} \tag{5}
\]

where \( \varepsilon \) = the wick porosity; \( f_D \) = the Darcy friction factor; \( \text{Re} \) = the Reynolds number.

While the capillary limit places a cap on the maximum heat transport capacity at nominal heat pipe temperature range, other limits are present as well. These are the viscous, sonic, entrainment, and boiling limit. However, these limits come only into play at low or high heat pipe temperatures. Together, with the aforementioned capillary limit they demarcate the operation region of the heat pipe, as shown in Figure 2.\(^4\)

**Figure 2:** Heat pipe performance bound by its limits.

**Fluid Performance**

The equations describing the capillary limit show the dependency on fluid properties. It is therefore interesting to be able to compare the performance of different fluids. Rearranging equation 3 leads to a term that is entirely fluid dependent, shown in equations 6 and 7, respectively.

\[
\dot{Q} = \left( \frac{N A_w}{w_h l_{eff}} \right) \left( \frac{\sigma_{lj}}{\rho_l h_{lv} \mu_l} \right) \left( \frac{2}{\varepsilon} \right) \tag{6}
\]

\[
M = \frac{\sigma_{lj} \rho_l h_{lv}}{\mu_l} \tag{7}
\]

This term can be used as a figure of merit for comparison of fluids. The resulting comparison can be found in Figure 3 where for different fluids this figure is shown as a function of temperature.\(^5\) It can be clearly seen why water, ammonia, and methanol are among the fluids most used in heat pipes.

**Figure 3:** Figure of merit for different heat pipe fluids.

For application in CubeSats, the actual choice for either of these fluids will not only depend on their performance, but also on the operational temperature range that the heat pipe will experience. In low-Earth Sun-synchronous orbit, CubeSats in general experience temperature extremes at the outer panels of -30°C and + 40°C. That said, ammonia and methanol seem the most likely candidates, considering their operating range. At the same time, the limited design space in CubeSats forces consideration of the fluid with the highest figure of merit; water. As the performance of the heat pipe also increases with heat pipe diameter, it means that the higher the figure of merit, the smaller the heat pipe can be. Also considering the fact that water is not hazardous in any way, this argues for water as prime candidate for acting as working fluid. Theoretical analysis of the heat transport capacity for a water heat pipe as a function of diameter and axial groove width is visualized in Figure 4. It shows that a 4mm diameter pipe and a 0.2mm groove width, already suffices in transporting a heat load of around 10W.
To show successful prove of concept the main aspects to test for are the actual performance of commercial water heat pipes, the effect of repetitive freeze/thaw cycling, and transient start up.

TESTING COMMERCIAL HEAT PIPES

Commercial heat pipes have been taken with dimensions based on theoretical analysis and complying with the earlier mentioned requirements for CubeSat integration. A diameter of 6 mm was chosen and a total heat pipe length of 200 mm. The performance of the three different types of heat pipes were tested: A sintered, axial grooved, and a mesh heat pipe whose cross-sections are shown in Figure 5.

Figure 5: Axial grooved, mesh, and sintered cross-sections.

The setup used for carrying out the tests is shown in Figure 6. The thermostat bath and thermo-electric cooler are able to keep the temperature of the heat pipe fixed while the heaters supply power directly to the heat pipe. Along the heat pipe, thermocouples are present to measure the temperature. The entire setup is isolated from the environment to minimize heat leakage.

Figure 6: Test set up for heat pipe performance testing.
The heat transport capacity is measured for different heat pipe temperatures. For an ideal heat pipe the temperature remains constant along its length, indicating that the heat at the evaporator section is transported fully to the condenser section, where it is removed by the thermo-electric cooler. The maximum transport capacity is defined at the point right before the temperature at the evaporator section increases to extremes.

The results of the tests are plotted in Figure 7, showing that axial grooved heat pipes have a clear benefit over the other two. Nonetheless, the sintered variant is also able to remove waste heat of more than 10W, making them both suitable for CubeSats. The performance of the mesh heat pipe proved to be not only less than the other two, it also showed irregular behavior, making the measurements less reliable.

![Figure 7: Heat pipe performance test results.](image)

These results show that the transport capabilities of small commercial heat pipes are sufficient to overcome the heat dissipation problem foreseen for current and upcoming CubeSat missions.

Another aspect that deserves attention is the repetitive thermal cycling of CubeSats in LEO. Roughly every 100 minutes temperatures vary internally from -10°C to 25°C. To see whether the commercial heat pipes are capable of surviving this environment, they have been subject to 100 freeze-thaw cycles. The condenser end has been cooled down to -15°C and heated up to 10°C for 10 cycles. Hereafter, the functionality was tested by elevating the heat pipe to a temperature of 30°C and applying a 20W heat load. Figure 8 shows part of these test-cycles.

![Figure 8: Repetitive freeze/thaw cycling of the heat pipe.](image)

After completion of 100 cycles, the heat pipes remained fully functional and both internal and external visual inspection showed no clear signs of damage. Although 100 cycles cannot be fully compared to the amount of cycles experienced during a CubeSats lifetime, it does show promising results.

**APPLICATION OF HEAT PIPES IN CUBESATS**

One of the earlier defined requirements states that integration of the heat pipe should not or have limited impact on any of the CubeSat its subsystems or structural elements. Next to this, integration will also define the coupling between the heat pipe and the heat source and sink. An improper coupling, incapable of transferring heat from source to the heat pipe will render this solution useless. The importance of this is shown in Figure 9 and Table 1, where the types and magnitudes of the resistances are listed, respectively.

![Figure 9: Order of magnitude of the different heat pipe resistances.](image)
The magnitude of the resistances clearly shows that the resistance between the heat source/sink and the evaporator/condenser section is by far the largest and thus dictate the overall performance of the design.

Table 1: Thermal resistances and their order of magnitude in heat pipes.

<table>
<thead>
<tr>
<th>Resistance</th>
<th>Interface</th>
<th>°C/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_1$, $R_2$</td>
<td>Heat source – Evaporator/Condenser</td>
<td>$10^1$-$10^2$</td>
</tr>
<tr>
<td>$R_3$, $R_4$</td>
<td>Heat pipe wall</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>$R_5$, $R_6$</td>
<td>Heat pipe wall – Wick structure</td>
<td>10</td>
</tr>
<tr>
<td>$R_7$, $R_8$</td>
<td>Liquid – Vapor</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>$R_9$</td>
<td>Vapor section</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>$R_{10}$</td>
<td>Heat pipe wall (axial)</td>
<td>$10^{-2}$</td>
</tr>
</tbody>
</table>

Both these aspects have been taken into account while designing a first concept for integrating the heat pipe into the CubeSat structure. The design is presented in both images in Figure 10. It incorporates a single heat pipe with contact to the heat source at the middle. This will result in two liquid-vapor cycles transferring heat from the source to both ends of the heat pipe, effectively acting as two separate, shorter heat pipes. The design uses the already present screw holes in the ribs for attaching the condenser interface to the structure, while it also still allows for a PCB to be placed above the one depicted.

Interestingly enough, the heat pipe itself does not distinguish between source and sink. Whenever heat is applied to a part of the heat pipe it will automatically start the liquid-vapor cycle and move heat from the hot to cold part.

HEAT PIPE TESTS
To show proof of concept of water heat pipes in CubeSats several tests have been executed: Heat pipe performance test, gravity-test, and transient start-up tests. For all tests, the same set up has been used.

Test Set Up
The test set up used is schematically depicted in Figure 11. A CubeSat is located in the center of a thermal chamber, with the internal PCB hooked up to a power supply and computer.

![Figure 11: Schematic test set up for CubeSat testing.](image)

A standard 2U ISIS CubeSat structure has been taken, including standard aluminum side panels. A custom PCB was designed capable of generating any desired heat dissipation in the center of the board. This was enabled by a set of resistors with a total area footprint comparable to FPGAs, large chips, or power amplifiers. The circuitry allowed connection of multiple thermocouples and read out of sensor data through USB. The custom designed board is shown in Figure 12, where the UC# indicate the integrated temperature sensors.
With the importance of a proper integration made clear in previous section, custom interfaces were designed for both the evaporator and condenser section. Copper was used because of its high conductivity. The condenser section was designed with a slightly smaller diameter than the heat pipe ensuring a tight coupling. The small gap along its length allowed for further clamping of the heat pipe once mounted to the external structure.

**Figure 13:** Custom designed heat source and sink interfaces.

The source interface was made equal in size to the heat source. Two grooves were designed that could fit either a 4mm or 6mm heat pipe. The heat pipe is clamped to the resistor area by using the custom design heat sink, as shown in Figure 14. Small aluminum strips tightly clamp the heat pipe with screws that are fastened to the bottom of the PCB.

**Figure 14:** Custom designed heat source and sink interfaces.

To further overcome the influence of convective heat transfer the chamber set point was controlled in such a way that the outer CubeSat panels were kept at a constant temperature.

**Heat Pipe Performance Tests Results**

The performance test is the main test to show whether the integrated heat pipe is capable of removing the 10 W continuous heat load. For comparison, a run has been carried out first to find out what temperature will be attained locally without a heat pipe. The temperature of the outer panels was set at a controlled temperature of 40°C, effectively bringing the internal PCB temperature to roughly 30°C. This is considered a hot-case experienced by CubeSats in LEO.

Figure 16 shows the resulting temperature measured in the center of the resistors on the PCB. The test without a heat pipe (red line) showed a rapid increase in temperature; at 3W the temperature had risen to a value of 103°C.
This is not surprising as all the heat generated can only escape through the PCB, which is a bad conductor due to the bulk material being FR4. The blue line shows the result of adding a heat pipe where the 3W heat load results in a temperature of 57.4°C; a remarkable ΔT of 45.6°C between both cases.

Even more interesting is to observe this effect by analyzing the temperature distribution over the PCB as shown in Figure 17 and Figure 18.

A clear difference is shown confirming that the heat pipe transports the majority of the heat generated by the resistors, as the temperature gradient over the PCB remains low in the latter case.

The final step for this test was to investigate whether the heat pipe was capable of successfully removing up to 10W of continuous power from the source. The result is shown in Figure 19. The plot shows different temperature readouts; one at the heat source, the evaporator section, the adiabatic section, and at the condenser section. Indicated in the plot is the step-wise elevation of power input applied during the test.

The successful functioning of the heat pipe during this test is proven by the almost identical temperatures at the
evaporator section and the adiabatic section. This indicates that the heat is successfully transported and not actively heating up the part of the heat pipe itself.

The step-wise power input shows the capability of the heat pipe: A total of 10 W continuous heat dissipation was applied, at which point the temperature at the heat source reached 95.8°C.

What becomes evident from the results though is the occurrence of an increased ΔT for higher heat inputs. This confirms the earlier emphasized role of the resistance and importance of a proper conductive coupling between the heat source and heat pipe. At a 10W heat load there is a temperature gradient of more than 20°C. Improving the current design, will allow a lowering of this value and reducing the overall PCB temperature. It has to be stressed that the conditions at which this test was carried out represent a hot-case. The heat pipe shows that even in this scenario it is capable of successfully transporting large amounts of waste heat. This is also one of the benefits of heat pipes as their performance improves at higher temperatures.

**Heat Pipe Gravity Test**

The second test carried out was to determine whether gravity influenced the operation of the heat pipe in this particular set up. The heat pipe was integrated in such a way that the heat sink was located at a higher position than the heat source, meaning that the liquid should have to work its way against gravity. To make sure the influence of gravity is negligible a test was conducted in which the CubeSat was placed upside down. The heat source temperature results are compared in Figure 20.

From the graph, it can be seen that the gravity has no clear effect on the operation of the integrated heat pipe; In both cases the resulting temperature and the profile are similar and show no significant deviations.

**Heat Pipe Transient Start-up Tests**

Finally, test runs were performed with temperatures below 0°C. Temperatures of the outer panels were kept at -20°C. 10W Heat was then generated to see whether the heat pipe was able to successfully thaw and start up before the component temperature limit was breached. Again, temperatures were measured at the heat source and condenser section. The other measurement locations were at the heat sink interface and on the heat pipe at the evaporator section. The result of the test is shown in Figure 21.

![Figure 20: Gravity and anti-gravity orientation compared.](image1)

![Figure 21: Temperature results for the transient start-up test.](image2)
source, and the condenser section show that much improvement can be made to the conductive coupling. This will further aid in the startup of the cycle from frozen conditions.

The temperature finally reaches 43°C, well within the limits of the heat source. Despite the initial sharp increase in temperature at the heat source and the frozen state of the heat pipe, copper conduction will already transport some heat fueled by the high ΔT arising between heat source and sink (panels).

DISCUSSION

The outcome of the tests has shown that the performance of commercial off-the-shelf heat pipes is sufficient to cope with the projected heat loads in high-performance CubeSat missions. The aspect of the freezing issue is tackled by showing successful startup with no limit being breached. The main advantage during occurrence of freezing is that the environmental temperature will be low as well, allowing for a larger temperature increase of the source before its limit is reached. Furthermore, the higher the temperature gets, the larger the ΔT becomes between source and sink, thereby increasing the conductive heat transfer and speeding up the thawing-process of the heat pipe.

The question is whether complete freezing will ever occur during a CubeSat LEO mission. As long as the component under consideration is dissipating (a small amount of) heat the evaporator section will never freeze.

CONCLUSION AND RECOMMENDATIONS

A first design has been presented for integration of a water heat pipe into CubeSats. The design has shown that integration of a heat pipe has limited to no impact on other subsystems or the structure. The ability to freely bend the heat pipe allows an unmatched freedom during integration.

Tests for a hot- and cold case have proven successful operation of the heat pipe, keeping a component dissipating a continuous 10W within its temperature limits.

To make a successful product out of this some steps need to be taken; A further development of the interface between heat source and sink and heat pipe is necessary to reduce the thermal gradient which arises at higher temperatures. This can be enabled by maximizing the surface contact area. For example, comparable to the design made for the condenser section, the evaporator section can be fully enclosed with copper as well. Application of thermal paste and improved clamping will further improve conductivity between heat source and the heat pipe evaporator section; Tests should be carried out which investigate the effect of vibrational loads onto the heat pipe and design; Finally, show proof of concept in orbit.

The CubeSat is the perfect platform to demonstrate new technologies, and with the inclusion of water heat pipes can be the enabler for even more advanced missions.

References