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THERMAL TESTING OF AN AMDROHP (ADDITIVELY MANUFACTURED DEPLOYABLE RADIATOR OSCILLATING HEAT PIPES) FOR USE IN HIGH-POWERED CUBESATS

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ABSTRACT

High-power small satellites will play an important role in reducing the cost of space missions. High power levels are required to satisfy high bandwidth communication needs, as well as to accommodate other critical systems such as propulsion and high-power electronics. One of the current high-power limitations is the need to overcome the thermal challenges associated with high thermal loads. While substantial work has been done in the development of deployable solar arrays, relatively little attention has been given to small satellite deployable radiators. Previous deployable small satellite radiators rely on a mechanical hinge to conduct heat from spacecraft to radiator. However, this presents a thermal choke point and limits heat flow. Thus, a deployable radiator design concept is currently being explored as a thermal solution for high powered electronics in CubeSats. This Additively Manufactured Deployable Radiator Oscillating Heat Pipes (AMDROHP) design concept combines the function of a deployable radiator with high performance Oscillating Heat Pipes in this compact thermal solution. In this project, significant efforts have gone into developing the mechanical, deployable aspect of this design while maximizing its thermal performance, and this joint development has been discussed in previous publication. This initial design was additively manufactured and thermally tested at the Jet Propulsion Laboratory. The results of the thermal testing of the initial AMDROHP design are discussed and presented in this work. The device is tested across a range of heat inputs under "micro-gravity" and "gravity-assisted" orientations for the working fluids R134a and Ammonia. The performance and behavior of the AMDROHP device are characterized by transient temperature measurement data under these different conditions. The results were interpreted to determine the feasibility of the design. Although AMDROHP did operate under "gravity-assisted" orientation, it did not start-up under "micro-gravity" orientation. Furthermore, the range of operation under "gravity-assisted" orientation was less than expected. Based on these results, possible design changes have been identified to improve AMDROHP performance under space-like conditions. These changes include creating a shorter adiabatic length by decreasing the path length of the helical joint, as well as increasing the inner channel diameter. These changes will allow for better thermal performance and to better avoid any imperfections in the additive manufacturing process to cause negative effects on OHP operation. In this study, experimental testing provided actionable information about the initial design of AMDROHP to lead to design improvements. These design improvements will be implemented in the next design iteration of AMDROHP.

1. INTRODUCTION

Thermal management systems are critical for keeping spacecraft operational by rejecting heat away from temperature sensitive parts, such as on-board electronic systems. As the demand to employ high power systems in small satellites grows, thermal management systems need to improve in parallel to meet the heat rejection requirement. Thermal radiators can effectively transfer heat away from heat loads. Effective radiators for small satellites should be able to conduct heat away from heat source and radiate that heat into space. The radiator should maximize this radiation surface area to meet high heat rejection demands.

Currently, in development to address this issue for a 3U CubeSat (miniature Cube Satellites) is Additively Manufactured Deployable Radiator Oscillating Heat Pipes (AMDROHP). The development of AMDROHP radiator serves to address the need for transfer and reject heat from electronics in small spacecrafts, through the use of a highly efficient heat transfer device known as Oscillating Heat Pipes (OHP). This implementation of OHPs is done as a complete, single additively manufactured part including deployable radiators. An image of AMDROHP can be seen in Figure 1, and it can been seen the evaporator panel where the heat load is applied to the device, the condenser panel where from which the heat is radiated from the device into space, and the hollow helical coil, joint hinge mechanism serves as a part of the fluid path for the two-phase device. This device can be stowed with the joints bent to a 90° angle, as well as be deployed, as seen in the figure, 40° outward.

The purpose of this paper is to evaluate the performance of the first design iteration of AMDROHP through experimental thermal testing. By evaluating the design of AMDROHP, it can be seen how well it performs its function as a thermal management system for small spacecraft, and its operating behavior can be characterized to help inform design changes to improve its function. The objective performance of AMDROHP is to be able to reject 25 W of heat at a conductance of 4-6 W/°C in a micro-gravity orientation, which it will expect to see in Low Earth Orbit.

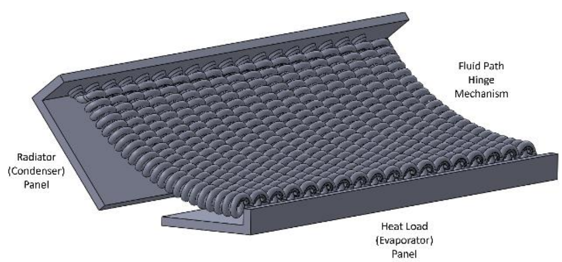

FIGURE 1: LABELED IMAGE OF AMDROHP DEVICE

OHPs are two-phase heat exchangers capable of operating passively, under high heat loads, with high thermal conductance. OHPs are a series of serpentine channels, charged with a saturated working fluid [1]. On one end of the OHP, the working fluid in the channels is evaporated, creating a high-pressure region. On the opposite end, the working fluid is condensed, creating a low-pressure region. This pressure difference drives the liquid from the evaporator to condenser, creating fluid motion [1]. Once the working fluid reaches the condenser end, the vapor ahead of the displaced working fluid in the condenser becomes highly compressed and pushes the liquid back to the evaporator. This process continuously occurs back and forth creating an oscillatory motion of fluid in the OHP, which leads to a highly efficient process of heat transfer through the primary means of sensible heat transfer [1]. Hisateru Akashi patented Oscillating Heat Pipes in 1990 and their introduction has brought interest through its high performance and applications [2].

In better understanding the working mechanisms of OHPs, research has been performed analyzing the effect of different parameters on the behavior and performance of OHPs. Channel diameter [3], [4], [5], working fluid [3], [6], [7], [8], and orientation [4], [9], [10] are some of these parameters that of interest to researchers in OHP research community. By better understanding the driving factors of OHPs, their performance and operation can be better controlled to allow for effective designs in application.

One of the big appeals of OHP technology is design flexibility and robust design constraints, as a loop of serpentine channels with evaporator and condenser regions, are the general design requirements to make an operating OHP. Beyond those requirements, there exists much freedom in how an OHP can be designed geometrically. Thus, OHPs are appealing to many researchers and engineers in creating unique designs, such as AMDROHP. Czajkowski et al. presented a large-scale "flower-shaped" oscillating heat pipe in a rotary system created for the application of mixing solvents [11]. This OHP design is 300 mm tall, with a 200 mm radius for the evaporator and condenser. The channels pass through multiple planes, and this OHP is expected to rotate up to 300 rpm. From the testing of this device, it was found that while a higher rpm increases the operating thermal resistance of the device, it was still possible to see start-up and consistent operation for such a design. These successful results offer one example of a working OHP with a unique function and geometry. Zhao et al. tested an OHP designed for thermal energy storage and recovery by making use of an internal expansion structure [12]. Similar to Czajowski, the geometry of this design was a flower-shaped channel path. This design, however, was circular in shape with the evaporator in the center, surrounded by an adiabatic region, and a condenser region on the outmost perimeter. In this design, the evaporator and adiabatic region are different in material to the condenser, of which the material operates by expanding to store energy. This device works by the heat being transferred from a central heat source at the evaporator to the condenser on the perimeter, where the energy is stored during operation. Then, once the OHP is not in operation, the thermal energy stored is resupplied to the system. From this testing, it was found that start-up will occur for a wide range of fill ratios for the device and that a minimum thermal resistance of about 0.125 °C/W (conductance of 8 W/°C) was achieved for this design. Luan et al. tested an oscillating heat pipe heat spreader design [13]. Similar to Zhao, the tubing exists in a radial pattern with the OHP turns carrying heat from a central region to an outer perimeter. Beyond the unique channel path geometry, this design also made use of tesla-type check-valves in intermediate regions of change from evaporator to condenser. Tesla-type check valves allow for unidirectional flow through use of a non-moving geometry through controlling the fluid path of forward and reverse flow [14]. These check valves are commonly used in liquid flowing microchannels. Through use of the check-valves, a steady supply of liquid will remain in the evaporator region, as opposed to being forced backwards into the condenser, which serves the purpose of increasing the overall thermal performance and operating life of the device. From this testing it was seen a sizeable decrease in temperature from the central heat source to the outer perimeter of the device for the heat spreader OHP, when compared to a conducting copper slab of the same dimensions. These results show the heat spreader OHP fulfills its purpose and offers another example of an atypical-shaped OHP that still offers effective heat transfer.

For the AMDROHP design to have effectively integrated a helical coil joint as its hinge mechanism, the entire path length of the joint needs to act as the adiabatic region (region between the evaporator and condenser) of the OHP. This presents some uncertainty with the design, as having a long adiabatic length improves the flexibility of the joint, but also adds uncertainty about the performance of the OHP. A long adiabatic length necessitates a larger pressure difference to be generated across the OHP, to enable the fluid to overcome friction in the adiabatic length and to make it back and forth between the evaporator and condenser. For this reason, the rest of the literature review is focused on OHP devices with long adiabatic lengths.

Perna et al. tested a deployable OHP device, similar in mechanical function to the AMDROHP, with a large coil each turn, serving as the deployment mechanism [15]. This OHP was designed with the lengths of the evaporator, adiabatic, and condenser regions to be 10 mm, 720 mm, and 75 mm, respectively. When compared to AMDROHPs respective dimensions of 133 mm, 611 mm, and 64 mm, a shorter evaporator and longer adiabatic length, means the results of the testing of this study by Perna et al. can help to provide representative results for what to expect from AMDROHP design. Further, this testing was performed with a larger inner channel diameter of 1.6 mm compared to that of AMDROHP (1.0 mm). Different configurations were tested with the OHP bent to different angles at the hinge. The 180° configuration, where the OHP is laying flat, with no bend in the adiabatic region, is of the most interest due to being the orientation that best minimizes the effects of gravity. From these results, it was seen that for this configuration, “small amplitude oscillations” occurred for a heat range tested of 20 to 40 W. These results showed a performance of 2.35 to 2.54 °C/W across those heat inputs, which equates to a conductance of 0.39 to 0.43 W/°C. While these results indicate some OHP operation and suggest OHP can operate with a long adiabatic length, there is still much room to improve on the performance of the OHP in terms of conductance. Czajkowski et al. performed a study on OHPs which included considering how OHPs with long adiabatic length perform based on the operating heat range along with temperature and pressure [16]. Tested in this study were adiabatic lengths of 500, 750, and 1000 mm which bound the adiabatic length of the AMDROHP of 611 mm. For this testing, a 2.5 mm inner diameter was tested. Additionally, the orientation of this testing was performed with the OHP vertically and the evaporator on the bottom, which helps to assist the OHP operation and will provide more favorable results than the micro-gravity orientation that AMDROHP will be expected to perform under. Based on the results it was seen that across the working fluids acetone, ethanol, and water, a minimum thermal resistance of 0.05 °C/W (20 W/°C conductance) was able to be achieved. Further, it was found that for a shorter adiabatic length, start-up occurs at a smaller heat load. For a longer adiabatic length, dry-out occurs at a larger heat load. Qu et al. tested a flexible oscillating heat pipe, bent to different shapes, including an "I", "stair-step", "inverted U", and "N" all in a gravity-assisted orientation [9]. These OHPs had dimensions of an adiabatic length of 870 mm and an inner diameter of 4 mm and were tested with ethanol as a working fluid to fill ratios of 50, 60, and 70% liquid to vapor. It was found through testing that across all these shapes, the “I”-shaped OHP without a bend in the adiabatic section performed the best. Start-up occurred from around a 20 to 30 W heat input and at that point. Once started-up, the thermal resistance improved as more power was input, with the best result of about 0.3 °C/W (3.33 W/°C conductance). While AMDROHP will be expected to perform in a micro-gravity environment, it is helpful to know that bends in the adiabatic can restrict performance in an OHP. Still, these results serve as examples of successful cases of operation in OHPs with long adiabatic sections. From the results of these studies, we can see examples of OHP parameters that offer success and can be implemented in the instance of unsuccess or underperformance in the AMDROHP.

2. SETUP AND PROCEDURE

Seen in Figure 2 is a labeled diagram of the test setup used in testing the AMDROHP device. An 80/20 framing rail test bed was used for the testing system to mount to. The AMDROHP device was mounted to the chiller powered cold plate using a series of bolted High Density Polyethylene mounting strips and clamps to apply force across the interface. A compressible pink gap filler interface material was used between mounting surfaces. A custom machined aluminum adapter plate was made such that the AMDROHP condenser could fit on the cold plate. The brand of chiller used for this experiment is the Julabo F32-He. A 1”x0.5” Vishay Dale 3.57Ω cartridge heater was placed onto the center of the back surface of the evaporator to serve as the heat source. This heater was connected to and powered by a Xantrex XFR 300-4, 300V, 4A power supply. T-type thermocouples were attached to the AMDROHP and wired to an Agilent 34972A data acquisition (DAQ) device. This DAQ was connected to a computer through a USB connection where the data was displayed and collected.

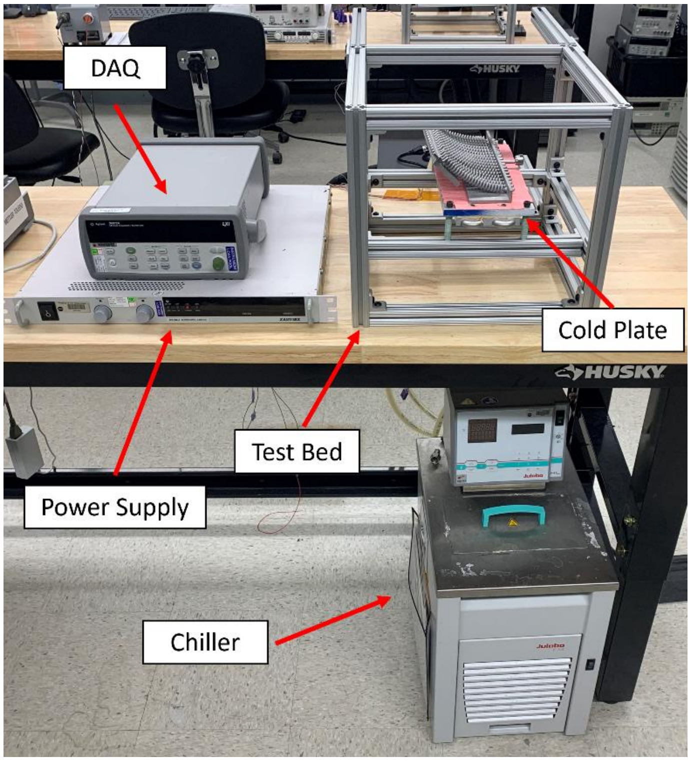

FIGURE 2: AMDROHP EXPERIMENTAL TEST SETUP

Figure 3 shows the thermocouple placement used in this experiment. Three thermocouples were placed each on the evaporator and the condenser and an individual thermocouple was placed on each the heater and cold plate.

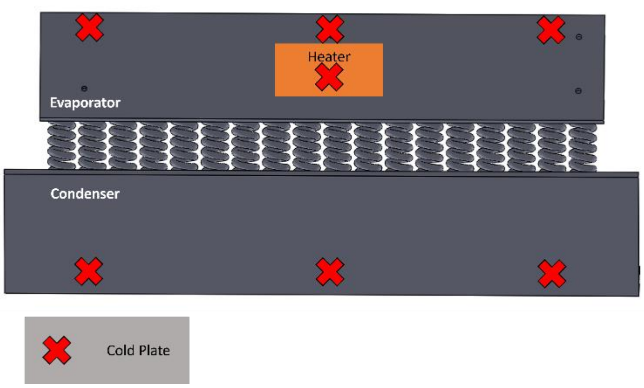

FIGURE 3: THERMOCOUPLE PLACEMENT FOR EXPERIMENTAL TESTING

The procedure for testing the AMDROHP device began with starting the data collection with the LabVIEW data logger on the computer connected to the DAQ. This software collects temperature data, at a set 1 Hz sampling rate, over time for all of the thermocouples attached to the device. Once the collection has started, the chiller is turned on and the temperature of the cold plate is allowed to reach a steady-state at a temperature of 10 °C. After this time, then the power supply is turned on and heat is put into the system. Through knowing the resistance of the system and the desired power input, the voltage is adjusted through the direct wired reading, in the software. Once the temperature reaches steady state, the heat input can be increased to the next step. This process was followed, increasing in increments based on judgement during the experiment. Heat load values are chosen to evaluate when the device achieves start-up, maintains operation, and dries out. This data was stored in a CSV file and processed and plotted through the MATLAB software to analyze the results.

The different test cases for this study include testing with two separate working fluids including R134a and Ammonia, as well as two separate orientations including a micro-gravity orientation and a gravity-assisted orientation. Images of these orientations can be seen in Figure 4. To achieve these different orientations, the test bed is rotated to sit flat on the necessary side. Stilts were used on the side of the test bed where the chiller lines run out to allow the test bed to be level and avoid damaging or restricting flow in the lines. These tests were performed under different power loads respective to the response of the AMDROHP device during these tests.

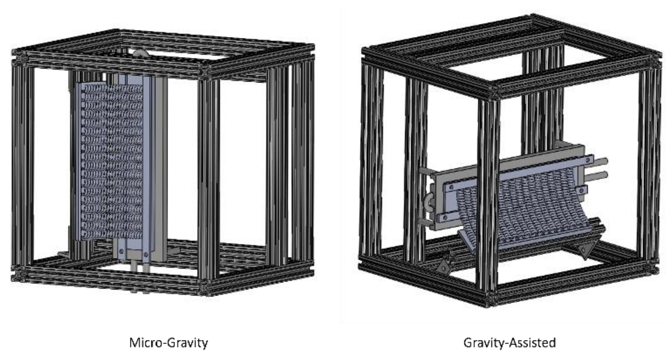

FIGURE 4: VISUALS OF ORIENTATIONS USED IN EXPERIMENTAL TESTING

3. RESULTS AND DISCUSSION

Before tests were performed for AMDROHP charged with R134a and ammonia, the conductance was found for when the device was empty of refrigerant. This value was found to be 0.25 W/°C. By knowing this value, the test results can be compared for the device when is not operating, only under conduction, versus when it is in operation.

Figure 5 shows temperature over time results for the micro-gravity orientation test case of the AMDROHP with R134a as a working fluid. Tested were the heat inputs of 0.5, 1, 2, 3, and 5 W. For the heat inputs of 0.5 – 2 W, there was OHP operation, though the operation was not completely stable. This is unstable operation is indicated by the inconsistent oscillations in the temperature. At 3 W it can be seen stable OHP operation with consistent oscillations. Finally, at 5 W, the OHP dries out, as seen by the gradual sloping increasing behavior of the temperature, indicating conductance and not OHP operation, is occurring.

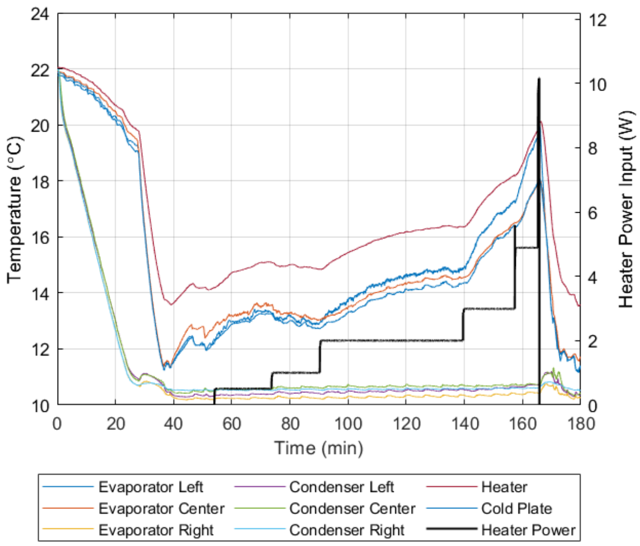

FIGURE 5: EXPERIMENTAL TEMPERATURE OVER TIME DATA COLLECTED FOR TEST CASE R134A MICRO-GRAVITY ORIENTATION

There exists a clear decoupled temperature between the evaporator and condenser across all power inputs. While the evaporator is experiencing clear oscillatory behavior, indicating phase-change and OHP operation, the condenser temperature is exhibiting no noticeable change compared to when no heat is being applied. This means that there is fluid motion and phase change occurring in the evaporator, however not in the condenser. Based on this evidence, it can be inferred that the liquid slugs are having trouble passing across the entire adiabatic length from the evaporator to the condenser. This is likely due to the long adiabatic length unique to this OHP design. The pressure-drop across the adiabatic length, generated by the evaporator and condenser, is not large enough to overcome the surface friction of the entire length of the adiabatic length. This presents a clear issue with the design that the adiabatic joint length is likely too long compared to pressure drop across the evaporator and condenser.

Furthermore, the entire range of operable heat inputs for the AMDROHP in this orientation for this working fluid is very low in magnitude. The reason for this is likely that the evaporator is being evacuated of liquid at relatively low heat input. This is due to the sufficient pressure being generated to push liquid into the adiabatic length toward the condenser; however, the pressure in the opposite direction is not high enough to move liquid back into the evaporator to resupply it with liquid. For this reason, liquid is moving out of the evaporator but not back in, creating a "dry-out" condition where there is no liquid in the evaporator at relatively low maximum heat input. Beyond this maximum heat input, the OHP can only move heat by conducting it through the metal. To improve the upper limit of allowable heat input, the issue of fluid motion across the OHP needs to be addressed in the design.

Figure 6 shows the conductance results for this R134a micro-gravity orientation test case. The conductance, once the temperatures have reached steady-state, for this test case has a range of values of 0.25 to 0.70 W/°C, increasing as the heat input increased. While this range of conductance values indicate OHP operation, as was evident by the temperature oscillation behavior, this conductance value is still low for what is expected out of OHP operation. With the majority of the oscillations happening on the evaporator end of the OHP, as was described, the performance is most likely limited by the length of the adiabatic region.

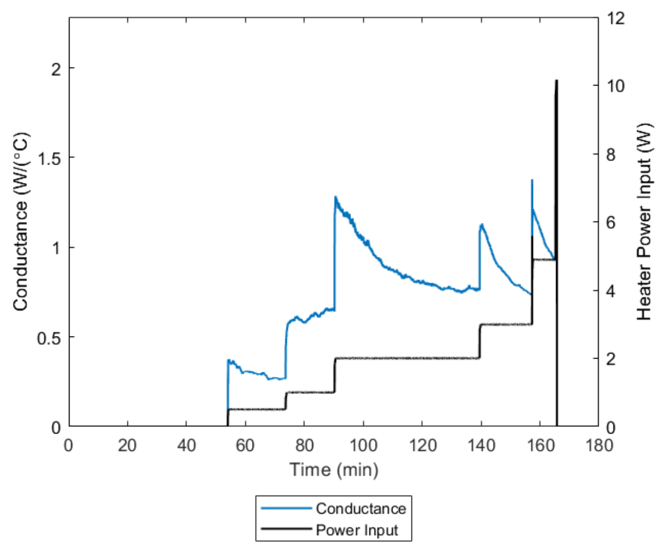

FIGURE 6: EXPERIMENTAL CONDUCTANCE OVER TIME DATA COLLECTED FOR TEST CASE R134A MICRO-GRAVITY ORIENTATION

Figure 7 shows the temperature over time results for the gravity-assisted orientation test case of the AMDROHP with R134a as a working fluid. Tested were the heat inputs of 0.5, 1, 3, 5, 6, and 8 W. Based on these heat inputs, the OHP showed operation for all heat inputs up to 8 W, where it then dried out. During operation, the evaporator showed clear oscillatory behavior across the OHP and some oscillatory behavior in the condenser. At 5 W, the left condenser measurement showed a jump in oscillations, indicating an increase in fluid motion in that region of the OHP. This improvement in the OHP performance, by evidence of the noticeable temperature oscillations and fluid motion in the condenser, can be attributed to the change in orientation to a gravity-assisted orientation. By orienting the OHP such that the joints are vertical, gravity is assisting the fluid in moving it through the adiabatic length from condenser to evaporator. This further supports the suspicion that the lack of stable operation and minimal fluid motion in the condenser can be attributed to the lack of liquid making it across the entire length of the adiabatic length.

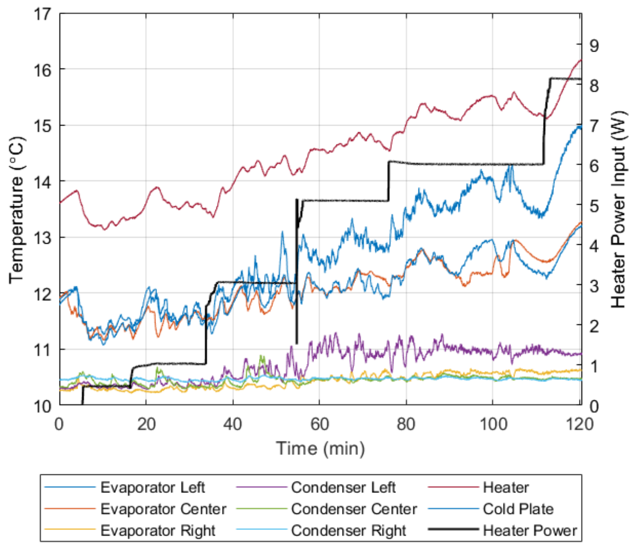

FIGURE 7: EXPERIMENTAL TEMPERATURE OVER TIME DATA COLLECTED FOR TEST CASE R134A GRAVITY-ASSISTED ORIENTATION

Figure 8 shows the conductance for the R134a gravity-assisted test case. The range of conductance, once the temperatures have reached steady-state, seen in this test is 0.89 to 4.5 W/°C. These numbers show a clear improvement over the OHP performance as was seen in the micro-gravity orientation for R134a. While a gravity-assisted orientation is not realistic for the conditions that the AMDROHP will undergo in Low Earth Orbit, performing these tests helps to give better insight into the two-phase characteristics of the device as an OHP. The improvement in conductance seen in this test case helps to further support the idea that there is difficulty in overcoming a large adiabatic length, because by introducing the support of gravity there was an improvement in performance of the OHP.

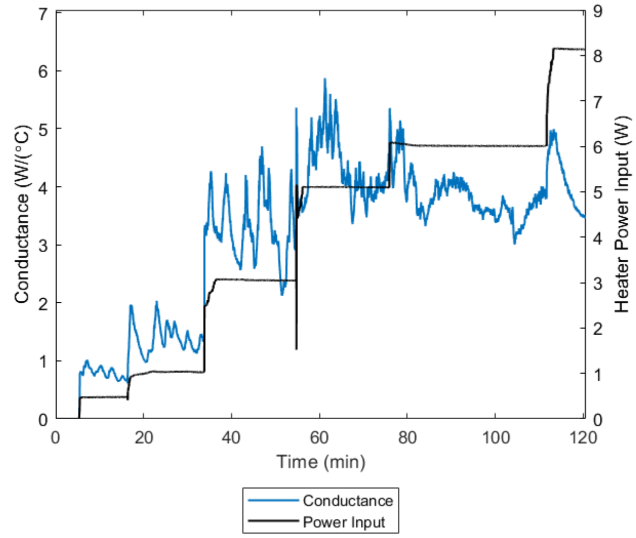

FIGURE 8: EXPERIMENTAL CONDUCTANCE OVER TIME DATA COLLECTED FOR TEST CASE R134A GRAVITY-ASSISTED ORIENTATION

Figure 9 shows the test case results for a micro-gravity orientation with Ammonia as a working fluid. For this test case, the heat inputs tested were 1, 2, and 5 W. Based on the temperature results, there was OHP operation for 1 and 2 W and the OHP dried out at 5 W. For 1 W, while there was OHP operation and motion, the oscillations were inconsistent showing an unstable operation. At the 2 W power input, the oscillations became more consistent, showing more stable operation. Ammonia is a less viscous fluid than R134a and as such, should be less inflicted by the issues of friction along the length of the adiabatic region. While this is the case, based on these results, there was still a clear decoupling of temperatures between the evaporator and condenser, showing that even for the less viscous working fluid, there is still the issue of generating a large enough pressure drop across the adiabatic length, especially in this case of a micro-gravity orientation.

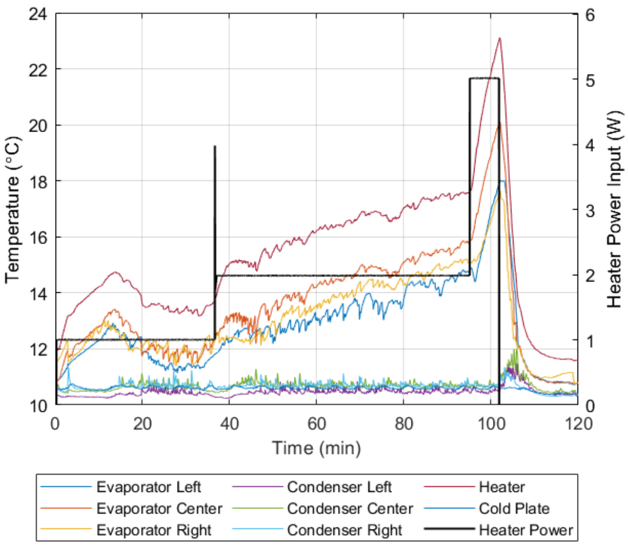

FIGURE 9: EXPERIMENTAL TEMPERATURE OVER TIME DATA COLLECTED FOR TEST CASE AMMONIA MICRO-GRAVITY ORIENTATION

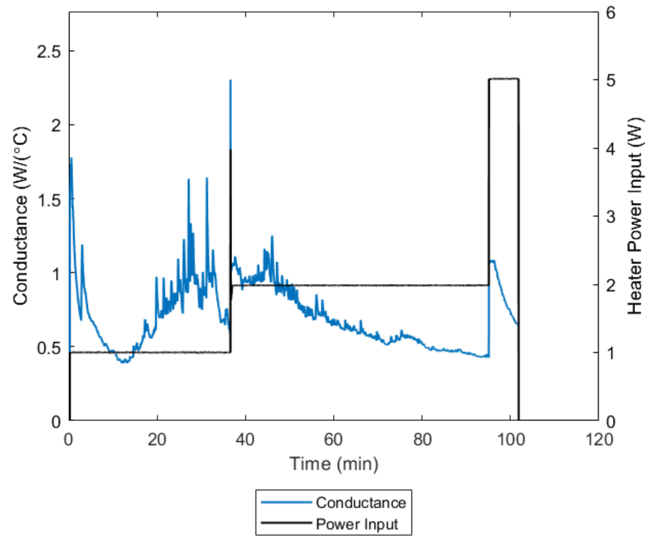

FIGURE 10: EXPERIMENTAL CONDUCTANCE OVER TIME DATA COLLECTED FOR TEST CASE AMMONIA MICRO-GRAVITY ORIENTATION

Figure 10 is the conductance results for the Ammonia, micro-gravity orientation. The conductance for this test case for the operable heat inputs tested, once the temperatures have reached steady-state, were 0.61 and 0.43 W/°C, respectively for 1 and 2 W. These results are about on par with the conductance results as seen for the micro-gravity test performed with R134a. While it would be expected that a refrigerant with less viscosity would flow better through the adiabatic length and as a result see an improvement in conductance, the temperature results showed that, even with a less viscous fluid, there was still trouble with the liquid moving across the adiabatic length completely for the micro-gravity orientation, which is likely why these conductance results are on par with the conductance seen for R134a micro-gravity orientation. These results continue to support the assertion that the liquid refrigerant is having trouble making it across the long adiabatic length of the device.

The next test case performed was for Ammonia with a gravity-assisted orientation, seen in Figure 11. The heat inputs tested for this test case were 1, 5, 10, 20, and 15 W. During this testing, the AMDROHP device saw operation at 1, 5, and 10 W. Dry-out was observed at 20 W. Then, 15 W was tried, but also saw dry-out. OHP operation at 10 W was the highest heat input that saw operation, across all of the test cases. Stable operation in the OHP occurred once the power input was at 5 W. The temperatures across all power inputs, for this test case, saw a much smaller decoupling of temperatures than what was seen from previous test cases. Further, this test case showed the clearest oscillations in the condenser, though still fairly low in amplitude. Being able to reach a relatively high heat input, when compared to the other test cases, as well as seeing more oscillations in the condenser can be contributed to the assistance of gravity in the joints, combined with the less viscous fluid. With this assistance, fluid was able to overcome friction better than in the other test cases, and the pressure drop across the adiabatic length was large enough to resupply the evaporator with liquid for longer.

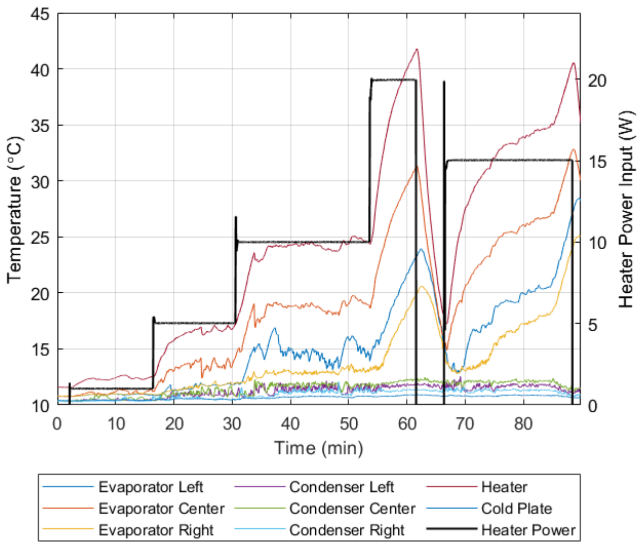

FIGURE 11: EXPERIMENTAL TEMPERATURE OVER TIME DATA COLLECTED FOR TEST CASE AMMONIA GRAVITY-ASSISTED ORIENTATION

Figure 12 is the conductance results for the Ammonia gravity-assisted test case. This test case saw a conductance values, once the temperatures have reached steady-state, of 2.02 to 3.29 W/°C for the operable heat inputs. Similar to what was the case for the R134a testing, a gravity-assisted orientation leads to better performing results in the OHP. While the Ammonia charged OHP led to a higher allowable heat input, the improvement in conductance did not reach as high of a maximum value that was seen for R134a. Still, the results for both refrigerants in the gravity-assisted orientation were comparable, showing that gravity played a larger role in improving the conductance of the device than the working fluid.

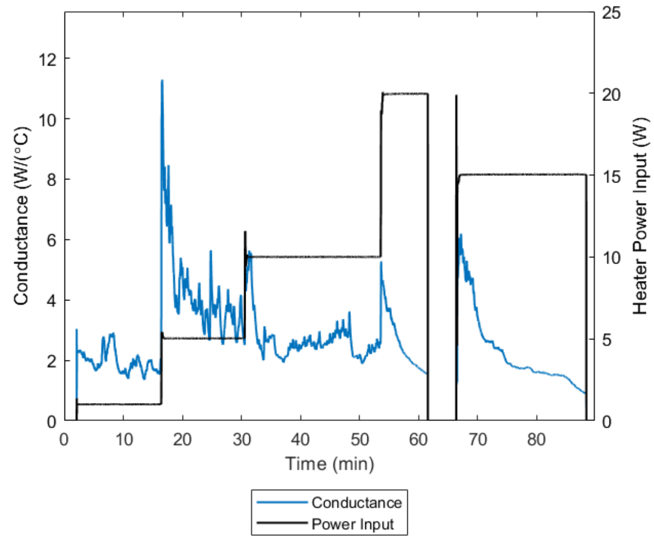

FIGURE 11: EXPERIMENTAL CONDUCTANCE OVER TIME DATA COLLECTED FOR TEST CASE AMMONIA GRAVITY-ASSISTED ORIENTATION

4. CONCLUSION

The goal of this study was to evaluate the thermal performance of the first design iteration of the Additively Manufactured Deployable Radiator Oscillating Heat Pipes (AMDROHP) through experimental testing. Tested in this study were the working fluids R134a and Ammonia for a micro-gravity and gravity-assisted orientation. The objective performance of this device was to reach a conductance of 4 to 6 W/°C for a 25 W heat input at a micro-gravity orientation. The results when AMDROHP was uncharged and inoperable, to serve as reference for comparison from the operating performance, was 0.25 W/°C. OHP operation was achieved, though not quite to the objective performance of the device. The main issue for this lack of performance is seemingly due to the long adiabatic length. With an inner tube diameter of 1 mm, the amount of friction the liquid refrigerant faced strongly inhibited fluid flow across the adiabatic, joint mechanism region. This resulted in a low conductance and early dry-out of the device. For future iterations of the design, the improvements that can be made to help this design would be to decrease the adiabatic length, as much as its mechanical function allows, as well as increase the diameter of the fluid channels to allow for a higher volume of liquid to overcome the friction in this adiabatic length.

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