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AN EXPERIMENTAL INVESTIGATION OF THE RELATIONSHIP BETWEEN EVAPORATOR AND CONDENSER SIZES WITH OSCILLATING HEAT PIPE START-UP

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ABSTRACT

Oscillating Heat Pipes (OHPs) are unique two-phase heat transfer devices with many advantages over standard and more widely adopted thermal control devices. Specifically, OHPs are able to operate passively, over a wide temperature range, and under high heat fluxes, with few design constraints. OHPs operate based on the process of evaporating and condensing a working fluid on opposite ends of a series of serpentine channels. The pressure difference causes an oscillating behavior of the fluid to travel along the direction of the channels enabling a high heat transfer rate. The capability of this technology has garnered much attention and interest for a variety of applications in different fields. While as a thermal management device, OHP technology shows much promise, there is still much to be understood about the fundamental principles of its operation. One of the most important aspects of OHP operation that is still not well understood is the phenomena known as "start-up". Start-up is when the proper conditions of an OHP are created such that the operating, oscillatory process of an OHP is enabled to begin. In this work, experimental testing is performed to investigate the relationship between evaporator and condenser length on OHP start-up. In this study, combinations of small, medium, and large length evaporators and condensers were used on a 42-turn OHP with 1 mm square channels, charged with R134a to 50% fill ratio with the goal to quantify the minimum heat that would initiate start-up. Before this test could be performed, issues in consistency of the start-up of OHP had to be resolved. A method to "reset" the liquid-vapor distribution to overcome any adverse history from previous OHP operation developed is discussed. Then, a zero-heat input method of confirming a liquid-vapor distribution favorable to start-up is outlined. After developing this method to achieve a consistent start-up heat input in the OHP, tests were performed for nine different configurations of large, medium, and small evaporator and condensers, to determine their relationship with the minimum heat required to start-up an OHP. It was observed that both the size of the evaporator and condenser both influence the start-up heat load. That is, a large condenser and evaporator can reduce the heat load required to start-up. Additionally, the size of a condenser is much more influential than the size of the evaporator. The overarching discovery is that the process of start-up relies heavily on the history of the OHP i.e., the initial liquid-vapor distribution of the working fluid in the channels. In measuring start-up, it is important to recognize and address how the current state of the OHP can lead to inconsistent results.

1. INTRODUCTION

Oscillating Heat Pipes (OHPs) are two-phase heat transfer devices with the advantages: 1) able to operate with high thermal conductivities 2) able operate under high heat fluxes, 3) able to operate passively, 4) lack of need for a wick, 5) able to operate over a wide range of temperature, 6) lack of many design constraints, and 7) lack of necessary gravity dependence. Furthermore, OHPs are configured in the form of a surface and are acutely applicable to heat spreading applications. This is a notable difference with other, more common types of heat pipes such as constant conductance and loop heat pipes that use a single line for heat transport. Patented in 1990 by Akashi, OHPs have received interest due to for their high suitability for electronics cooling [1]. OHPs exist as a loop of serpentine channels, charged with a saturated liquid-vapor working fluid. On one end of an OHP, an evaporator partially evaporates the liquid supply of working fluid creating a high-pressure region. On the opposite end, a condenser partially condenses the vapor supply of working fluid creating a low-pressure region. With this pressure difference created across the OHP, a phenomenon occurs where the working fluid begins to oscillate across the serpentine channels. This phenomenon produces a highly effective process of heat transfer from one end of the OHP to the other.

While OHPs are promising thermal management devices, their fundamental operating principles are not fully understood [2]. One popular focus of OHP research in using experimental testing to characterize the operating principles of OHPs to see what factors drive their operation and performance. A number of studies have been performed to quantify the effects of channel diameter [3, 4, 5], channel shape [6, 7], working fluid [3, 8, 9, 10], filling ratio [3, 5, 11, 12], and orientation [7, 4, 13] on OHP thermal performance. These studies illustrate the complexity of OHP operation and that a complete description of OHP operation remains elusive and is still being investigated [2].

Many engineers are drawn to OHPs for the reason that they are not confined by strict design limitations [14]. Past work have shown that OHPs can be shaped into unique geometries and can function comparable to that of well-studied planar OHP designs. For example, Qu et al. tested a flexible OHP, bending it in different shapes including an "I", "stair-step", "inverted U", and "N"-shape, and compared the operation in each shape finding that a bend in the adiabatic region of the OHP leads to degraded performance [7]. Czajkowski et al. tested a flower shaped OHP in a rotary system and demonstrated that an OHP functions in this environment. Furthermore, they found that OHP thermal performance improved with accelerations up to 5g [15]. Thompson et al. tested a "3D" Oscillating Heat Pipe with staggered micro-channels, under a vertical and horizontal configuration, finding that it was able to handle heat fluxes as high as 300 W/cm^2 [14].

Furthermore, one of the most important but least understood aspects of OHP operation is what is known as start-up. Start-up is the transition from non-operation to steady operation of an OHP. Under operating conditions with an application of sufficient heat input, oscillatory fluid motions will occur. Naturally, there is strong interest in investigating the drivers of OHP start-up and how a thermal management system can be designed in order to promote and ensure OHP start-up. Qu and Ma performed an experimental visualization of the start-up of an OHP using a clear glass tube OHP [16]. They qualitatively found the requirements to initiate start-up are:

1. A large enough temperature difference between the capillary wall and liquid bubble in the evaporator.
2. A high enough vapor pressure in the evaporator to drive a train of vapor bubbles and liquid slugs.
3. A high enough pressure difference between the evaporator and condenser to overcome the pressure drop in the flow channel.

A durable pressure difference to maintain the start-up.

A study by Stevens et al. found that, regarding start-up, double-sided over single-sided cooling configurations and butane over R134a lead to a more consistent start-up from test to test [13]. Patel et al. ran a set of experiments comparing the start-up performance for various different working fluids finding that acetone and methanol required less heat to start-up over other tested fluids and fluid mixtures [10]. It was concluded that this was due to these working fluids having a reduced surface tension when compared to a working fluid like water, which took the most heat to start-up in this study. Yin et al. built a theoretical model that provides the upper limit for fill ratio that allows for start-up in an OHP [17]. Through this model they found that a high filling ratio requires more heat to start the oscillatory motion of the fluid. One promising study done by Drolen and Smoot includes an effort to bound the limits of OHP performance by identifying the limits of two-phase channel flow and heat transfer. Although this work is useful is determining operational limits of OHPs, it cannot be used to quantitatively predict performance or start-up [18].

The aforementioned work has identified a number of factors affecting OHP start-up; however, one question of particular interest to engineers is how the sizes of the evaporator and condenser play a role in start-up. From previous work, it is clear that the sizes of the evaporator and condenser are important in steady OHP operations, however it is unclear how they factor into start-up behavior [19]. Knowing the effects that evaporator and condenser sizes have on start-up is important as thermal designers will need to know what these sizes should be in order to use OHPs as plug-and-play thermal solutions. The goal of this study is to address this question. Experiments are performed for three different evaporator and condenser sizes each, for a total of nine combinations, allowing for the investigation of the start-up relationship between the area of evaporator and condenser. The heat input to obtain start-up will be determined. In this paper the process and findings of this study will be described. Further, to obtain standardized conditions for the OHP to achieve consistent start-up results, methods of resetting the liquid-vapor distribution and determining a proper liquid-vapor distribution were discussed. The experimental setup and procedure used for the testing of this study will be outlined, the results of the experiments performed will be reported, and the qualitative and quantitative findings will be discussed.

2. SETUP AND PROCEDURE

The OHP used for this experiment is an additively manufactured flat plate OHP with inner channels. The OHP is printed with a material of Aluminum 6061 RAM2, with square channels and 42 turns. The OHP was tested using R134a as the working fluid at a 50% fill ratio.

TABLE 1: OHP SPECIFICATIONS

Material	Aluminum 6061 RAM2
Channel Shape	Square
Number of Turns	42
Channel Square Length (mm)	1
Turn Radius (mm)	1
Plate Length (mm)	200
Plate Width (mm)	90
Plate Thickness (mm)	4
Working Fluid	R134a
Fill Ratio (%)	50

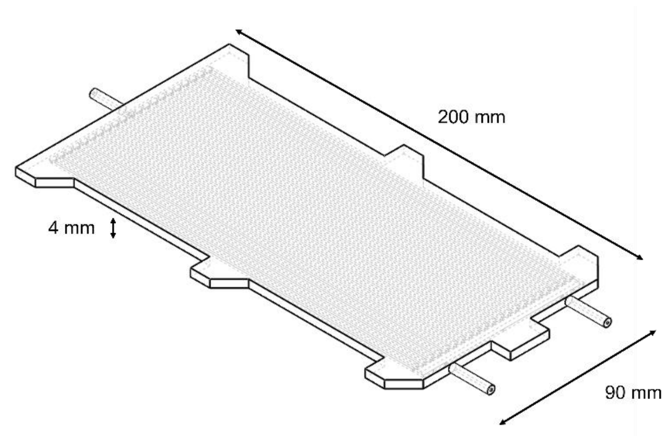

FIGURE 1: OHP GEOMETRY

The test setup shown in Figure 2 was used for performing experiments in this study. A testbed made of 1 ft. aluminum t-slotted framing rails were used as a structure for the OHP mounting. An Advanced Thermal Solutions, Inc. ATS-CP-1001 cold plate was mounted to the testbed with Garolite spacers and has its temperature regulated by a Polyscience LS51MX1A110C chiller. The chiller powered cold plate allows for a constant and controlled temperature for the OHP condenser. The OHP was then mounted to the cold plate. The OHP was mounted with the interface of an aluminum condenser block and silicone gap filler on the top and bottom surfaces of the block. Three different sizes of condenser blocks were machined for this experiment. These three blocks machined to sizes of 90 mm by 99, 66, and 33 mm for a large, medium, and small condenser block. These dimensions can also be seen listed in Table 2. Likewise, three evaporator blocks were machined to the same size as the condenser blocks, respectively. These evaporator blocks were fitted with heaters of similar size to the blocks. By using these evaporator blocks, heaters can be reused and swapped between experiments. These blocks have sufficient thickness to distribute the heat to the surface area of the block. The evaporator blocks were attached to the OHP through a thin, double-sided thermal tape. An image of the condenser and evaporator blocks are shown in Figure 3.

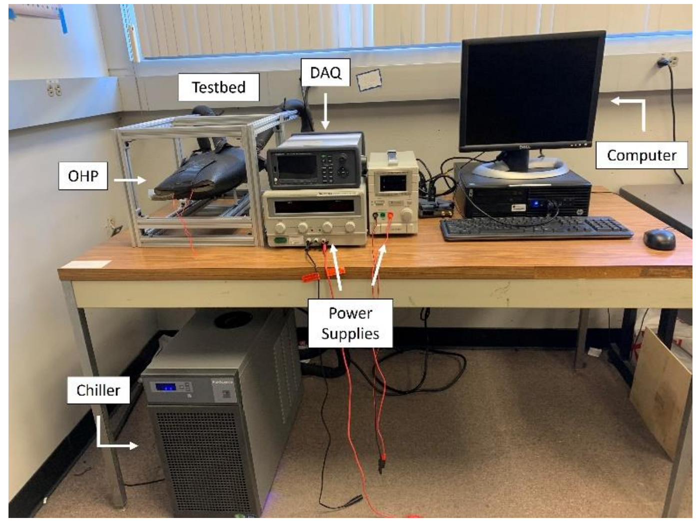

FIGURE 2: OHP TEST SETUP

Three different types of thin polyimide heaters were used for this experiment. From large to small, the heaters were a Minco brand 3x3 in. 166 Ω heater, a Tayco 2x3 in. 105.5 Ω heater, and two Minco brand 1x1 in. 100 Ω heaters. Two different power supplies were used for powering the heaters including a GW Instek GPR-30H10D 300V/1A power supply and a CircuitSpecialists CSI5003XE 50V/3A power supply. The large and medium evaporator blocks only make use of a single heater and thus were powered solely by the GW Instek power supply. The small heater block uses two heaters and thus the second CircuitSpecialists power supply was additionally used.

used along the length of the OHP in which the thermocouples were centered to the evaporator, adiabatic, and condenser regions. Additionally, the temperature is recorded for the cold plate and heater(s). The thermocouples were routed to a Keysight DAQ970A data acquisition device which is connected to a desktop PC. The PC displays, records, and saves the collection of data through the LabVIEW software. Finally, the OHP and cold plate were wrapped with a flexible two-layer insulation to minimize any heat leaks or environmental effects. The experiments in this study were conducted in a room of conditioned air maintained around room temperature.

The testing process began with recording the data through a computer data logger. The data logger used for this study was LabVIEW. The chiller-powered cold-plate was turned on and the system let reach steady state. The cold plate temperature was fixed at 10 °C for all of the tests run in this study. Once the system reaches steady state, the system was let sit for another 15 minutes at steady state for a baseline observation of non-operation of the OHP. After this period, the power supply was turned on and heat was supplied to the evaporator. Based on the resistance of the heater and a current/voltage input, the desired power input can be calculated and adjusted to. For the small evaporator configuration, the power supply for each heater was adjusted to be half of the total desired heat input.

For this experiment, six different power inputs were tested including 0, 5, 10, 25, 50, and 75 W, from least to greatest, until start-up was observed in the OHP. The reason that these set, discrete values were used for this testing is because it is hard to pin-down an exact reproducible start-up power. It is more practical to identify a broad range of start-up powers, thus this expected range of heat values was decided on. Once the heater is inputting a power value, that temperature is allowed to reach steady state and record 15 minutes of steady state data. At this point, the behavior of the temperature is evaluated to determine if the OHP has started-up, and if it has not, the next heat is increased to the next highest value. Start-up can be observed through temperature data and a calculation of the conductance, both done in real-time during the experiment.

Visually, start-up can often be observed by the temperature behaviors of the OHP. When start-up occurs, the is a sharp increase in the condenser and decrease in the evaporator temperatures. At this point, the temperature difference across these regions is much smaller, making for a lower overall conductance. This calculation of power input over the difference in evaporator and condenser temperature can be compared to the conductance of an empty OHP to see if there was an increase in performance due to the OHP operating. These methods of visual observation and conductance calculations were used during the experiment to determine if the OHP is started-up or if a high power level needs to be tested.

Additionally, for some of the experiments, a maximum temperature is reached before start-up occurs. A maximum temperature of 200 °C was set based on the maximum temperatures that the heaters can operate at before potentially burning. When running these experiments, the OHP was tested until either start-up occurred or the maximum temperature was

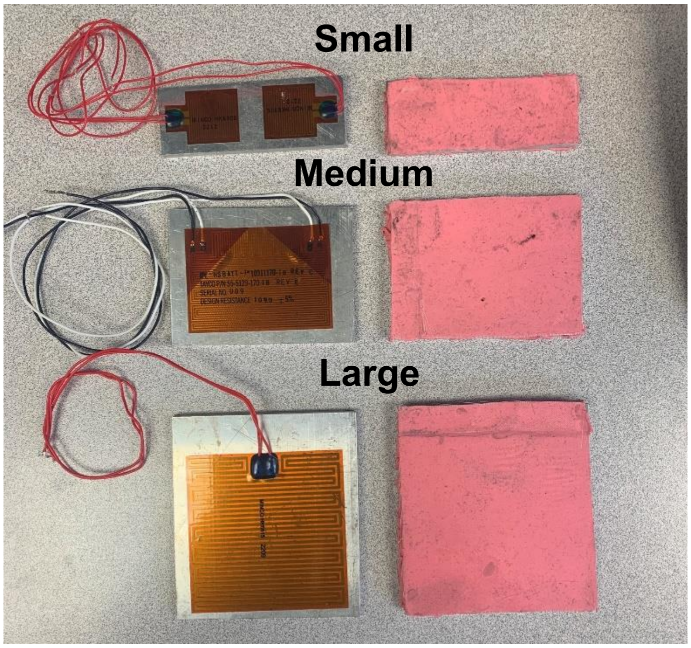

FIGURE 3: EVAPORATOR AND CONDENSER BLOCKS

TABLE 2: EVAPORATOR AND CONDENSER BLOCK SIZES

Block Size	Width (mm)	Length (mm)
Small	90	33
Medium	90	66
Large	90	99

The OHP is clamped to the cold plate through a system of pressure plates, shown in Figure 4. The inner layers of the pressure plates were a non-conductive high density polyethylene strips while the outer aluminum layer was added for stiffness. Bolts and nuts were then used to apply the pressure, clamping the OHP to the condenser block and cold plate using the pressure plates. A set of pressure plates is used for each end of the OHP to ensure even pressure.

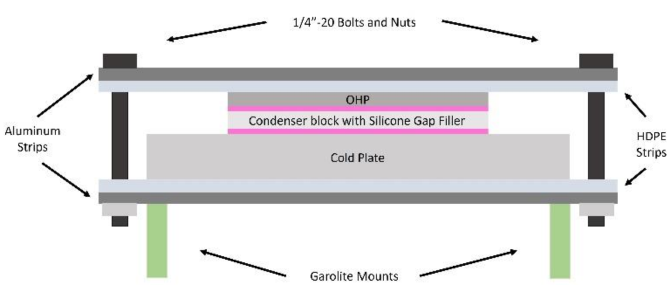

FIGURE 4: OHP MOUNTING SYSTEM

Data was measured through T-type thermocouples. The thermocouples were attached to the OHP through two strips of thin double-sided thermal tape. A 4x3 grid of thermocouples was reached. If start-up is not achieved and the maximum allowable temperature is reached, the power supply(s) were immediately shut off and the run was ended. This process of testing was followed for nine test setups including every combination of large, medium, and small evaporator and condenser. To ensure consistency of the results of each configuration, 3 trials were run for each configuration to support the repeatability of the reported results. Through testing each configuration, a relationship between evaporator and condenser size with start-up was analyzed. The tests of this study include an investigation into unstable OHP temperatures at a 0 W heat input, understanding liquid-vapor distribution and developing a method of "resetting" the liquid-vapor distribution for consistent start-up results, and finding the minimum required heat input for start-up in an OHP through 9 different combinations of large, medium, and small evaporator and condensers.

3. RESULTS AND DISCUSSION

3.1 Recognizing OHP Start-Up

To be able to study when start-up occurs, it is necessary to be able to have a method to detect start-up from the operating temperature data of the OHP. For this experiment, a method of visual inspection of temperature data to determine start-up was used. Figure 5 shows an example of when an OHP is in operation vs. non-operation from the temperature vs. time data collected. For an OHP that has not started-up, the OHP heat transfer will be in conduction, making the change in temperature very gradual with a smooth increase to steady-state and once at steady state, flat with little oscillatory behavior. From time 88 to 138 min, an example of non-startup behavior can be seen. With an increase in power, the temperature gradually increases until it reaches steady-state and holds a temperature with little oscillation once at the steady state temperature. When an OHP starts-up, there is an increase in the conductance in accordance with a decrease in the difference in temperature between the evaporator and condenser. When start-up occurs during the increase of a power input to the OHP, the start-up is reflected through a sudden decrease in temperature of the heater and evaporator and a sudden increase in temperature of the condenser. Further, once the OHP has entered the mode of operation through start-up, the steady-state temperature occurs with oscillatory behavior of a higher amplitude than the non-operation conduction mode. An example of this process of start-up occurring can be seen in from time 138 to 166 min where, after the heat is put into the OHP and the OHP reaches a high enough temperature, there is a sudden drop in the evaporator temperature and rise in the condenser temperature, as well as oscillatory behavior once at steady state. This type of analysis of the data was the process used to determine if the OHP had started-up for the given heat input, during the case studies of this experiment.

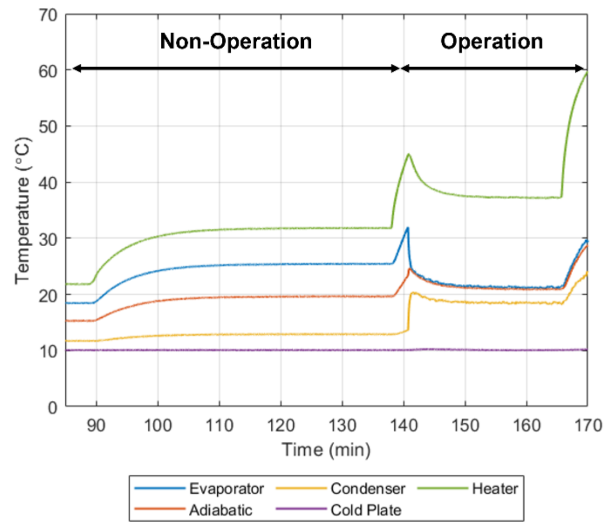

FIGURE 5: EXAMPLE OF OHP OPERATION VS. NON-OPERATION

3.2 Effect of Liquid-Vapor Distribution and "Resetting" Method

When performing the experimental testing for this study, the initial tests showed inconsistent results for at what heat input the OHP started-up at. For different trials of a single configuration, the power required for start-up changed from trial to trial. Even in some instances, the OHP would start immediately while in other trials the OHP would not start at all. Instances of inconsistent results occurred most frequently for the configurations with a smaller condenser or evaporator when the OHP had experienced dry-out in recent tests. The inconsistent results were caused by varying distributions of liquid and vapor in the channels at the start of the tests. For a small evaporator or condenser, a small region is present for there to be the necessary liquid or vapor to enable evaporation and condensation in that region for start-up to occur. An unfavorable liquid-vapor distribution could cause further difficulty for these configurations to start-up if the evaporator and condenser did not have sufficient respective liquid and vapor supplies.

Thus, method of "resetting" the liquid-vapor distribution, such that the OHP would hold the exact same conditions for every test is required. The method found to work the best to address this issue was using gravity to move the liquid to the evaporator region, leaving the condenser occupied with vapor. This was done through flipping the orientation from the horizontal orientation, in which gravity has a negligible effect with the OHP lying flat, to a gravity-assisted vertical orientation with the evaporator at the bottom. An image of these orientations is shown in Figure 6. Between each power input, the heat would be turned off, the OHP cooled, flipped to gravity-assisted orientation, and let sitting in that position for about 15 minutes, then back to horizontal orientation to reach steady-state for that position. Performing this resetting method ensures that there was liquid in the evaporator and vapor in the condenser to enable start-up. Use of this method led to much more consistent results for lower values of heat input. Three trials were performed of each configuration of the later results, after performing the resetting method, showed that the minimum heat required to start the OHP was not changing from trial to trial. This exploration confirmed the idea that the history of the OHP affects future operation of the OHP in that the initial liquid-vapor distribution of the OHP can affect when the OHP will start-up. Further, this finding showed that resetting the liquid-vapor distribution is critical for configurations with a small condenser or evaporator.

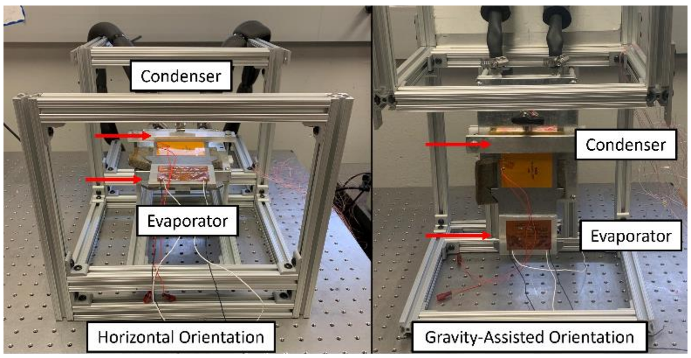

FIGURE 6: OHP ORIENTATIONS (HORIZONTAL VS. GRAVITY ASSISTED)

During this method of resetting the liquid-vapor distribution, because the OHP was left in the horizontal orientation for enough time, the liquid of the OHP was likely majorly in the evaporator section while the vapor in the condenser. When initial tests were run before prior to developing the resetting method, there were a range of values of start-up heat inputs achieved, from low to high values. After performing this resetting method, not only were consistent results achieved, but these consistent results were consistently the lowest heat input results of the range of values, from the initial tests run. For this reason, it can be inferred that the optimal liquid-vapor distribution is to have all of the liquid on the evaporator side of the OHP and all of the vapor on the condenser side.

The suggested method of "resetting" the liquid-vapor distribution of OHPs in this paper, by means of turning the OHP on its side, has been shown to be effective for achieving consistent start-up, within the confines of the experimental test setup used in this study. In practical applications of OHPs, it may not be possible to perform such a method of turning the OHP on its side. While this is the case, for most applications of Oscillating Heat Pipes, the OHP is under high heat loads, well above the necessary power to start the OHP. For this study, OHP conditions were created to test the minimal power to achieve consistent OHP operation. In practice, it is most likely the case that the OHP in use will not face the issues of liquid-vapor distribution driving start-up, as the designed heat-load will be well above the power required, even for a poor distribution. However, if very low heat input is expected and the OHP cannot be turned on its side to reset the liquid-vapor distribution, then an alternative resetting method will need to be developed and used.

3.3 Detecting Proper Liquid-Vapor Distribution in OHPs

Something that was noticed during testing was a phenomenon that occurred at steady-state for the OHP without any input of heat for certain configurations. In such an instance of a 0W heat input steady-state, rather than the temperature data being very flat and unchanging as one would expect in non-operation conduction steady-state, the temperatures showed oscillation beyond expected noise levels of the instruments. This behavior of the data indicates that there exists some fluid motion at 0 W in these instances.

It was found that this "unstable" 0 W behavior only occurred after the OHP liquid-vapor distribution was in a favorable state. For the case that the previous test had resulted in dry-out, the OHP would not exhibit this behavior before the next test when the OHP returned to steady state temperature at 0W input. Thus, when resetting the OHP, this unstable behavior served as an indication that the OHP was reset properly. Empirically, this unstable behavior was found to be crucial to the performance of OHP start-up. The OHP would exhibit consistent start-up and would start-up at its lowest heat input than when the resetting method was performed. Without this unstable behavior, having not properly reset the OHP, the start-up performance would start at an inconsistently higher power than when oscillations are present, sometimes not starting-up at all.

The question arose of why this unstable behavior was occurring. With the system insulated, the temperature across the OHP should be uniform with the temperature of the cold plate. When analyzing the temperature in operation however, there did exist a small temperature difference from the evaporator to the condenser, leading to this fluid motion without any heat input from the heater. This meant that there was heat entering the system coming from a source other than the heater. Based on this evidence, the natural step was to test if an imperfect insulation led to this phenomenon. A study was performed, analyzing the behavior of the 0 W heat input steady state OHP, based on the temperature of the cold plate. If the unstable behavior occurred only when there is a large enough temperature difference between the cold plate and room, it can be said the motion of fluid is occurring due to heat entering the system through the insulation. To perform this study, a range of temperatures from room temperature to below room temperature is analyzed for when this unstable behavior of temperature occurs.

This study was performed in the large evaporator, large condenser configuration, where this phenomenon was commonly seen. The cold plate temperatures tested were 23 °C, 20 °C, 15 °C, and 10 °C. By testing in this order, any potential effects of imperfect insulation should be seen to grow as the difference in temperature of the room and of the cold plate and system grow. Figure 7 shows the complete trial of cold plate data, while Figure 8 shows the windows of the steady state data for each cold plate temperature tested, with equally sized scales of the temperature axis and the time axis at when it was performed in the complete test. From the data, there is a clear progression of the instability of the steady-state temperature increasing as the temperature of the cold plate decreases. While the cold plate is at room temperature, the temperatures of the OHP are very stable, however as the difference in temperature of the cold plate and room increase, the instability increases noticeably. This shows that this fluid motion-enabled instability in the temperature data is caused by heat entering the system from the room, through imperfect insulation.

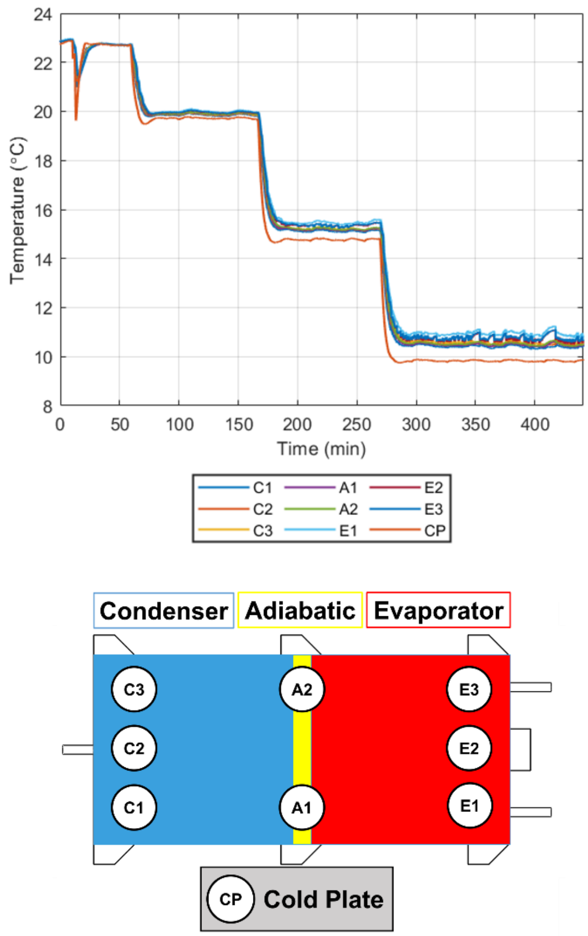

FIGURE 7: INVESTIGATION OF INSTABILITY OF TEMPERATURE OF 0 W STATE OF OHP WITH THERMALCOUPLE PLACEMENTS

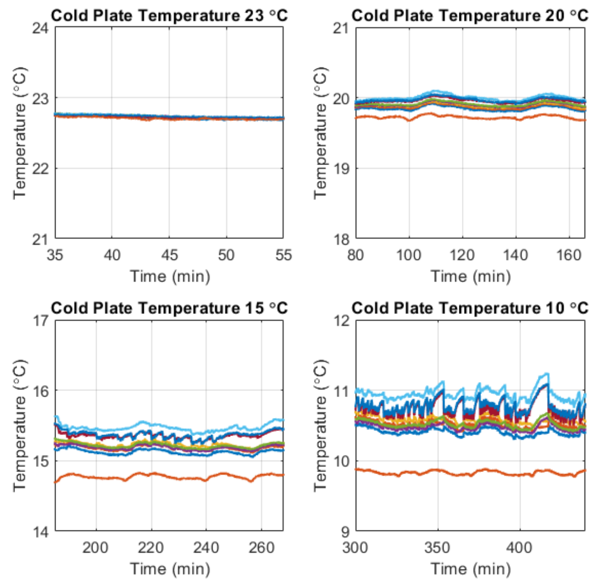

FIGURE 8: INVESTIGATION OF INSTABILITY OF TEMPERATURE OF 0 W STATE OF OHP - MAGNIFIED

While these findings show that there was an imperfect insulation within this test setup, the effect of these imperfections are minimal after start-up. At the same time, the minimal heat leak provided important insights into OHP behavior. For a single configuration, the behavior would sometimes exhibit unstable behavior and sometimes would not. What we were able to deduce is that this information is tied back to the liquid-vapor distribution of the refrigerant in the OHP. When the OHP had previously experienced dry-out, the 0W steady-state instability would not occur. After resetting the OHP with the method outlined in the next section, the phenomenon would occur consistently in every trial. Thus, this unstable behavior helped to serve as confirmation that the resetting method had been performed correctly and effectively. Once the resetting method is performed, if the OHP exhibits the unstable behavior, then the resetting method can be said to have been performed properly. If this behavior did not show, then the resetting method needs to be continued to be performed until it did. Having an imperfect insulation allowed for a slight amount of heat to enter the system and confirm that the OHP was in a position to start-up favorably with even a small heat input, confirming that it was in the intended favorable state created.

3.4 OHP Start-Up Results by Configuration

Tests were performed to determine the minimum required heat input for an OHP of different configurations of condenser and evaporator size. Three trials for each configuration were performed and across each configuration, after performing the discussed liquid-vapor distribution resetting method, every trial showed the same value of power required to start the OHP. Table 3 shows the results of every configuration for the minimum power input required for start-up. For a condenser that is smaller, it takes a larger heat input to achieve OHP operation than for a condenser that is larger. From these results, the important point can be made that the minimum heat required to enable OHP start-up relies on both the size of the condenser and evaporator, allowing for the earliest start-up to occur for an OHP configuration with a large condenser and evaporator.

TABLE 3: MINIMUM REQUIRED HEAT FOR START-UP BY EVAPORATOR AND CONDENSER SIZE

		Evaporator Size		
		Large	Medium	Small
Condenser Size	Large	1 W	1 W	1 W
	Medium	1 W	10 W	No Start-Up
	Small	25 W	No Start-Up	No Start-Up

Looking deeper into these results shows more about how the condenser and evaporator sizes play a role in start-up. From the three configurations of the large condenser, it can be seen that the required heat input for start-up is the same, starting immediately regardless of the evaporator size. This shows that for a condenser that is long enough, early start-up can be achieved without needing the help of a long evaporator. The same, however, cannot be said for the evaporator. For the three large evaporator configurations, while there is immediate start-up for the large and medium condenser combinations at 1W, for the small condenser configuration there is a larger necessary required heat input for start-up to occur. This shows that, no matter how large the evaporator is, there will still be a reliance on the condenser size to achieve early start-up. From this it can be said that while both the condenser size and evaporator size matter for OHP start-up, a large condenser size has a predominant impact over a large evaporator.

Because the OHP length is constant throughout the series of configurations tested, it is the case that as the evaporator and condenser size decrease, the adiabatic length increases. When considering these results that show, as the evaporator and condenser sizes decrease, the start-up results improve, the role of the adiabatic length needs to be considered. Based on the trends of the evaporator and condenser sizes, the same results can be applied to adiabatic length in that generally, as adiabatic length increases, the start-up results worsen. This raises the question of whether the evaporator and condenser sizes did have an effect on the start-up results, or if it was solely a product of the adiabatic length. Looking at the configurations of small condenser-large evaporator, medium condenser-medium evaporator, and large condenser-small evaporator, these configurations all share the same adiabatic length. For these configurations, however, the start-up results are not the same being 25 W, 10 W, and 1 W, for these three configurations, respectively. For the same adiabatic length, different start-up results were achieved for different proportions of condenser and evaporator sizes. This shows that there is indeed a level of dependency of start-up heat input on evaporator and condenser size, and not just adiabatic length. To investigate the role of adiabatic length on start-up, further tests would need to be performed.

4. CONCLUSION

In this study, an additively manufactured Aluminum 6061 RAM2 flat plate OHP was tested with R134a to investigate the relationship between evaporator and condenser size and start-up. Through this study, there was the following findings:

- A large evaporator (90 mm) and large condenser (90 mm) are the most favorable for achieving start-up with a low power input, at <1W.
- A large condenser (90 mm) can achieve early start-up (<1W) for an OHP, independent of the size of the evaporator.
- A large evaporator (90 mm) is favorable to early start-up in an OHP, but start-up is still dependent on the size of the condenser.
- The history of the OHP matters with the liquid-vapor distribution driving the amount of heat required for start-up.
- A suggested "resetting" method of the liquid-vapor distribution was developed and shown to achieve a consistent minimum start-up power.
- An indication to confirm the resetting method, seen through a 0W heat input fluid motion caused by imperfect insulation in the test-setup, was outlined.

These findings give further insight into the behavior and drivers of OHP start-up. Through these findings, more information can contribute to building a more comprehensive understanding of this aspect of OHP operation.

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REFERENCES

[1] H. Akachi, "Structure of a heat pipe". Patent US4921041A, 1990.

[2] D. Bastakoti, H. Zhang, D. Li, W. Cai and F. Li, "An overview on the developing trend of pulsating heat pipe and its performance," Applied Thermal Engineering, vol. 141, pp. 305-332, 2018.

[3] J. Qu and Q. Wang, "Experimental study on the thermal performance of vertical closed-loop oscillating heat pipes and correlation modeling," Applied Energy, vol. 112, pp. 1154-1160, 2013.

[4] P. Charoensawan, S. Khandekar, M. Groll and P. Terdtoon, "Closed loop pulsating heat pipes: Part A: parametric experimental investigations," Applied Thermal Engineering, vol. 23, no. 16, pp. 2009-2020, 2003.

[5] H. Yang, S. Khandekar and M. Groll, "Operational limit of closed loop pulsating heat pipes," Applied Thermal Engineering, vol. 28, no. 1, pp. 49-59, 2008.
[6] C. Hua, X. Wang, X. Gao, H. Zheng, X. Han and G. Chen, "Experimental research on the start-up characteristics and heat transfer performance of pulsating heat pipes with rectangular channels," Applied Thermal Engineering, vol. 126, pp. 1058-1062, 2017.
[7] J. Qu, X. Li, Y. Cui and Q. Wang, "Design and experimental study on a hybrid flexible oscillating heat pipe," International Journal of Heat and Mass Transfer, vol. 107, pp. 640-645, 2017.
[8] K. Natsume, T. Mito, N. Yanagi, H. Tamura, T. Tamada, K. Shikimachi, N. Hirano and S. Nagaya, "Heat transfer performance of cryogenic oscillating heat pipes for effective cooling of superconducting magnets," Cryogenics, vol. 51, no. 6, pp. 309-314, 2014.
[9] Y. Zhou, H. Yang, L. Liu, M. Zhang, Y. Wang, Y. Zhang and B. Zhou, "Enhancement of start-up and thermal performance in pulsating heat pipe with GO/water nanofluid," Powder Technology, vol. 284, pp. 414-422, 2021.
[10] V. M. Patel, Gaurav and H. B. Mehta, "Influence of working fluids on startup mechanism and thermal performance of a closed loop pulsating heat pipe," Applied Thermal Engineering, vol. 110, pp. 1568-1577, 2017.
[11] R. Sarangi and M. Rane, "Experimental Investigations for Start up and Maximum Heat Load of Closed Loop Pulsating Heat Pipe," Procedia Engineering, vol. 51, pp. 683-687, 2013.
[12] C. Hu and L. Jia, "Experimental study on the start up performance of flat plate pulsating heat pipe," Journal of Thermal Science, vol. 20, no. 2, pp. 150-154, 2011.
[13] K. A. Stevens, S. M. Smith and B. S. Taft, "Variation in oscillating heat pipe performance," Applied Thermal Engineering, vol. 149, pp. 987-995, 2019.
[14] S. M. Thompson, H. B. Ma, R. A. Winholtz and C. Wilson, "Experimental Investigation of Miniature Three-Dimensional Flat-Plate Oscillating Heat Pipe," Journal of Heat Transfer, vol. 131, no. 4, 2019.
[15] C. Czajkowski, A. I. Nowak and S. Pietrowicz, "Flower Shape Oscillating Heat Pipe – A novel type of oscillating heat pipe in a rotary system of coordinates – An experimental investigation," Applied Thermal Engineering, vol. 179, 2020.
[16] W. Qu and H. Ma, "Theoretical analysis of startup of a pulsating heat pipe," International Journal of Heat and Mass Transfer, vol. 50, no. 11, pp. 2309-2316, 2007.
[17] D. Yin, H. Rajab and H. Ma, "Theoretical analysis of maximum filling ratio in an oscillating heat pipe," International Journal of Heat and Mass Transfer, vol. 74, pp. 353-357, 2014.
[18] B. L. Drolen and C. D. Smoot, "Performance Limits of Oscillating Heat Pipes: Theory and Validation," Journal of Thermophysics and Heat Transfer, vol. 31, no. 4, pp. 920-936, 2017.
[19] O. Castro, K. Wolk, B. Furst, E. Sunada, S. Roberts, T. Daimaru, J. Kuo and J. Bellardo, "Experimental Investigation of Evaporator and Condenser Placement Configuration for Oscillating Heat Pipes," in Proceedings of the ASME 2022 International Mechanical Engineering Congress and Exposition, Columbus, 2022.