Lab 2: Heat Pipe

Jacob Ivanov

Seth Utter

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Jacob Ivanov contributed to Calculations, Results & Discussion, Figures, and the Conclusion

Signature: J Ivanov

Seth Utter contributed to the Abstract, Introduction, Methods, Conclusion and Editing/Grammar

Signature: *Seth Utter*

Abstract
Heat pipes are typically used for heat transfer between devices, but it is unknown whether a heat pipe is truly better than just a rod of material. An experiment was done to compare the thermal conductivity between a copper heat pipe and a copper rod. This was done qualitatively by boiling and cooling the two items and then quantitatively by measuring the temperature of a heated copper heat pipe, calculating its effective thermal conductivity, and then comparing that to the thermal conductivity of the copper rod. It was found that the heat pipe had a higher thermal conductivity than the copper rod. It was found that the average effective thermal conductivity for the heat pipe was approximately 6107±291 W/m•K and the heat pipe had a higher effective thermal conductivity than the solid rod. This means that heat pipes are more effective heat transfer devices than solid rods.

Introduction
Heat pipes are devices that transfer heat by utilizing phase transitions from one solid surface to another solid surface [1]. It works by having the working fluid in the pipe evaporate to a vapor that absorbs thermal energy. Then, the vapor begins to migrate along the cavity in the pipe to the lower temperature end. Then, the vapor condenses back into a fluid and gets absorbed by a wick. Thermal energy is released as the fluid gets absorbed. Once done, the fluid then flows back to the higher temperature end and the cycle repeats. These kinds of systems are typically used for applications that generate a lot of heat like, for example, computer systems. With heat pipes, however, their overall performance is dictated by their effective thermal conductivity. The higher the thermal conductivity, the higher the performance. In general, thermal conductivity is defined as a material property for a certain kind of material like a rod of copper or aluminum. However, since a heat pipe is not just a solid rod of material, an effective thermal conductivity is defined for it instead. The problem, however, is that it is unknown whether copper heat pipes truly have a higher thermal conductivity in comparison to a regular copper rod. If the copper rod still has a higher thermal conductivity than the heat pipe then there wouldn't be any point in using the heat pipe in the first place. To figure this out, the effective thermal conductivity of a heat pipe will have to be calculated but to do this, temperature differences between the evaporator and condenser portion of the heat pipe will have to be recorded. It should be noted that to calculate the effective thermal conductivity, it will be assumed that there will be a linear temperature profile to make calculations simple. A comparison will then be made with other solid materials to see if any material would be capable of having a higher thermal conductivity than the copper heat pipe. It is hypothesized that the heat pipe will have a higher effective thermal conductivity than the thermal conductivity of a solid copper rod due to the convective heat transfer within the heat pipe.

Methods
Equipment used for this experiment includes a 0.2m copper-water heat pipe, a DC power supply, a DAQ system, a copper-water heat pipe, a copper rod, and cold/hot water in a Pyrex beaker. In terms of software needed, Labview, Excel, and Python were used for recording data and conducting effective thermal conductivity calculations. Temperature measurements were taken using thermocouples along the heat pipe that is connected to a DC power supply which had voltage and current controls. Environmental room temperature was the initial starting point.

To start the experiment, the thermocouples on the heat pipe should be zeroed to make it so that all the temperatures on the heat pipe are the same temperature as the current air temperature in the room. The

Labview run should then be started and should continue for the rest of the experiment. This made it easier when plotting all the data later. The heater (or DC power supply) should then be turned on and voltage/amperage should be set to 3W within ± 0.1W. As there was no power reading, the power had to be calculated in Excel using the following equation:

$$P = IV \tag{1}$$

where P is the power, I is current, and V is the voltage. Once the power reaches approximately 3 W, the heat pipe was monitored for about 10 to 15 minutes to ensure that the pipe reached a steady state temperature. Steady state was assumed to be reached once the temperature stopped increasing/decreasing by 0.5ºC after about a minute elapsed. Once it was found that steady state was reached, a temperature was recorded for reference and then the power was increased by another 3W. This continued until 15W was achieved or when the heat pipe reached a temperature of 100ºC. This was done to ensure that no damage to either the heater or the thermocouple would occur as these were the device thresholds for both. Once the limit was reached, the data taken was then saved on an Excel sheet for effective thermal conductivity calculations. As this was all occurring, a qualitative test was done to see how fast a heat pipe thermally conducts in comparison to a heat pipe. This was done by simply putting both into boiling water and seeing which one would become hot first.

With this, effective thermal conductivity calculations were made. First, it should be noted there were seven thermocouples used on the heat pipe, where three thermocouples are for the evaporator side of the heat pipe and four are for the condenser side of the heat pipe. As such, an average temperature on the evaporator side and an average temperature on the condenser side were used for effective thermal conductivity calculations. Graphs of the ave\rage temperatures as well as a graph of the power input versus temperature drop were made to see the data a bit easier. Once done, the effective thermal conductivity was calculated using the following equation:

$$k_{eff} = \frac{Q_{HP}(L_e + L_c)}{2A_c(T_{e,ave} - T_{c,ave})} \tag{2}$$

where k_{eff} is the effective thermal conductivity, L_e is the length of the evaporator section of the tube, L_c is the length of the condenser section of the tube, Q_{HP} is, essentially, the power calculated in equation 1, $T_{e,ave}$ is the average evaporator temperature, $T_{c,ave}$ is the average condenser temperature, and A_C is the cross-sectional area of the pipe. A comparison with the thermal conductivity of the copper material was then done to see if the hypothesis in the Introduction was correct. An analysis was also done on how the input power may change the effective thermal conductivity of the pipe. This was to see if the effective thermal conductivity increases or decreases with increasing power input and a graph was made to see the change. A final analysis was then done by comparing the qualitative results from the boiling water experiment to the quantitative data to make a conclusion on the hypothesis.

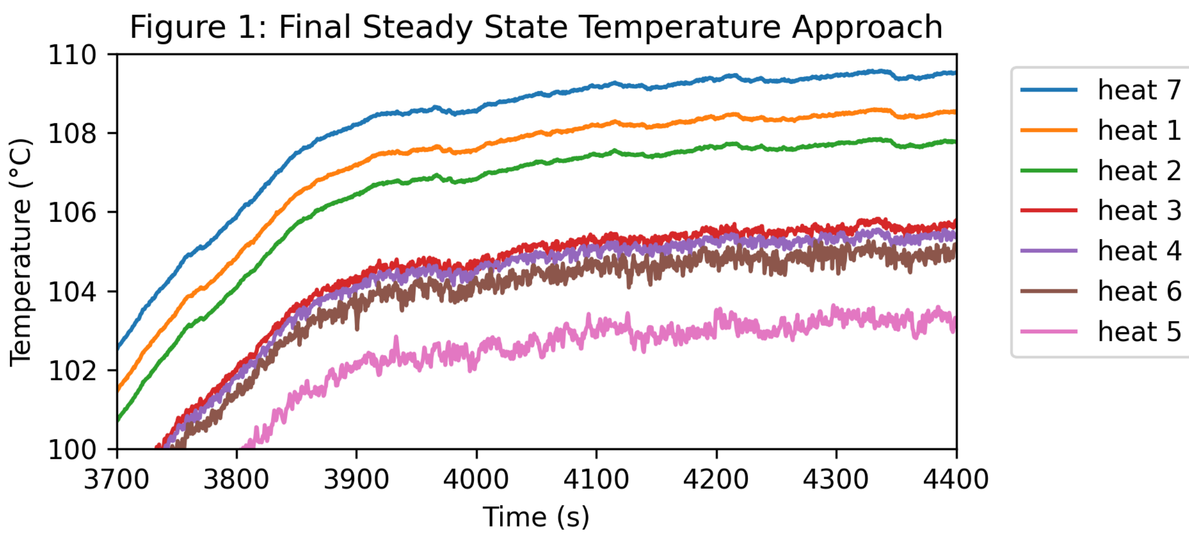
It should be noted that uncertainties in the voltage and the amperage were assumed to have zero-order uncertainties and for uncertainties in temperature, a 95% confidence interval based on the signal's noise was used. The confidence interval method was used for uncertainty to take into account any noise the data had during testing. Effective thermal conductivity uncertainties were calculated by using propagation of error, specifically sequential perturbation. The equation for this is as follows:

$$u_f = [D_1^{\,2} + D_2^{\,2} + ... + D_L^{\,2}]^{\frac{1}{2}} \tag{3}$$

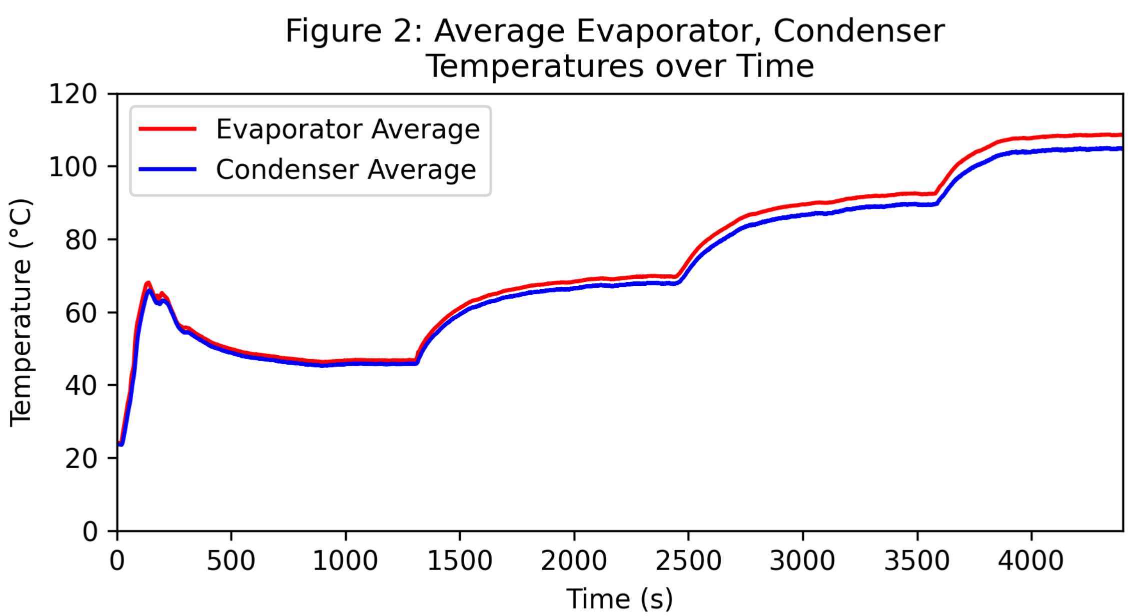
where u_f is the final uncertainty and D_1, D_2, D_L, etc. are the disturbed values which are found by calculating the uncertainty of the functions by sequentially perturbing the input values by their uncertainties [2]. This ensures that uncertainty does not have too big of an effect on the values calculated, otherwise, the experiment will need to be redone.

Results & Discussion

For this section, all relevant hand and code calculations can be found in the Appendix for reference. The results are as follows:



Though the Labview experimental setup wasn't labeled clearly, it can be seen in Figure (1) above that there are two distinct groups of thermocouple sensor readings. Since it is known that the evaporator section is hotter than the condenser section, thermocouples referred to as 'heat 7', 'heat 1', and 'heat 2' are assumed to have tracked the temperatures for the evaporator while 'heat 3', 'heat 4', 'heat 6', and 'heat 7' were assumed to have tracked the temperatures for the condenser section of the heat pipe.



By averaging the evaporator section and condenser section thermocouples and then plotting their temperatures over time, a clear trend was found in Figure (2) above. The trend is that with each increase in power input, the evaporator and condenser average temperatures diverge by a greater amount.

Values from the DC power supply during the experiment were tabulated and can be found in Table (1) in the Appendix, along with the approximate steady state temperature for the power supply found using Equation (1). It can be stated that with an increase in electrical power supply, the steady state temperature rises. A hypothetical control volume would see an increase in input energy without an increase in energy being removed. However, as the temperature rises, the higher temperature will result in a higher level of convection according to Newton's Law of Cooling, restoring the energy equilibrium at steady state.

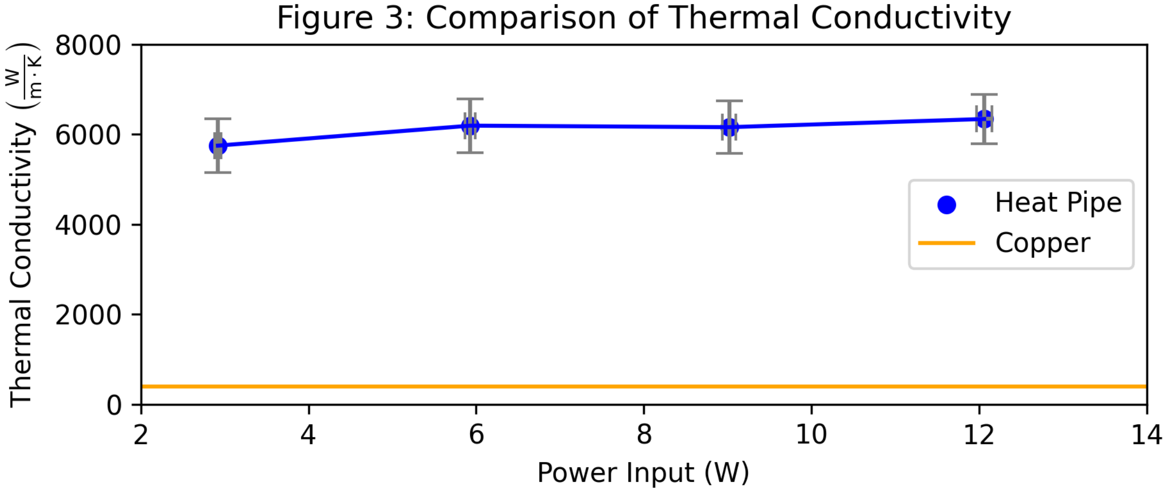
As seen in the data and Figure (2), the steady state time periods are 1100-1300 s, 2300-2400 s, 3400-3550 s, and 4150-4350 s from the initial start time. Using the Numpy Python library, the mean temperatures and their standard deviations were found for each time period. This was combined to yield the average section temperatures and therefore their differential. The results were tabulated below in Table (2).

Table 2: *Steady State Temperature Values*

Power Supplied (W)	**Average Evaporator Temperature (°C)**	**Average Condenser Temperature (°C)**	**Temperature Differential (°C)**
2.92±0.04	46.733±0.068	45.722±0.079	1.011±0.104
5.93±0.06	69.783±0.124	67.877±0.136	1.906±0.184
9.02±0.08	92.384±0.194	89.469±0.194	2.915±0.274
12.06±0.09	108.476±0.204	104.690±0.252	3.786±0.324

From these values, one can use Equation (2) to find the effective thermal conductivity of the heat pipe at each steady state temperature, knowing that the Q_{HP} term is the power supplied to the heat pipe.

Figure 3: Comparison of Thermal Conductivity



Values for the effective thermal conductivity were plotted against the power input in Figure (3) above with the thermal conductivity of pure copper also shown for reference [3]. Exact values can be found in Table (3) in the Appendix. While it shows that the effective thermal conductivity of the heat pipe has a slightly positive trend with increasing power input, the magnitude of the error bars and data sparsity prevents any rigorous trendline analysis. It should also be noted that metals usually have a decreasing thermal conductivity with increasing temperature since increasing the temperature obstructs the flow of free electrons [3]. Regardless, with an overall average effective thermal conductivity of 6107±291 W/m•K, the original hypothesis can be accepted. The hypothesis is that due to the convective heat transfer in the heat pipe, it will have a much higher heat transfer rate than a purely conductive rod of the same material. In this case, uncertainty is not big enough to falsify this conclusion on the hypothesis.

The hypothesis was also qualitatively tested by immersing a dimensionally similar copper rod and heat pipe into a hot water bath and gauging which reached steady state temperature the fastest. As expected, the heat pipe became hot faster than the copper rod. Additionally, both rods were then placed in a cold water bath, and the heat pipe cooled faster than the copper rod. Though not particularly scientifically rigorous, this qualitative experiment supports the original hypothesis.

Conclusion

In this experiment, it was found that the average effective thermal conductivity was 6107±291 W/m•K for the heat pipe. This effective thermal conductivity was drastically larger than the thermal conductivity of a solid copper rod, which is approximately 400 W/m•K, proving the original hypothesis to be true. This was also proved qualitatively since the heat pipe was capable of heating/cooling faster in boiling/ice water than the solid copper rod. This implies that heat pipes are effective devices for transferring heat from one device to another in comparison to just solid rods due to the design's use of inner convective heat transfer. The uncertainty for this calculated effective thermal conductive was not large enough to impact the final conclusion. However, it was significant enough to prevent establishing a formal trend that effective thermal conductivity increases with increasing power input.

As such, it is believed that there were several potential sources of error in this experiment of varying significance that were unaccounted for that contributed to the significance of the uncertainty. The experimental sensor setup was not labeled properly in the Labview software, and so, the demarcation of evaporation/condenser sensor data is based on the expected temperature differential along the heat pipe, rather than definitive testing. This potential source of error can be entirely removed in a future experiment by simply labeling the sensors and wiring. It was noted that the setup was near a lab window which could not completely isolate the inside temperature from the outside temperature. It’s possible that this affected the final results, though any error would be consistent across the data. In the future, this should be avoided by placing the experimental setup more toward the center of the room.

Additionally, it should be noted that this experiment was done on only copper. While the results could extend to other metallic materials, the results may change with a ceramic or polymer material. An investigation could be done to see if different materials have the same effect. The steady state temperature range (as a result of the range in power applied to the system) also prevents extending the analysis to extreme temperatures, where it is known that thermal conductivity is not as constant.

References

[1] Faghri, A. (2016). Heat Pipe Science and Technology. Global Digital Print.

[2] ME3264 – Lecture 4, Error Propagation, Sequential Perturbation [pdf]. Retrieved February 10th, 2023, from UConn ME3264 Blackboard

[3] *Metals, metallic elements and alloys - thermal conductivities*. Engineering ToolBox. (n.d.). Retrieved February 10, 2023, from https://www.engineeringtoolbox.com/thermal-conductivity-metals-d_858.html

[4] Ivanov, J. (2023, February 22). *jacobjivanov/ME3264L-Applied-Measurements-Laboratory: The following is code done for the ME 3264L: Applied Measurements Lab course at the University of Connecticut*. GitHub. Retrieved February 22, 2023, from https://github.com/jacobjivanov/ME3264L-Applied-Measurements-Laboratory

Table Appendix

Table 1: *Power Supply Values*

Power Supplied (W)	Voltage (V)	Current (A)	Approximate Steady State Temperature (°C)
2.92±0.04	7.9±0.05	0.37±0.005	46
5.93±0.06	11.4±0.05	0.52±0.005	68
9.02±0.08	14.1±0.05	0.64±0.005	91
12.06±0.09	16.3±0.05	0.74±0.005	106

Table 3: *Effective Thermal Conductivity of the Heat Pipe*

Power Supplied (W)	Effective Thermal Conductivity (W/m•K)
2.92±0.04	5745.94±596.29
5.93±0.06	6189.59±600.80
9.02±0.08	6155.99±581.21
12.06±0.09	6337.19±544.39