ND*nano* Undergraduate Research Fellowship (NURF)
2015 Project Summary

1. Student name: Brian Buechler

2. Faculty mentor name: Dr. Tengfei Luo

3. Project title: Thermal Rectification in a Hexadecane-Paraffin Wax Junction

4. Briefly describe any new skills you acquired during your summer research:

In order to determine the thermal conductivity of the junction we created, I learned how to calibrate and operate the Unitherm 2022 system. In this process, I experimented with the various parameters of the machine in order to obtain the most accurate measurement, including sample thickness and the temperature difference across the sample. Additionally, I learned about the uses for various types of thermocouples, temperature controllers, and relays, as well as how to wire them for use in the laboratory.

5. Briefly share a practical application/end use of your research:

The intent of this research is to create a component that controls heat flow similarly to the way in which a diode controls the flow of electricity. This technology could potentially be used to control the heat in microelectronics.

Begin two-paragraph project summary here (~ one type-written page) to describe problem and project goal and your activities / results:

Since the creation of a few key electronic devices led to the development of information technology, researchers have shown interest in making analogous devices to control heat flow. A device, which allows heat flow in only one direction, is called thermal diode. Anomalous interest has been drawn to the design of devices that can rectify heat flow in the past century[1-7], due to its potential wide application in phononics, microelectronics[8], and energy storage.[9-11] For thermal rectification in bulk materials, it is necessary that the thermal conductivity is a function of both space and temperature.[12] We designed our thermal diode as a Paraffin wax-hexadecane junction to satisfy the requirement for a function of space, and the requirement for a function of temperature is also satisfied by utilizing hexadecane, which has a sharp thermal conductivity change above or below transition temperature due to solid-liquid phase transition.[13] Such a bi-material junction design utilizing materials' phase transition to achieve thermal rectification has been theoretically studied in the past.[14] As shown in Figure 1, when a temperature difference is applied across such a junction, the hexadecane could either be liquid or solid, depending on the direction of the temperature gradient. If the hexadecane is on the colder end of the junction and exists in the solid phase, heat can flow relatively freely through the junction. This is called the "forward" case. If the temperature gradient is reversed, the hexadecane will be on the hot end, causing the hexadecane to melt. This will allow for less heat to flow through the junction and is called the “reverse” case. The rectification factor can be defined as the percent increase in thermal conductivity of the junction from the reverse case to the forward case.

The goal of this project was to create the thermal diode using a junction of hexadecane and paraffin wax to achieve a rectification factor that is as high as possible. Although the thermal conductivity change of hexadecane during phase transition was reported,[13] a reproduction of this temperature-dependent thermal conductivity in hexadecane is still necessary to evaluate the performance of the Unitherm 2022 before any serious measurement of the thermal diode effect. Although the machine is capable of measuring the thermal conductivity of both liquid and solid, the measurement during phase transition is challenging: the phase transition of hexadecane from liquid to solid would cause significant volume contraction, creating an air gap that would cause inaccuracy. To avoid this problem, we designed a modified measurement cell that allowed for the expansion/contraction of the hexadecane without creating such an air gap. Our new design also included an O-ring on both caps of the cell to better seal the liquid. Better sealing of the liquid enables the flipping of the cell upside down without leaking, and by flipping of cell, the hexadecane end can directly contact either the heat source or the heat sink, allowing heat fluxes in different directions. We were then able to model the new cell in Creo Parametric, and we had the necessary pieces machined and 3D printed. (Figure 2)

Using the Unitherm machine, the thermal conductivity of hexadecane in liquid phase was measured at an average temperature of 29 degrees Celsius, and the measured conductivity was 0.11 W/(mK). The thermal conductivity of hexadecane in solid phase was measured at an average temperature of 8 degrees Celsius, and the thermal conductivity is found to be 0.31 W/mK, showing an increase of roughly 3 times. To further measure the thermal diode effect, 1.3 mm of paraffin wax and 0.7 mm of hexadecane were used to form the junction, according to the length ratio of the two materials calculated in the case with optimized rectification factor. The thermal conductivity of the junction was then measured at an average temperature of 19.3 degrees Celsius, with a temperature drop of ~10 degrees Celsius across the entire junction. From reverse case to the forward case, by simply switching the direction of temperature gradient, the thermal conductivity of the junction was found to increase from 0.175 W/(mK) to 0.231 W/(mK). This produced a rectification factor of 32%, which is among the highest reported so far in literature.[15]

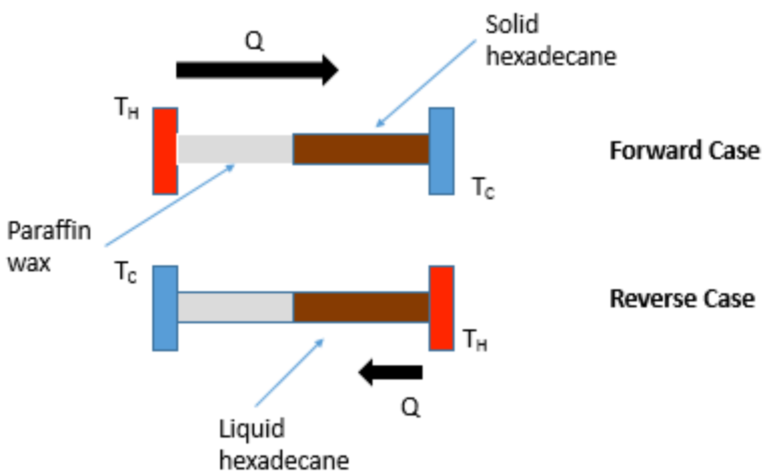

Figure 1: Paraffin Wax-Hexadecane Junction. When hexadecane (brown) is contacting the heat sink (T_C), it exists in the solid phase, allowing for increased heat flow, Q. When hexadecane contacts the heat source (T_H), it becomes liquid, and the magnitude of heat flow in the opposite direction is reduced.

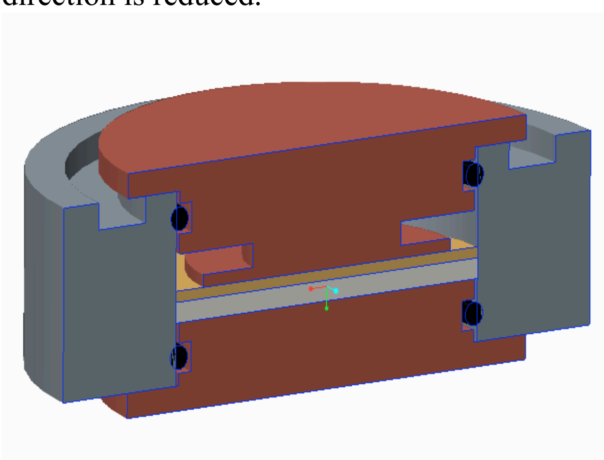

Figure 2: Drawing of hexadecane-wax junction inside new measurement cell

References

[1] G. Casati, *Nat. Nanotechnol.* 2007, 2, 23
[2] N. Li, J. Ren, L. Wang, G. Zhang, P. Hänggi, B. Li, *Rev. Mod. Phys. 2012, 84, 1045*
[3] N. A. Roberts, D. G. Walker, *Int. J. Therm. Sci.* 2011, 50, 648.
[4] C. Starr, *J. Appl. Phys.* 1936, 7, 15.
[5] C. Dames, *J. Heat Transfer* 2009, 131, 061301.
[6] B. Li, L. Wang, G. Casati, *Phys. Rev. Lett.* 2004, 93, 184301.
[7] B. Li, L. Wang, G. Casati, *Appl. Phys. Lett.* 2006, 88, 143501.
[8] M. Arik, M. Iyengar, V. Gektin, S. Narasimhan, M. Hodes, K. Geisler, *Panel Session at ITherm2010,* Las Vegas NV, June 2010.
[9] B. Norton, S.D. Probert, *Appl. Energy,* 1983, 14, 211.
[10] B. Zalba, J. M. Marín, L.F. Cabeza, H. Mehling, *Appl. Therm. Eng.* 2003, 23, 251.
[11] S.A. Omer, S. B. Riffat, X. Ma, *Appl. Therm. Eng.* 2001, 21, 1265.

[12] D.B. Go & M. Sen, "On the Condition for Thermal Rectification Using Bulk Materials" *J. Heat Transfer,* 2010.
[13] C. Vélez, M. Khayet, J. M. Ortiz de Zàrate, *Appl. Energy,* 2015, 143, 389.
[14] T. Zhang & T. Luo, "Giant Thermal Rectification from Polyethylene Nanofiber Thermal Diodes," *Small,* 2015.
[15] J. Zhu, K. Hippalgaonkar, et. Al., *Nano Lett.* 2014, 14, 4868.