Combined Convective and Radiative Cooling of Objects in the Environment
MCE 313 - Experiment 2

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Team 3

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Abstract

In order to experimentally understand the heat transfer phenomena, an observation of two copper cubes, a copper sphere, and a stainless steel sphere undergoing convective and radiative cooling is made. Digital software, TracerDAQ, is used to collect the temperature data via thermocouples (Type T) attached to each object and one thermocouple measuring the ambient temperature [4] [5]. The objective of this experiment is to find the heat transfer coefficient, Biot number, and specific heat of each object. The Biot number is a value used to assume uniform internal temperature of an object. If the Biot number is smaller than 0.1, then the assumption is that the internal temperature is constant and has an error of less than 5%. The general procedure of this experiment is all objects are placed in boiling water, and after about 10 minutes are suspended from horizontal rods. Each object is partitioned by a screen [1]. Thermocouples are attached to each object, as well as one measuring the ambient temperature [5].TracerDAQ software measures the temperatures of each object until the ambient temperature is reached [4]. Geometric effects of convective and radiative cooling were observed looking at the two copper cubes. Based on the data obtained, it was determined that the orientation with respect to the direction of gravity does not have an impact on the heat transfer coefficient. The percent difference between the heat transfer coefficients between the corner of the copper cube and the center of the copper cube is 6.23744%. Material effect of convective and radiative cooling was also observed from the two spheres, copper and stainless steel. The data collected revealed material properties do have an impact on the heat transfer coefficient of a uniform temperature body. The percent difference between the stainless steel sphere and copper sphere heat transfer coefficients is 38.3739%. A percent difference this high indicates the material properties having an impact on the heat transfer coefficient of the body being observed.

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Nomenclature

Symbols & Units

dT/dt	Temperature change as a function of time
h	Heat transfer coefficient
k	Coefficient of heat conduction
m	Mass of specimen
q	Heat transfer rate
t	Time
$(T - T_\infty)$	Difference between ambient temperature of fluid and temperature at surface
A	Area exposed in direction of heat transfer
B_i	Biot number
C_p	Specific heat of a material
L^*	Ratio between area and surface area
T	Temperature
T_∞	Ambient temperature
T_i	Initial temperature
τ	Time constant

1 Introduction

The objective of this experiment is to experimentally understand heat transfer. Heat transfer consists of three primary methods: conduction, convection, and radiation. Heat transfer is applicable in several engineering disciplines and is used in a variety of systems that we use in our daily lives. Such systems include furnaces, refrigerators, electrical equipment, and radiators. In this lab the team observed heat transfer through different materials and shapes, as well as becoming familiar with data acquisition software, TracerDAQ and associated collection instruments. Heat conduction is an application of the first law of thermodynamics, stating that energy is conserved within an isolated system. Therefore conduction is heat transfer through a medium whose surface and contents coincide. Using this theory and respective equations, the specific heat of a material can be determined. Convection cooling is the transfer of heat from one place to another by the movement of fluids. Using this theory and respective equation, the heat transfer coefficient can be found. Radiative cooling is a method of heat transfer that does not rely upon any contact between the heat source and the heated object. Heat is transmitted through a vacuum in the form of electromagnetic waves is known as thermal radiation [2]. Note that none of these equations include gravity. The Biot number is a value that validates the assumption of uniform inner temperature of an object [1]. A Biot number of less than 0.05 validates the assumption. A Biot number greater than 0.05 does not verify the assumption, thus the data may not be analyzed using the fundamental equations for conduction, convection, or radiation. The Biot value is initially assumed then verified for all objects observed in this experiment. This allows us to utilize the definition equations for convection, conduction, and/or radiation. If the Biot number is less than 0.05, an energy balance equation can be used to find the heat transfer coefficient from an energy balance equation if the material properties are known. Also, if the Biot number is less than 0.05, the body is lumped, and are assumed to have constant temperature. [2].

The purpose of this experiment is to study heat transfer by the method of convection in a controlled environment.This experiment focused on four objects: two copper cubes, a copper sphere, and a stainless steel sphere. Two effects were observed and concluded on: geometric and material effect. Briefly, the procedure of the experiment went as follows: all four objects are placed in boiling water. After approximately 10 minutes, objects are removed from the water and left to be suspended from horizontal rods.There are thermocouples (Type T) are embedded with in each object at their geometric centers. These thermocouples are connected to an amplifier, which is attached to an A/D board. Using TracerDAQ, the time history of the temperature of the cubes and spheres can be measured as they cool [4].

The geometric effect of heat transfer in this experiment is analyzed by observing the orientation of the two copper cubes. These two cubes are oriented with respect to the direction of gravity. By using the convection equation after verifying uniform inner temperature, the significance of orientation of an object during the convective cooling process is determined [1]. The heat transfer coefficient of each cube is also determined. Performing this experiment. It was found that the cube suspended by its corner has a heat transfer coefficient of $13.23365203 W/m^2K$ where as the cube suspended at the center of one of its surfaces has a heat transfer coefficient of $13.37268697 W/m^2K$. This demonstrates that the heat transfer was not affected by the orientation of the blocks.

The material effect of heat transfer in this experiment is analyzed by observing the heat transfer coefficient of the copper and stainless steal spheres. A differences in the heat transfer coefficients will quantify the effects of using different metals in the cooling process. In conclusion, the experiment revealed that copper sphere has a much higher heat transfer coefficient of 18.75055278 W/m^2K where the stainless steel transfers heat more slowly transferring 12.71354667W/m^2K.

2 Theory

Heat transfer is characterized by three primary methods conduction, convection, and radiation. Each one of these equations has geometry of the medium as a determining factor [2]. The three main shape factors are Polyhedron, which are shapes with flat sides or slab; a cylinder, which have 2 flat surfaces and a minimum of 1 curvilinear surface; and an ellipse, which has only curvilinear surfaces (the most basic ellipse is a sphere and is used in this experiment) [3].

The first law of thermodynamics states that energy is conserved within an isolated system. This can be understood as by an object whose surface coincides with its contents or is solid and uniform. Heat transfer through such a medium is known as conduction. Heat transfer found in the form of conduction refers to heat traveling to solid materials. In this case coper and stainless steel are used as our conduction medium. Heat conduction follows the following equation:

$$q = mC_p \frac{dT}{dt} \tag{1}$$

Where q shows to heat transfer rate, m denotes mass, C_p represents the specific heat, and $\frac{dT}{dt}$ indicates temperature change as a function of time [1, 2]. Gravity is not a factor in this equation.

Newton suggested the characterization the transfer of heat between the surface of an object undergoing conductive heat transfer into a fluid. The phenomenon referred is known as convection. Conceptually conduction and convective transfer methods are very similar however have one major difference. Convective heat transfer refers to heat transfered through a fluid including gases that act as fluids. Convective heat transfer follows the equation below.

$$q = -hA(T - T_\infty) \tag{2}$$

where q shows heat transfer, $-h$ is the heat transfer coefficient through fluids and is assumed constant, A refers to the area exposed in the direction of heat transfer, finally $(T - T_\infty)$ is the difference between the ambient temperature of the fluid and the temperature at the surface [1]. The equation above assumes that heat is being transfered from high temperature to low temperature. Gravity is not a factor in this equation.

In order to evaluate a system undergoing cooling due to conductive and convective cooling a combination of the equations (1) and (2) is used as follows:

$$mC_p\frac{dT}{dt} = -hA(T - T_\infty) \tag{3}$$

In order to use this equation to find temperature the equation must be simplified the following form:

$$\frac{dT}{T - T_\infty} = -\frac{dt}{\tau} \tag{4}$$

where

$$\tau = \frac{mC_p}{hA} \tag{5}$$

In this form the expression may be directly integrated when several assumptions are made. First, the object must be characterized by a single temperature. In this case the core temperature measured by the Type T thermocouple is used. Second, the average heat transfer coefficient, h, must be constant. This assumption is verified using the Biot number, Bi, for the system in question. If the Biot number is below a certain threshold the assumption is true. In this experiment the Biot number threshold is 0.1 which allows us to assume an error less than 5% [1].

The Biot number is a ratio between the average surface heat transfer coefficient to the internal heat conductance. The Biot number may be expressed:

$$Bi = \frac{hL^*}{k} \tag{6}$$

This equation considers k which represents the coefficient of heat conduction; h, the heat transfer coefficient for convection; and L^*, a ratio between area and surface area. For this experiment the Biot is initially assumed to be less than 0.1 and is later confirmed using the values representing heat conduction coefficient, found experimentally. To find h and K see the provided table [1].

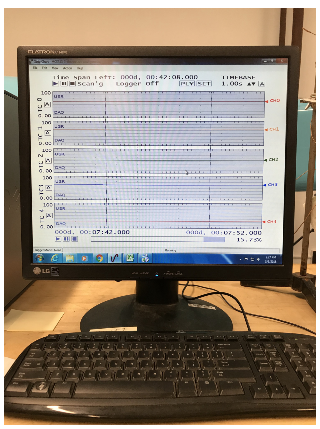
After verifying assumptions, the integration my be carried out and simplified giving the equation:

$$\frac{T - T_\infty}{T_i - T_\infty} = e^{-\frac{t}{\tau}} \tag{7}$$

This equation shows an exponential decrease in temperature from the initial value T_i to to its final temperature T_∞. The temperature T represented at a specific time t.

3 Experimental Apparatus and Procedures

In this experiment, heat transfer processes of convective and radiative cooling were analyzed using data acquisition software, TracerDAQ (Figure 1). Four objects of interest are observed during this experiment: two copper cubes (Figure 3), a copper sphere (Figure 2a), and a stainless steel sphere(Figure 2b). The cubes had a side length of one inch and the spheres have a diameter of one inch [1]. All objects have Type T (copper-constant) thermocouples embedded within them, and are located at the objects geometric center. Type T Thermocouples have an average deviation of $\pm 0.246°C$ for 0°-600° [4]. Each thermocouple has a differential input voltage range for various sensors of $\pm 0.080V$. The type T thermocouple has a sensitivity of about $43\mu V/C°$. The thermocouples are attached to an amplifier, which is attached to an A/D board. The USB-TC converts the analog input from the thermocouples to digital inputs with a 24-bit resolution and transfers the data to TracerDAQ. [4, 5]. At this point TracerDAQ can be used to measure the temperature of each object as they cool.



(a)

Figure 1: a) TracerDAQ data collection

The procedure of this experiment is as follows: first, measure the ambient temperature in the lab using channel 4. Turn on the boiler (Figure 4) and heat the water in the container until boiling. While the water is boiling, open and setup TracerDAQ. On the first window, it should be noted that channel 0 is the copper sphere, channel 1 is the stainless steel sphere, channel 2 is the corner of the copper cube, and channel 3 is the center of the copper cube. The frequency should be set at 10 Hz, so that 10 data values are collected every second. Due to past experience, the total time it takes the objects to cool is about 45 minutes [1].

Once the water is boiled, place all four objects in the container of boiling water for approximately 10 minutes, so the objects attain constant, uniform temperature. When TracerDAQ is ready to start recording data after the objects have been moved so that they are suspended on horizontal rods, held by stands. Place each object at the end of the horizontal rod so that each object is suspended freely, in order to avoid unwanted conduction. Partition screens should separate each object and from disturbances of the surroundings in order to avoid unsteady heat transfer. Once objects are properly placed on the rods and swaying of the objects stops, start data collection on TracerDAQ [1].

After data is collected for 45 minutes or until temperature reaches ambient temperature, the computer software will end the task and the data can be saved as a *.txt and *.csv file. Lastly data will be plotted and analyzed to find heat transfer coefficient, specific heat of material, and Biot numbers for each object being observed. Comparisons will be made based on geometry and material. Unknown values may be found in table 3 in the appendix.

(a) (b)

Figure 2: a) Copper Sphere (Left), b) Stainless Steel Sphere (Right).

(a) (b)

Figure 3: a) Copper cube were the thermocouple is located in the corner (Left), b) copper cube where the thermocouple is located in the center of a surface (Right).

(a)

Figure 4: a) The boiler used in order to preheat the specimen

4 Presentation of Results

The first graph shown represents all of the data recored as a function as time. This was done in order to decide whether or not any modifications of the data were required.

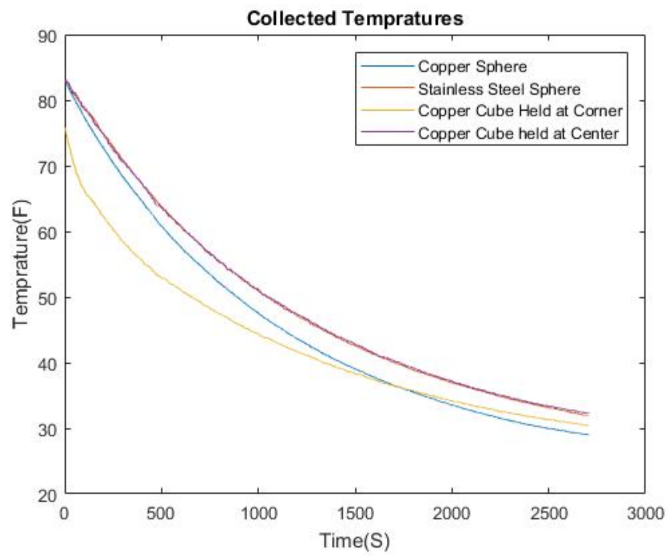


Figure 5: Shows the change in temperature over time for all 4 specimen.

The data shows no outstanding abnormalities allowing us to continue with this data set. In order to find the heat transfer coefficient the h, the corresponding τ value must be obtained. This is done by plotting the data for each specimen on a semi-log graph following equation (7). The slope obtained of the semi-log function represents $-\frac{1}{\tau}$. This is used to calculate h with values referenced in table 3.

As in figure 6 the copper sphere semi-log has a best fit line with a slope of -0.0012882. This gives $h = 18.75055278$.

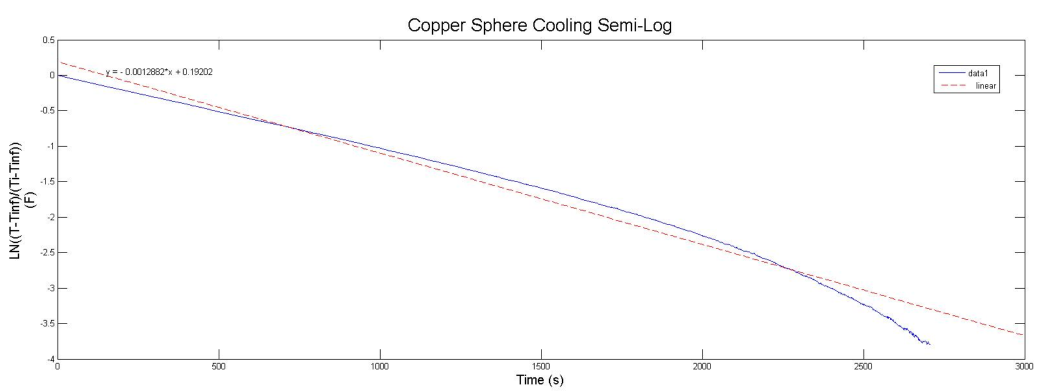


Figure 6: Shows the best fit line of the Semi-Log curve for the Copper Sphere plot

The figure 7 represents the graphed data according to equation (7) for the copper sphere.

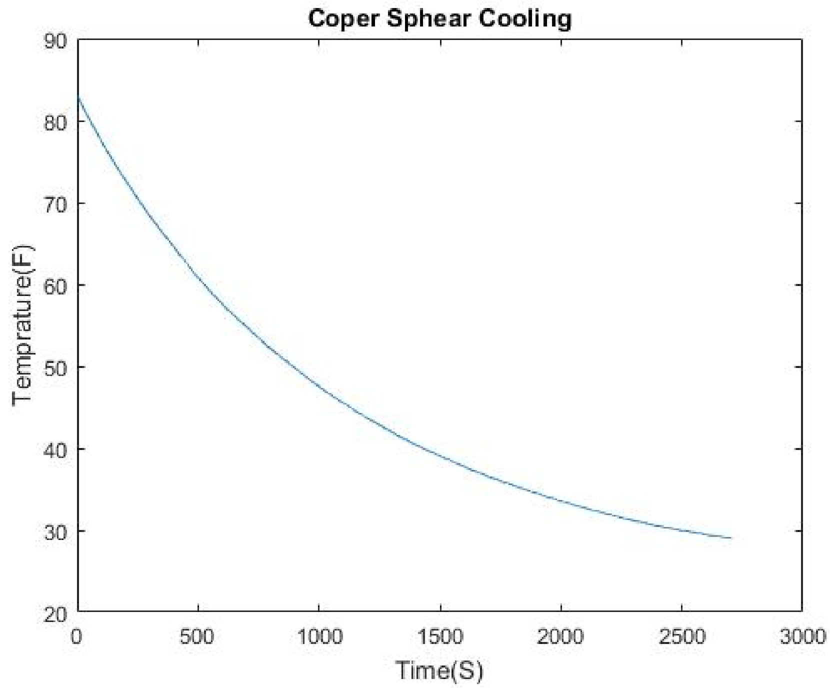


Figure 7: Shows the decrease in temperature over time

As shown in figure 8 the copper sphere semi-log has a best fit line with a slope of -0.0009385. This gives $h = 12.71354667$.

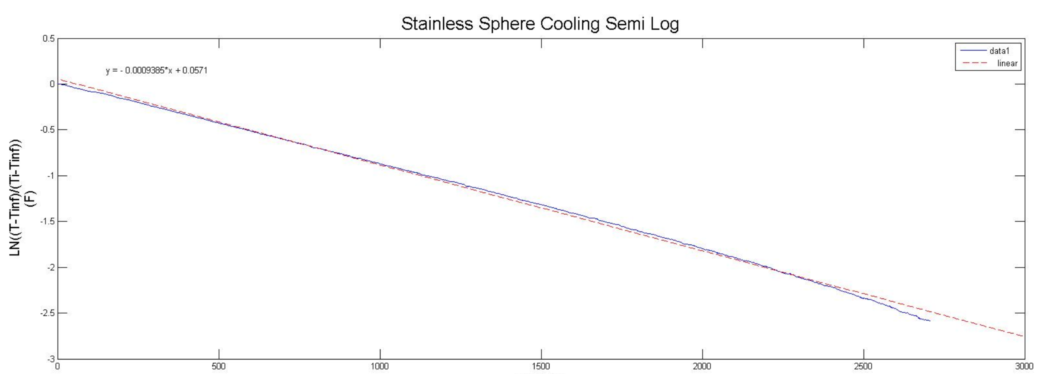


Figure 8: Shows the best fit line of the Semi-Log curve for the stainless steel Sphere plot

The figure 9 represents the graphed data according to equation (7) for the stainless steel sphere.

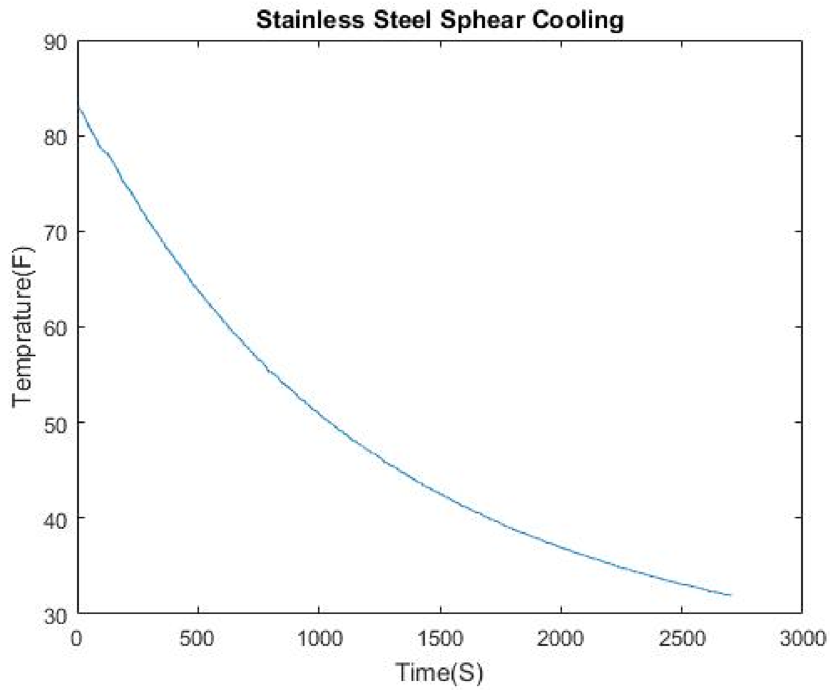


Figure 9: Shows the decrease in temperature over time

As shown in figure 10 the copper Cube suspended from the corner semi-log has a best fit line with a slope of -0.00097788. This gives $h = 14.23365203$.

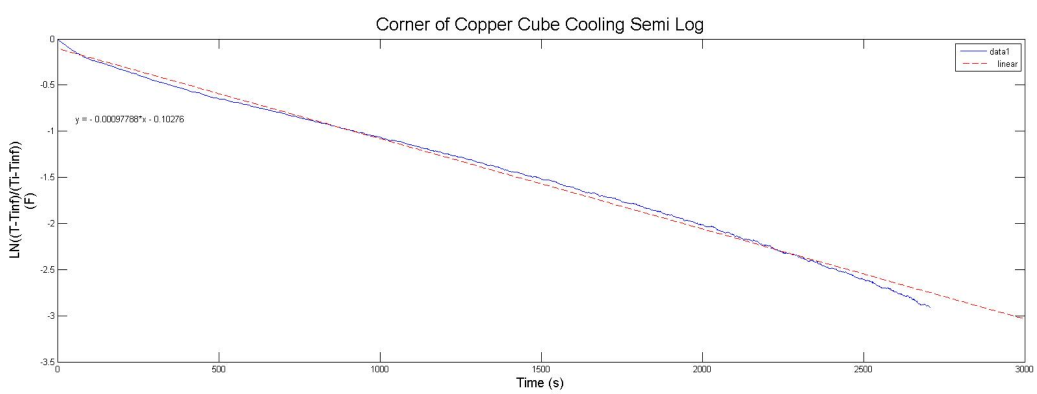


Figure 10: Shows the best fit line of the Semi-Log curve for the corner held copper cube plot

The figure 11 represents the graphed data according to equation (7) for the copper cube held at a corner.

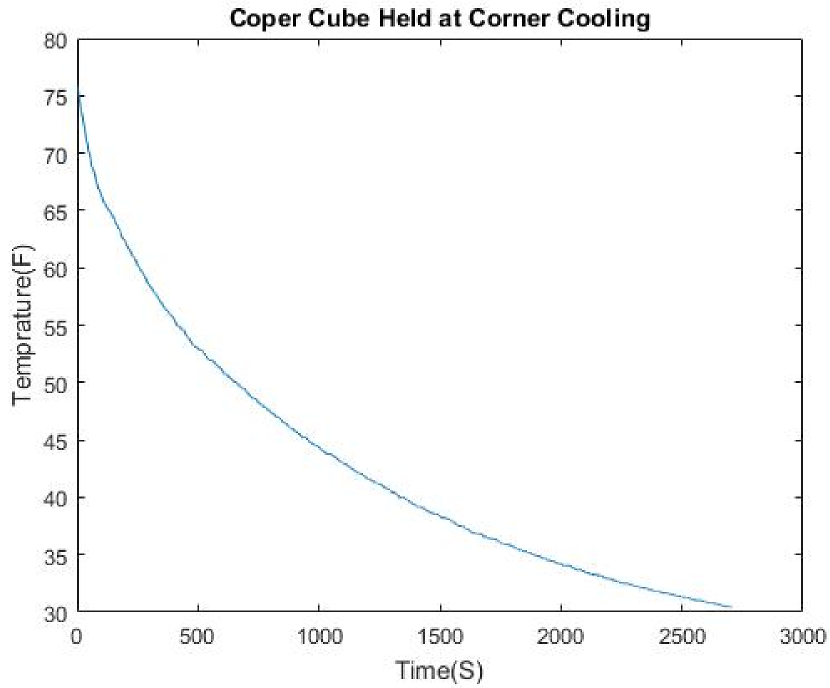


Figure 11: Shows the decrease in temperature over time

As shown in figure 12 the copper Cube suspended from the corner semi-log has a best fit line with a slope of -0.0091873. This gives $h = 13.37268697$.

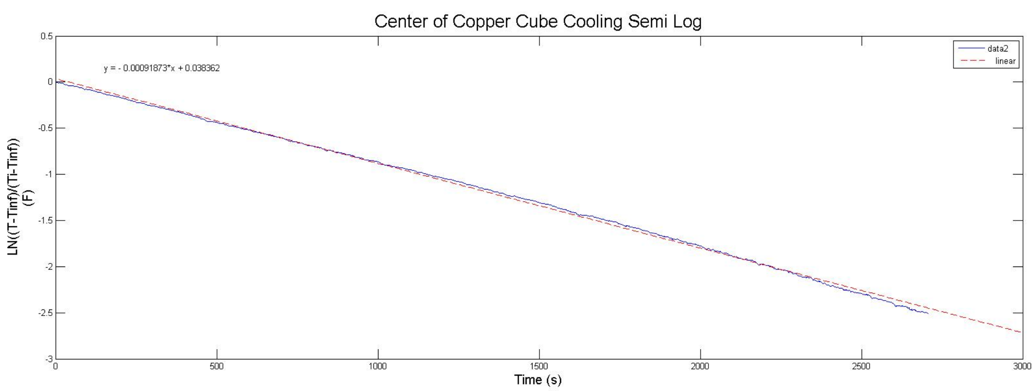


Figure 12: Shows the best fit line of the Semi-Log curve for the center held copper cube plot

The figure 13 represents the graphed data according to equation (7) of the copper cube held at the center of one surface.

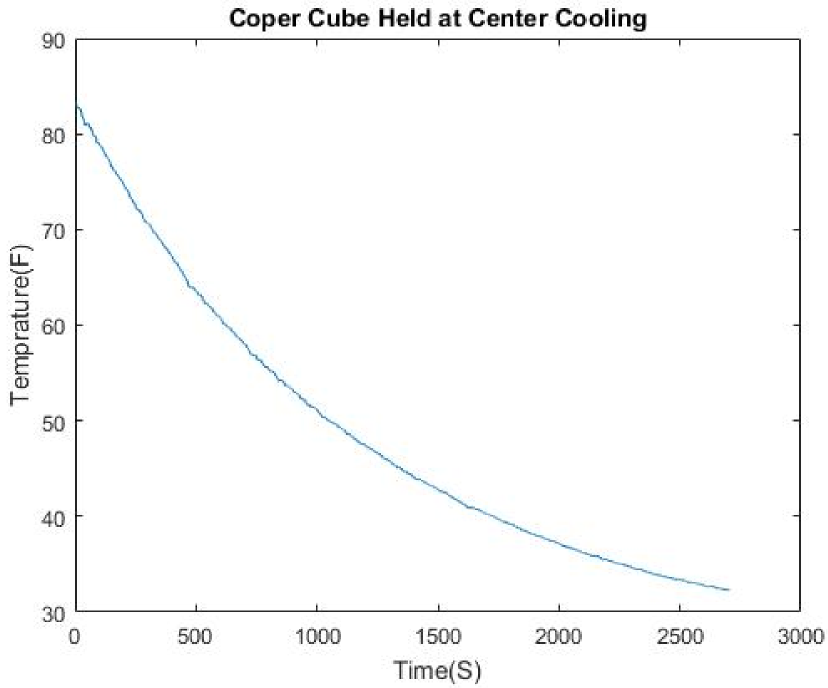


Figure 13: Shows the decrease in temperature over time

The following table shows our experimentally obtained $-\frac{1}{\tau}$ value as well as calculated τ, h, and the Biot number.

Table 1: Corresponding Values for Experimental Results

Specimen	$-\frac{1}{\tau}$	τ	h (W/m^2K)	Biot Number
Copper Sphere	-0.0012882	776.2769756	18.75055278	0.000199440553
Stainless Steel Sphere	-0.0009385	1065.530101	12.71354667	0.00390004934
Corner of Copper Cube	-0.00097788	1022.620362	14.23365203	0.0001513964663
Center of Copper Cube	-0.00091873	1088.459068	13.37268697	0.0001422387977

5 Uncertainty Analysis

The standard deviation for the data set obtained in this experiment are analyzed in relation to each fit, as shown in the table below. This table also identifies the number of points that didn't fall inside two standard deviations of each fit. For each object 2707 data points were collected.

Table 2: Uncertainty Analysis Values

Object	Mean	Standard Deviation	# Outside 2 STD	% Outside 2 STD
Copper Sphere	2.588070641	1.641090268	1174	43.37
Stainless Steel Sphere	1.063063009	0.561920268	1542	56.96
Corner of Copper Cube	-1.730387879	1.660750244	579	21.39
Center of Copper Cube	0.708758957	0.410678298	1332	49.21

From the table above, none of the objects fall within two standard deviations with respect from their linear fit. The copper sphere has 43.47% of its data points outside of the two standard deviation range. However, of these points, all of them fall within three standard deviations of the fit. The stainless steel sphere has 59.96% of its data points outside of the two standard deviation range. Similar to the copper sphere, the points fall within three standard deviations of the fit. The corner of the copper cube has 21.38% of its data points outside of the two standard deviation range. This again, is a less good fit, but is the closest fit in terms of the other objects observed. The center of the copper cube has 49.21% of its data points outside of the two standard deviation range in relation to the fit. Looking at all of these objects, none have a qualified good fit. However, all data points fall within three standard deviations of the fit. The error in the data point collection is likely due to improper placement of the objects, resulting in extra swaying at the start time of data collection. It is also possible a nearby vent or fan had an impact on the airflow in the room, indirectly skewing the results of the data collected during the experiment.

The USB-TEMP and TC series USB-TEMP-AI and USB-TC-AI specifications manual [5], states that the maximum accuracy error for a 24-bit Type T thermocouple device is 0.870%. In comparison to the typical accuracy error of 0.290% at 0 degrees celsius, and at 400 degrees celsius the maximum accuracy error is 0.569% with a typical accuracy error of 0.208%. The temperature in this experiment ranges from about 20 to 100 degrees celsius, thus the actual error values are between the given error values. For the entirety of the analysis, the maximum accuracy error value of 0.870% will be used to be safe. This is still a small error, even though our data values are lower than this range.

In the following analysis, each object's calculated heat transfer coefficient will be compared to its respective pair. The copper and stainless steel sphere, and the corner of the copper cube and the center of the copper cube will be compared. Using the h values calculated in Table 2, when comparing the h value of the corner of the copper cube to the center of the copper cube, the percent difference was 6.23744%. This percent difference is below 10%, which implies that the orientation of the object doesn't impact heat transfer. The percent difference between the copper sphere and the stainless steel sphere is 38.3739%. A percent difference higher than 10% implies that the assumption of this case is false, thus the material of the sphere impacts heat transfer.

6 Discussion of Results

The calculated Biot number had to have a value below 0.05 for the object to be assumed lumped, that the temperature is uniform for each object. The Biot number for the copper sphere is 0.000199440553, which is magnitudes lower than the cap value of 0.05. The Biot number for the stainless steel sphere is 0.00390004934, which is one magnitude lower than 0.05. The Biot number for the corner of the copper cube is 0.0001513964663, which is a couple degrees of magnitude lower than 0.05. The Biot number for the center of the copper cube is 0.0001422387977, which is a couple of degrees of magnitude lower than 0.05. Based on these values, the assumption that all of the objects have uniform temperature can be verified. As well, the lumped assumption is valid. These assumptions can be further confirmed by looking at the plots for each object. All of the plots show exponential decay, which is representative of the general form of the heat transfer equation for a lumped body. The semi log plot of the objects appears to be linear, which continues to confirm the the lumped assumption and equation (7). With the data collected from this experiment, the linear fit did not accurately represent the data. All data points were not within two standard deviations of the fit, which suggests that the data was not within a 95% confidence interval. However, all data points were within a three standard deviation range of the fit. Based on these results, one would not be confident in the numbers derived from these results, including the heat transfer coefficient.

Where the thermocouple was located and the orientation of the geometry of the object did not affect heat transfer for uniform objects. The calculated heat transfer coefficient for the corner of the copper cube is approximately 14.234 W/m^2K and the heat transfer coefficient of the center of the copper cube is approximately 13.373 W/m^2k. The percent difference between these two values is 6.23744%, which is less than 10%. A percent difference within this range means that the location of the thermocouple and the orientation of the the geometry do not impact the heat transfer of the body with uniform temperature. The slight difference may be due to unforeseen airflow. Sources of airflow include swinging of the object as well as unforeseen air currents in the room across the chamber. Another possibility is any residual water on the cubes as the water would transfer its own heat from the cube.

The heat transfer coefficient values obtained for the spheres of different materials suggest that material has an impact of the heat transfer of a body with uniform temperature. The heat transfer coefficient of the copper sphere is approximately 18.751 W/m^2K and the heat transfer coefficient of the stainless steel sphere is approximately 12.714 W/m^2K. the percent difference between these two values is 38.3739%, which falls outside of 10% threshold. Based on these calculated values and the data collected in this experiment it can conclude that the material properties have an impact on the heat transfer of an object with uniform temperature.

7 Conclusions and Recommendations

This experiment productively and successfully represented the theory of a lumped body subjected heat transfer. This experiment tested for objects: a copper sphere, a stainless steel sphere, the corner of a copper cube and the center of a copper cube. All objects were attached to a Type T thermocouple, which tracked the objects separately using a USB-Based Temperature measurement device and the digital software, TracerDAQ. The Type T thermocouple in conjunction with the USB-Based Temperature Measurement Device were used due to their extremely low error. The typical error for these devices is, for temperature ranges 0°-600°, $\pm 0.246°C$ [4]. The USB-Based temperature measurement device reads with 24-bit resolution and has has 8 analog channels, of these 5 were used. See manual for in depth channel distribution [1] [5]. Channels 0-3 were used to measure temperature for objects bit 4 was used to obtain the ambient temperature [1].

The objects were heated in boiling water for about 10 minutes then removed quickly to be hung on a horizontal rod inside a containment vessel. Data was then collected for 45 minutes as the objects cooled. Data for each object was collected and organized in an excel file. Using a a combination of MatLab and excel, the data was analyzed. Two hypotheses were tested. The first hypothesis states: does the orientation of the the object impact the heat transfer? The second hypothesis investigates: whether or not the material properties impact the heat transfer of an object.

The two copper cubes, both had similar values for their heat transfer coefficient. The corner of the copper cube had a calculated heat transfer coefficient value of 14.234 W/m^2K and the center of the copper cube had a calculated heat transfer coefficient of 13.373 W/m^2K. these numbers are within an accepted range and have a percent difference of 6.23744%. The conclusion of these results is that the orientation of a lumped body does not have an impact on the heat transfer coefficient.

The copper sphere and stainless sphere have significantly different heat transfer coefficients. The copper sphere has a heat transfer coefficient of 18.751 W/m^2K. The stainless steel sphere has a heat transfer coefficient of 12.714 W/m^2K, resulting in a percent difference of 38.3739%. this percent difference suggests that the material properties have an impact on the heat transfer coefficient of the lumped body being analyzed.

The Biot numbers for each object being analyzed were calculated to verify the uniform temperature of an object assumption, the lumped assumption. In order for this assumption to be verified, the Biot number must be less that 0.05. The Biot number for the copper sphere is 0.000199440553. The Biot number for the stainless steel sphere is 0.00390004934. The Biot number for the corner of the copper cube is 0.0001513964663. the Biot number for the center of the copper cube is 0.0001422387977. All of these values are lower than 0.05 by at least one or two degrees of magnitude, which means that the lumped assumption can be made, and all objects are safely assumed to have uniform temperature.

If this experiment were to be repeated, several changes should be taken into consideration. The first change is to have the objects stay in the boiling water for a longer period of time. this would have the objects have a starting temperature closer to 100 degrees Celsius. The second alteration in repeating this lab is to prevent the objects from swinging. The swaying of objects could have skewed the first data points that were collected in this experiment. This can be done by placing objects more carefully on the stand, or changing the apparatus so that the process is likely to involve swaying of the objects. The last change to be made is performing this experiment in a more controlled environment. Doors being opened or closed, fans, vents, could all create an air current, causing the temperature to fluctuate in the room. The third consideration to take into account is to verify that there is no residual water drops on any of the objects. All of these factors that were not changed in the original experiment could have impacted the values of heat transfer coefficient calculated per object, changing the overall results of the experiment.

8 Acknowledgements

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9 Appendices

Table 3: Physical properties of copper and 316 stainless steel at 20°C

Material	k (W/m^2K)	ρ (kg/m^3)	C_p (J/KgK°)
Copper	398	8954	384
Stainless Steel	13.8	800	400