

Senior Lab 1

Bret Comnes

Humboldt State University

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Abstract

Measuring the specific heat capacity of objects using simple calorimetry techniques is a common undergraduate laboratory activity. Measuring the heat capacities of certain materials and samples can easily introduce or amplify errors in the data collected. We attempted an investigated how surface area of a lead mass sample and resolution increasing techniques affect the data collected in a simple undergraduate lab activity that aimed at measuring the heat capacity of a lead sample.

I. INTRODUCTION

The purpose of the original lab was to measure the equilibrium temperature between room temperature water and lead at 100c in order to calculate the specific heat capacity of lead, C_{Pb} . The original procedure reportedly produced adequate results with the use of mercury/alcohol, but obviously large errors were detected once the labs began the use of digital thermocouples which provided more accurate and realtime results. Data was initially taken according to the original procedure. Once sufficient understanding of the procedure was developed, a number of changes were implemented to reduce suspected sources of error. Quite a number of different problems were initially suspected, but one seemed to stand out from the rest. This suspected source of error related to the surface area of our lead mass. The test masses used in the lab had a large surface area to mass ratio due to their flat, thin shape. Similar to the role of a fin making up a heat sink, the flat, thin shape of the test mass was suspected to cause rapid heat energy loss to outside of our measurement system. In order to address this, alternate shaped test masses were used with the objective of minimizing the surface area to volume ratio. Ideally, spherical lead masses would be tested, as they have the smallest surface area to volume ratio, although this shape was not available at the time of analysis. Changing the shape of the mass led to improved results, but inconsistencies were still occurring indicating there were still issues preventing accurate reproducible data. The original styrofoam cups did not accommodate the replacement mass as ideally and required additional amounts of water in order to completely submerge the test masses. The second change made was to use a taller cup with a smaller radius. This allowed the use of less water in order to submerge the new masses entirely in order to detect a larger change in temperature of the water. This seemed to minimally improve the consistency of the data, which still seemed susceptible significant introduction of error relating to the duration our mass sample remained between the boiling water and our calorimeter.

II. HEAT ENERGY LOSS

Ideally, all of the heat energy contained in the lead mass from the boiling water would transfer into the water sample, without any loss to the outside or introduction of heat energy from contaminants. Clearly, this is not the case as the experiment called for an open

air calorimeter made of Styrofoam and a transfer of the sample from boiling water through air into the calorimeter without any way of removing excess water from the sample. The method of adding heat energy to the lead required that the lead remain in a boiling water bath, which had detectable temperature gradients when heated on a standard laboratory hotplate. When removing the lead mass, droplets from the boiling water would remain on the surface of the lead and would often carry over to the calorimeter, affecting the measurements to some degree. In order to decrease the amount of heat energy lost during the transfer between the boiling water bath and the calorimeter, it was decided to decrease the surface area of the mass in order to minimize the rate at which heat energy was lost.

A. The Fourier heat conduction law

In order to minimize the conduction of heat out of our sample, it helps to understand the relationships of the process. **The Fourier heat conduction law**[5] states that the amount of heat transfer during a duration of time is proportional to a number of factors including surface area, temperature difference, as well as the material in which the conduction is occurring.

$$\frac{Q}{\Delta t} = -k_t A \frac{dT}{dx} \quad (1)$$

Where $dT = \Delta T = T_2 - T_1$, A is the area, $k_t A$ is a constant called the thermal conductivity which varies with different materials and Δx is the thickness of the conducting layer. The possible conducting layers that our system will exchange heat with is air, water, polystyrene ("styrofoam") and lead.

TABLE I. Thermal Conductivity of Materials Involved[1]

Material	$k_t (\frac{W}{mK})$
Air	0.025
Water	0.600
Lead	35.30
Polystyrene	0.030

According to this equation and these thermal conductivity values, it is clear that lead conducts a lot of heat energy fairly quickly. This can be a tad bit deceiving since the

equation deals with heat energy flowing in or out of a particular layer. Considering our system, heat energy is able to enter or leave our lead sample quickly, but is limited by the material surrounding it. If one were to hold a hot sample of lead in air, the actual amount of heat energy lost will be considerably less than what you would calculate as the air would create a thin layer of insulation due to its relatively low conductivity. This insulating layer of air however, would not be as effective if the sample were moving as this insulating layer would not form as the air rushed around it. Changing the surface area by approximately 4 times less, we attempted to reduce this rapid loss of heat.

III. ORIGINAL PROCEDURE

The original procedure had a number of contradictions written in that had to be interpreted as best as possible. The process of testing the specific heat capacity of lead required that the lead sit in a boiling water bath to reach equilibrium with the known temperature of the boiling water. The hot lead sample was then transferred using a piece of sting to a known mass of room temperature water in an open Styrofoam dish. The original lead mass used in the lab was thin and flat. Once the transfer was made, the temperature of the water was monitored using a thermocouple and a digital meter. While the procedure did not call for mixing of the samples, temperature gradients while reaching thermal equilibrium were observed and it was decided that it would be best to stir the water using the thermocouple to sample a larger range of water as well as the promote homogeneous mixture of water. Once an equilibrium is reached, the final temperature was noted. Following that,

$$M_{Pb}C_{Pb}\Delta T_{Pb} = M_W C_W \Delta T_W \quad (2)$$

$$C_{Pb} = \frac{M_W C_W \Delta T_W}{M_{Pb} \Delta T_{Pb}} \quad (3)$$

the specific heat capacity was able to be calculated. The results from the original procedure are in TABLE II. As noted above, there are a number of sources error that contribute to different degrees, but just as a reference, the accepted value of lead and water is,

$$C_{Pb} = 0.128 \left(\frac{J}{g^{\circ}C} \right) \quad (4)$$

$$C_{H_2O} = 4.179 \left(\frac{J}{g^{\circ}C} \right) \quad (5)$$

TABLE II. Original Procedure.

	$M_{Pb}(g)$	$M_W(g)$	$T_{Eq}(^{\circ}C)$	$\Delta T_{Pb}(^{\circ}C)$	$\Delta T_W(^{\circ}C)$	$C_{Pb}(\frac{J}{g^{\circ}C})$
Run 1	116.58	127.32	22.2	75.7	1.8	0.109
Run 2	116.58	127.32	24.	74.	3.2	0.098

The sources of error reportedly had less of a detectable presence when the experiment was performed using alcohol thermometers. The digital thermocouples used in the original procedure are able to detect up to a tenth of a degree about every second which helped improve the accuracy of the measurements, but also amplified the presence of the sources of error.

IV. REDUCING SURFACE AREA

In order to test our theory that excess heat energy was being lost during the sample transfer due a large mass surface area, two different mass shapes were tested. In addition to changing the shape of the mass, a different Styrofoam cup was used that allowed us to use the minimum amount of water in order submerge the alternate masses completely. In retrospect, making the two changes simultaneously obscured the indications our data contained.

A. Donut Shaped Mass

A doughnut shaped mass with a smaller radius but thicker diameter with a similar mass to the original sample was tested. This mass had issues with large beads of water remaining in the divot in the middle and it was determined that this was a variable not present on the original sample. Two runs were conducted with this sample utilizing different configurations to quickly submerge the mass in the calorimeter water, but results were considered of little value as there was a significant amount of boiling water contaminant due to the shape.

TABLE III. Donut Shaped Mass

	$M_{Pb}(g)$	$M_W(g)$	$T_{Eq}(^{\circ}C)$	$\Delta T_{Pb}(^{\circ}C)$	$\Delta T_W(^{\circ}C)$	$C_{Pb}(\frac{J}{g^{\circ}C})$
Run 1	117.23	91.73	20.6	78.5	2.9	0.121
Run 2	117.23	61.93	20.9	78.3	3.8	0.147

B. Teardrop Shaped Mass

The second shape tested was an elongated tear drop, while having less mass, had approximately a fourth of the surface area of the original test mass. The results varied a bit. It was noted that the time and speed at which the mass was transferred from the boiling water to the cup had some affects on the numbers (less time during the transfer resulted in a larger measured heat capacity). While modifying the surface area of the mass seemed to help somewhat with preserving the expected value of heat energy we were to find in the lead sample, it was not entirely convincing that what we were measuring was mostly reflecting the heat capacity of the lead. There was still a fairly significant amount of contaminant boiling water droplets that surly contributed heat energy to what we measured and the behavior witnessed seemed to indicate that the results were still very much dependent on the way the sample was transferred. This could possibly indicate that we were measuring some kind of average state of the heat energy contained in our combination of sample and contaminant boiling water.

TABLE IV. Teardrop Shaped Mass

	$M_{Pb}(g)$	$M_W(g)$	$T_{Eq}(^{\circ}C)$	$\Delta T_{Pb}(^{\circ}C)$	$\Delta T_W(^{\circ}C)$	$C_{Pb}(\frac{J}{g^{\circ}C})$
Run 1	85.4	75.37	21.4	99.0	2.5	0.123
Run 2	85.4	78.99	23.7	75.6	2.5	0.128
Run 3	85.4	74.52	24.2	75.1	2.3	0.112
Run 4	85.4	81.51	24.9	74.4	2.4	0.130

V. INCREASING RESOLUTION

One of the changes, that unfortunately, was not tested independently but later realized as a likely important aspect to our results, was attempting to increase the change in temper-

ature to something more easily measured. While finding a more desirable shape for our test mass, we happened to decrease the total mass of the sample due to the materials available. This resulted in less heat energy potentially being transferred over to our room temperature water resulting in even less of a change in temperature of the water that we could measure. One attempt was made to increase the total mass used in a test by combining three total teardrop masses. This also increased the surface to mass ratio significantly so it is expected that heat loss problems similar to the first test mass will occur so this measurement is not terribly sound.

TABLE V. Three Teardrop Shaped Masses

$M_{Pb}(g)$	$M_W(g)$	$T_{Eq}(^{\circ}C)$	$\Delta T_{Pb}(^{\circ}C)$	$\Delta T_W(^{\circ}C)$	$C_{Pb}(\frac{J}{g^{\circ}C})$
219.4	94.39	27	72.3	4.6	0.114

Changing the size and shape of the cup in order to minimize the amount of water was a performed change that was never independently tested, which was a procedural mistake of the lab. The objective of this change was to reduce the amount of volume the heat energy from our test mass would equilibrate in. While this should have helped make the change in temperature of the water more apparent, it resulted in some issues itself. With less water surrounding the lead sample, temperature gradients were increasingly apparent in the water sample which made it difficult to determine a peak equilibrium temperature.

The extent of the measurements made stops at this point. We do have enough to reason some additional changes that could yield better results in a similar experiment though.

VI. HEAT ENERGY LOST AND FURTHER TESTING

In order to understand the magnitude of our measurements, we can make some simple assumptions. If we use the accepted values for C_{Pb} and C_W we can calculate how much the temperature did not rise.

$$C_{Pb} = \frac{M_W C_W (\Delta T_W + x)}{M_{Pb} (\Delta T_{Pb} - x)} \quad (6)$$

In using the data collected with the teardrop masses, the temperatures should have changed an additional $0.308738(^{\circ}C)$ which is 13% of our change in water temperature. With

this in mind, we can see that we lose a certain degree of energy due to our system configuration to cause our water raise 13% less than what it is supposed to reach. If one were to use a sample with a similar heat conductivity constant (such as Iron, $k_t(\frac{W}{mK}) = 34.6[2]$) such that the amount of heat lost remained approximately the same as our lead sample, but had a significantly higher Specific Heat Capacity, the lost heat energy would be less of an overall percentage of what the sample could contain. In the case of Iron, ($C_{Fe} = .449(\frac{J}{g^{\circ}C})[5]$) which has a heat capacity about 3.5 times larger than Lead, the percent of energy lost will be significantly lower, resulting in a more accurate measurement than what the heat capacity actually is.

Because, relative to the Heat capacity of the water, our sample was not capable of transporting much energy, our data was more susceptible to things like surface area and heat loss during the transfer as our measurement would only vary by a few degrees. If one were to use a sample with a larger heat capacity such as lead, these variables should theoretically become less important. Testing a sample such as Aluminum would be a good choice if continuing investigation into this lab as the heat capacities are approximately 7 times larger than the heat capacity of Lead and should result in a much larger temperature change in water. The conductivity constant for copper is much larger, but should have less of an effect as the amount of energy lost will be considerably less than what the material is capable of transporting. (note, I have more comprehensive analyses of this idea have not had time to include. Are future rewrites allowed?)

A. Additional Sources of Error

An additional source of error as mentioned above had to do with temperature gradients existing in the water in which the temperature is measured. If a thermocouple was attached somehow onto the metal sample, which maintains a much more uniform temperature gradient, there would be less confusion over what a proper equilibrium temperature value is. If this was coupled with some form of digital acquisition, a more accurate interpretation of when the equilibrium state occurs could be recorded.

VII. CONCLUSION

There were a number of issues relating to the procedure followed during this lab. To many aspects were changed at once, and changes were not thoroughly planned out. As a result, while certain aspects such as surface area were tested to some degree of accuracy, the main issues were not foreseen. While it appears that surface area may lead to rapid heat energy loss in samples that do not transport much total heat energy, as the amount of energy lost is a rather large portion of its total amount of heat energy, it is unclear how this factor translates to other materials that have larger heat capacities and can result in more measurable results. Often these metals conduct heat at a faster rate, but also can carry around seven times more heat energy than Lead.

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- [1] *Kay Laby: Tables of Physical Chemical Constants.* National Physical Laboratory,
http://www.kayelaby.npl.co.uk/general_physics/27/279.html.
- [2] *Thermal Conductivity of Metals.* <http://www.engineeringtoolbox.com/thermal-conductivity-metals-d858.html>.
- [3] *List of thermal Conductivities.* http://en.wikipedia.org/wiki/List_of_thermal_conductivities, February 2010.
- [4] CRC. *Handbook of Chemistry and Physics.* 90th edition edition, 2009 - 2010.
- [5] Daniel V. Schroeder. *An Introduction to Thermal Physics.* Addison Wesley Longman, 2000.