

AC 2008-292: A HOMEMADE 2-DIMENSIONAL THERMAL CONDUCTION APPARATUS DESIGNED AS A STUDENT PROJECT

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Abstract:

It can be fairly expensive to equip a heat transfer lab with commercially available devices. It is always nice to be able to make a device that provides an effective lab experience for the students. It is an extra bonus if the device can be designed as a student project, giving the students working on the device both a real design experience and a better understanding of the principles involved with the device and the associated lab exercise.

One example of such a device is a 2-dimensional heat conduction device which was designed and built as a student senior design project by mechanical engineering technology students at Penn State Erie, The Behrend College. The device described in this paper allows the students to determine the thermal conductivity of several different materials, and to graphically see the effect of contact resistance in the heat conduction path. The students use the conductivity information to try to determine what material the test samples are made of.

This paper describes the design of the device and the basic theory including a description of how it applies to this particular device. Finally, typical data and results are shown.

Introduction:

One-dimensional heat conduction is a very fundamental principle that students in an introductory heat transfer course must understand. The basic theory can be taught in a lecture, but a laboratory exercise that demonstrates the principle can greatly enhance the students' understanding. Several companies offer conduction test devices to use for this purpose, but they can be fairly expensive. At Penn State Behrend the thermal sciences lab has three work stations, so it is ideal to have three separate devices for testing. This can push the overall cost of the equipment to prohibitive levels. A decision was made to have a Mechanical Engineering Technology student design and build a conduction test device as a senior design project.

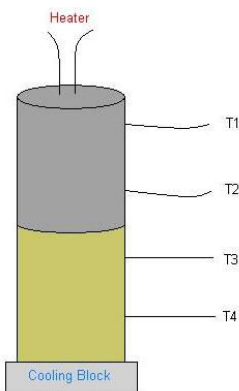


Figure 1

Figure 1 shows the basic design of the device. It consists of a heater section, test section, and cooling block. The details of this design will be discussed later in this paper. Heat is conducted through the device from top to bottom. The section between the top (T1) and bottom (T4) thermocouples is insulated, so the conduction is primarily one-dimensional. There are convection losses above the insulation, but that is accounted for in the calculations. A small amount of heat is lost through convection from the insulated section. The losses are small enough to minimize the error, and the final results for thermal conductivity fall within approximately 5% of published values. The theory and sample calculations are discussed later in this paper.

The purpose of this device is to demonstrate one-dimensional heat conduction principles to the students, and to give them some feel for the differences in conductivities among various metals. This device clearly shows relative relationships between conductivity values for several different materials, but is not intended to provide extremely accurate values for each material. The device also clearly shows the effect of contact resistance in a heat conduction circuit. The students can plot the temperature drop across either a dry contact or can see the effects of using thermal paste or other thermal interface materials, which will also be discussed later in this paper.

Theory:

One-dimensional heat conduction is governed by Fourier's law ^[1]:

$$q = kA/\Delta x (T_2 - T_1) \quad \text{Eq. 1}$$

- q = rate of heat flow (watts)
- k = thermal conductivity (W/m-°C)
- A = cross-sectional area (m²)
- Δx = length (m)
- T = temperature (°C)

For this device, the conductivity of the heater section material is known, so temperature data from that portion of the device can be used to determine the amount of heat flowing through the device as a direct application of equation 1. The cross-sectional area and the distance between thermocouples are physical properties of the device which can be easily measured, and the temperatures are the data that is collected when the test is run. Once the heat flow is known, the temperature data from the test specimen can be used in equation 1 to determine the conductivity of the unknown material.

It is assumed that the temperature profile for each of the sections is linear. A possible future enhancement to the design involves adding one or two thermocouples between the existing ones. The data from more than two would be used to show that the temperature profile truly is linear (or very close to it). Using this assumption, physical measurements from the parts, and equation 1 the measured temperature data can be extrapolated to the interface surface of each material. The difference between these interface temperatures gives the temperature drop across the interface.

This device can also be modeled as a thermal circuit with three resistors (Fig. 2).

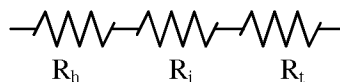


Figure 2

- Where: R_h = Thermal resistance of the heater section
- R_i = Thermal interface resistance
- R_t = Thermal resistance of the test section

The thermal resistance values can be determined by Equation 3 below.^[1]:

$$\text{Heat flow} = \frac{\text{thermal potential difference}}{\text{thermal resistance}} \quad \text{Eq. 2}$$

or:
$$R_{th} = (T_2 - T_1)/q \quad \text{Eq. 3}$$

Where: R_{th} = thermal resistance ($^{\circ}\text{C}/\text{W}$)

This calculation is used to determine the thermal resistance of the interface.

Design of the Device:

Figure 3 shows the overall design of the device. The bottom plate is made from painted steel to help keep the center of gravity low for stability. The top plate and the upper heater section are made from aluminum. Both of these pieces are electroless nickel plated to improve wear and durability. There are a variety of test specimens made from different materials. Currently specimens are available in aluminum, brass, bronze, cast iron, and stainless steel. The heater section and the test specimens are 1.25 in. in diameter. The bottom cooling block is made of aluminum with a manifold system drilled in to provide a path for cooling water. The four corner posts are steel all-thread with stainless steel tube sleeves used to properly space the upper and lower plates.

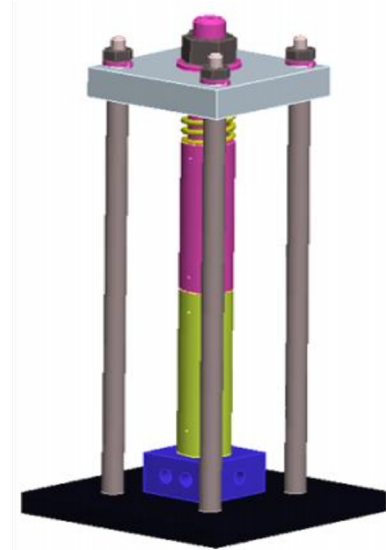


Figure 3

The upper heater section and the lower test specimens each have two small holes for thermocouples. The holes are spaced 3 inches apart on each piece. The temperature difference between the heater section thermocouples is used to determine the total heat flowing through the device, and the temperature difference between the two thermocouples in the test specimen is used to determine the thermal conductivity of the test specimen material.

Notice in Figure 3 that there is a spring located between a shoulder on the heater section and the top plate. This is a key feature of the design. When the nut on top is fully loosened the spring provides the pressure at the interface. The spring used for this device is designed to provide 30 lbs of force. This value is not critical though. When the nut is tightened it compresses the spring and makes it possible to remove the

test specimen. This is done to assure that the pressure at the interface is consistent from test to test, and so that over-tightening the nut will not cause possible damage to the specimens. Figure 4 is the original sketch made by the student showing details of the upper portion of the design. Notice that there is an elongated hole in the upper plate and flats on the upper portion of the heater section to prevent the section from rotating while the nut is being tightened or loosened.

Another important feature of the design can also be seen in Figure 4. Notice that there is a small shoulder on the bottom of the heater section and a small counterbore on the top of the specimen. This is done to assure alignment of the parts. The shoulder and counterbore are sized so that there is always a small gap around the outer ring causing the interface to be in the large center area. Interestingly, one of the test specimens was machined wrong, allowing the interface to be

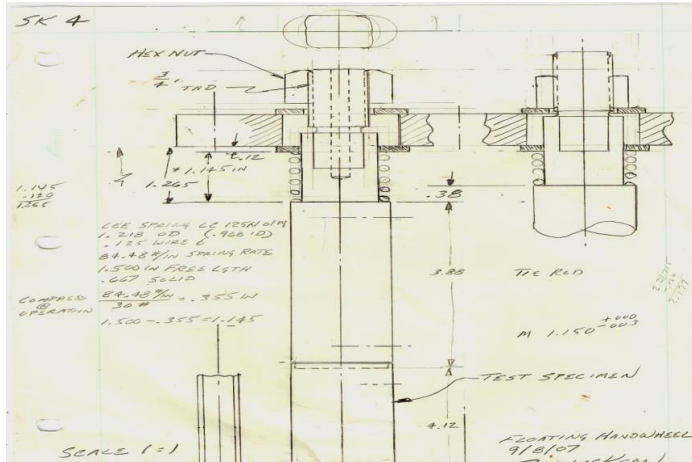


Figure 4

around the smaller outer area. This resulted in a very large temperature drop across the interface which was easily detectable on the data collection screen (described below). Although this was completely unexpected it did provide a wonderful teaching moment. A similar thing is done at the interface between the specimen and the cooling block at the bottom.

Ordinary foam pipe insulation is used to insulate the heater section and the specimen from the top plate to the bottom plate. This is done to minimize the heat lost to convection throughout that section. While this is not perfect, it does provide enough insulation to yield very reasonable conductivity values for the test materials. An estimate of the heat lost in this section can easily be made when using the aluminum test specimen. That will be shown later in this paper.

Test Set-up and Procedure:



Figure 5

Figure 5 shows the test set-up. The test device is shown on the left. Note the cooling water connections at the bottom. A rheostat is used to vary the input power, which is measured with the wattmeter shown in the foreground. A USB based data acquisition unit accepts the thermocouple information which is sent to a computer.

The wattmeter is not used to determine the actual amount of heat that flows through the device. It is used primarily during the warm-up of the device to monitor the power to the heater and to help avoid overpowering the heater during that stage. The wattmeter information can also be used to estimate the heat lost from the device above the insulated section.

Running the actual test is quite simple. A test specimen is installed in the device. The thermocouples, heater, water lines, insulation and instrumentation are installed. The rheostat is adjusted to provide 30-35 watts to the device, and the temperature at the upper most thermocouple is monitored. When the temperature reaches approximately 70° C, the current is reduced to 20 watts. The temperature then starts to drop, eventually reaching a steady state. This warm-up procedure greatly reduces the time it takes to reach a steady state at an input of 20 watts. When steady state is reached the temperatures at the four thermocouples are recorded.

Data is collected and plotted using a LabView virtual instrument (VI). Figure 6 shows a screen view for a typical test. Notice that it is quite apparent when the power is turned down. For certain materials with low conductivity values the curve continues to rise past the 70° C mark. This indicates that the steady state temperature for an input of 20 watts has not yet been reached. It is recommended that lower power levels be used for those types of materials to avoid excessive temperatures. A steady state temperature in the 100° C range was reached using 304 stainless steel for the test specimen. This can be dangerous to the students and should be avoided. The test plot shown below is not quite at steady state yet, but was truncated to show representative curves.

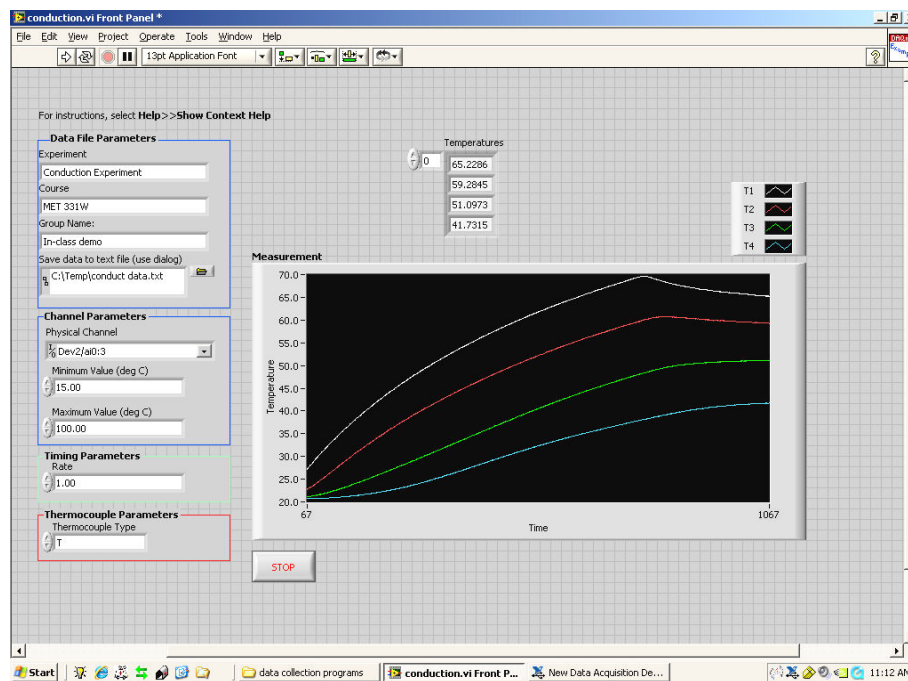


Figure 6

The temperatures shown at the top center of the screen are the temperatures at the four thermocouples. These values can be read directly from the screen or the data can be sent to a file, with the last four recorded values used for the calculations.

It is the nature of heat transfer tests that they can take fairly long times to reach steady state. For example, the test shown above was stopped at about 18 minutes, but it would have probably taken 20-25 minutes to actually reach steady state. A nice by-product of having these curves shown continuously on the screen is that it helps to maintain the students' interest in the test.

Various teaching points can be made while they are watching the screen. For example, why are the curves non-linear? What is the significance of the distance between the top two curves compared to the difference between the bottom two curves? Why does the bottom temperature rise even though the water temperature remains constant at the bottom?

During a recent round of testing all of the students were asked these and other questions as the parts were warming up. This forces the students to think about the concepts involved instead of just sitting and waiting. Some of the responses were quite revealing in terms of their understanding of the material. For example, in the above test the temperature at the lowest thermocouple reads 41.7° C, but the cooling water temperature is below 20° C. No one recognized that a lot of that temperature difference could be attributed to the interface resistance between the test specimen and the cooling block, providing an excellent opportunity to discuss the effects of contact resistance. The same group of students was asked why the difference between the top two temperatures was different than the difference between the bottom two temperatures. Amazingly, a large number of students thought it was caused by different amounts of heat being transferred through the top and bottom parts rather than being caused by different material properties. This is a good example of how simple lab exercises can go beyond just the classic “cookbook” labs that we are all familiar with.

Typical Results:

Figure 7 shows a tabulation of typical results for the various test specimens. The calculated values for thermal conductivity come from the test data. Typical k values are found in a variety of handbooks. Notice that there is fairly good agreement between the values. Most of them are within 5% or less. The only exception is bronze, which is within 5.5%. The calculations used to determine these values will be shown later in this paper.

Material	Temp 1	Temp 2	Temp 3	Temp 4	Calculated k Value	Typical k Values found
Aluminum	65.5	58.9	44.5	38.1	185.6	180
Brass	69.3	64.3	56.6	48.6	112.5	118
Bronze	69.3	64	54.7	41.2	70.7	67
S.Steel	66.5	64.2	56	29.8	15.8	15.5
Cast Iron	69.9	64.6	53.3	33.3	47.7	50

Figure 7

Figure 8 shows a typical plot of the temperature profile along the device between the top and bottom thermocouple. The sections between T1 & T2 and T3 & T4 are assumed to be linear. (This is not exactly true because of small losses in these areas, but is a good enough approximation for this test). Using this assumption, the temperatures at the top and bottom of the interface can be estimated by extrapolating the curves to the interface. The resulting plot gives the students a very graphic representation of the interface resistance. Various greases or interface pads could be used to demonstrate if the temperature drop across the interface is reduced, providing more good teaching opportunities.

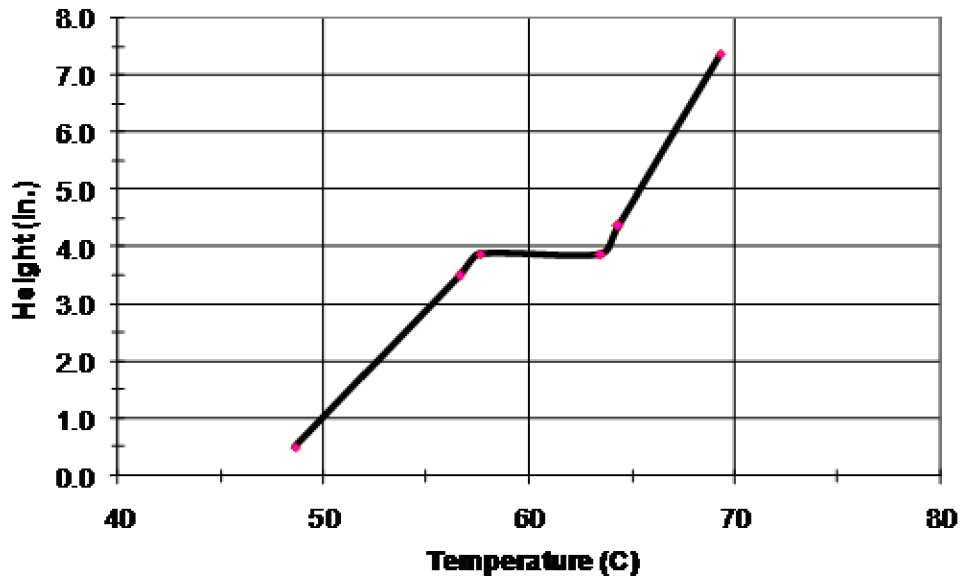


Figure 8

Typical Calculations:

Known information:

Specimen diameter = 1.25 in.

Distance between T1 and T2 = 3.00 in.

Distance between T3 and T4 = 3.00 in.

Distance from T2 to the interface surface = 0.50 in.

Distance from the interface surface to T3 = 0.38 in.

Note: all of these dimensions are converted to meters for the calculations shown below.

The sample calculations shown here are for the aluminum test specimen. The reason the aluminum specimen is chosen for these sample calculations is that the amount of heat being lost in the insulated portion of the device can be estimated based on the results from this specimen. That is shown at the end of this section. The temperatures that were recorded are:

$$T1 = 65.5 \text{ }^{\circ}\text{C}, T2 = 58.9 \text{ }^{\circ}\text{C}, T3 = 44.5 \text{ }^{\circ}\text{C}, T4 = 38.1 \text{ }^{\circ}\text{C}$$

The steps in the calculations include:

- Calculate the total amount of heat flowing through the heater section using the top two temperatures and equation 1. The heater section is made of 6061 aluminum with a published thermal conductivity of $k=180 \text{ W/m}\cdot^{\circ}\text{C}$.
- Calculate the thermal conductivity of the test specimen material using the bottom two temperatures, equation 1, and the results from the first calculation.
- Extrapolate the temperatures of the heater section and the test specimen to the interface using equation 1.

Figure 9 gives the results of these three calculations for the aluminum test specimen and the above data.

Heat transfer through the heater section	12.34 Watts
Conductivity of the test specimen	185.6 W/m- ⁰ C
Temperature at the upper interface surface	57.8 ⁰ C
Temperature at the lower interface surface	45.3 ⁰ C
Figure 9	

Notice that only 12.34 watts is actually flowing through the device. The total input was 20 watts, so 7.66 watts is being lost, mainly in the area above the insulation. It is interesting to see if the students understand this.

At this point the temperature profile can be plotted (similar to figure 8). It might also be interesting to determine what the thermal interface resistance is for this case. Using equation 3:

$$\text{Thermal interface resistance} = 1.013 \text{ W}^0\text{C}$$

This would be the end of the calculations for most of the specimens, however, since this sample is made of the same material as the heater section it is possible to extend these calculations to enhance the learning experience. The thermal conductivities should be the same for each part, but there is a calculated difference (180 vs. 185.6). If the conductivity of the test specimen were the same as the heater section, the heat flow through the test specimen would be 12.0 watts, not 12.34 watts. This is a 4.2% difference, giving some indication of how much heat is being lost from the insulated portion of the device.

Summary:

The device described in this paper provides a fertile test platform for demonstrations of heat conduction. At the most basic level, students are able to see how thermal conductivity values for unknown materials might be determined. While the test is running there are many teaching opportunities to discuss such issues as transient heat transfer such as why it is not critical to have the sections before the first thermocouple and after the last thermocouple insulated, and thermal interface resistance. The ongoing temperature plots on the computer screen tend to hold the students' interest better than just watching numbers on a meter. Looking at the relationships between the temperature plots on the screen can lead to discussions of how changing various parameters such as materials, heat input, pressure on the interface or cooling water temperature would change the relationships. This can get students to think about the principles involved rather than just record and analyze data.

This device was designed and built by one Mechanical Engineering Technology student during one semester as a senior project. There are many well recognized benefits for a student participating in this type of project. First, the project exposes the student to the difficulties involved in defining real world problems and in meeting important deadlines. At Penn State Behrend, the capstone experience requires the student to formally define the scope and

limitations of the project and to provide a Gantt chart showing the project schedule. Students must work diligently throughout the semester to meet important milestones along the way. This particular project involved the engineering and design work necessary to produce a fully working test device. The student was able to put his design and sketching skills to great use by providing several alternative designs for consideration. Figure 4 shows only the one that was ultimately selected. The student involved in this project was a non-traditional student and had not taken heat transfer for several semesters. This project provided him an opportunity not only to brush up on some heat transfer concepts that he was rusty on, but, according to him, actually taught him several concepts he was not familiar with. At the end of the project he was required to make an oral presentation to several faculty members and other students. This requirement is intended to provide an opportunity to develop oral presentation skills. Overall, this student said that he was very pleased with this experience, and that he learned a lot.

Three copies of the device were produced for a total cost of under \$1000. For more information on the design contact the author by e-mail at rce2@psu.edu.

References:

- [1] Y. Cengel, "Heat and Mass Transfer – A Practical Approach", Third Edition, McGraw Hill, 2007.