AC 1998-278: In Class Thermal Conductivity Experiment for Sophomore Materials Science and Continuum Mechanics Courses

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In Class Thermal Conductivity Experiment for Sophomore Materials Science and Continuum Mechanics Courses

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Introduction

Texas A&M University is part of a National Science Foundation supported program entitled the Foundation Coalition.[1] There are six other educational institutions involved in the coalition. As part of the Texas A&M program, a group of faculty have been working on developing a sophomore engineering science core of courses built on the thrusts of the Foundation Coalition.[2] These are: active learning (teaming and collaborative activities)[3], technology-enabled education, integration of course material, and lifelong learning.

The faculty decided to base the teaching of the program on a previously developed NSF program that stressed the use and application of conservation principles and the second law of thermodynamics.[4] This framework helps in the integration process by enabling students to concentrate on ideas and concepts rather than memorization of equations. The current arrangement at Texas A&M University consists of five courses, and these are listed in Table 1.[5]

Table 1. Arrangement of courses.

Semester	Engineering Area	Course Numbers for 97-98
Fall	Mechanics	ENGR 211
	Thermodynamics	ENGR 212
Spring	Materials	ENGR 213
	Continuum Mechanics	ENGR 214
	Electrical Circuits and Electronics	ENGR 215

As part of the integration, the faculty decided to develop several experiments that can be performed during the class, and can be used to help integrate the courses. The abstract mentions three experiments that are being developed. The first is a 3-point bend experiment that is used to obtain the modulus of elasticity and allows the students to perform an uncertainty analysis. This experiment was reported on at the National Educators Workshop on Experiments in Materials Science: Update 1997, in Seattle, WA.[6] The second involves the determination of the thermal conductivity in a material. The third uses a photo-elastic material, a loading arrangement, and a polarizer to demonstrate the effect of stress concentrations around stress concentrators. This paper will concentrate on the second of the three experiments.

The experiments provide the undergraduate students an opportunity to have hands-on activities. Most of our students have very little experience with equipment, measuring instruments, the process that goes into making a measurement, and being comfortable that the number arrived at is reasonable.

Approach

The development of a thermal conductivity experiment satisfied the integration of the materials (ENGR 213) and the continuum mechanics (ENGR 214) courses. For example in the materials course, students learn about the thermal properties of materials from the atomic viewpoint. Generally, the heat capacity, coefficient of thermal expansion, and the thermal conductivity are discussed.[7] Students are able to describe how and why thermal conduction takes place in metals and insulators as a function of temperature.

The one-dimensional heat conduction equation is used as a means of examining the changes in the thermal conductivity, k of various materials.

$$\frac{\partial Q}{\partial t} = -\mathrm{kA}\frac{\partial T}{\partial x}$$

Q- heat
t- time
k- thermal conductivity
A- cross-sectional area
T- temperature
x- distance

In addition, earlier in the course the students have seen Fick's first law used in discussing solid state diffusion.[8] The idea of a flux and a driving force related to each other by a coefficient should be familiar to the students. Concurrently in the continuum mechanics course, the students arrive at Fourier's one-dimensional equation as a special case of the three-dimensional problem. At this point, the courses couple nicely because the continuum mechanics is talking about smeared out or averaged properties while the materials course is examining the atomic scale, and describing the process of heat conduction in materials.

In addition, the third calculus course, which most of the students are taking, has studied a finite difference method for solving differential equations. This gives the engineering courses an opportunity to integrate with the mathematics, and to try and demonstrate to the students how mathematics can be used as tool in the solution of engineering problems. Using the finite difference method allows the variation temperature as a function of time to be solved for numerically. This additional step will not be discussed further in this paper.

Experiment

Figure 1 (after Bibliography) is a drawing of the thermal conductivity apparatus.[9] The initial setup has two, 2.5 cm diameter aluminum rods in contact. The rods are about 8 cm long and each has four thermocouples inserted into the center of the rods. The thermocouples are 1.5 cm apart, and wrapped around the cylinders before passing out through the insulation. Two electric heaters are inserted into the bottom brass block, which sits on an aluminum plate. The top aluminum plate is air-cooled, and the entire apparatus is insulated to minimize heat losses in the x-y plane. Although, not shown in Figure 1, the support fixture for the experiment consists of four all–thread rods that will allow the two aluminum cylinders to be separated and have a cylinder of unknown material inserted between them.

The equipment required and the costs for the thermal conductivity experiment are listed in Table 2. The individual units cost about $430, and we made six replicas.

Table 2. Components and costs for thermal conductivity experiment.

Item	Cost, $	No.
HH-21 Digital Thermometers	120	1
965A-3CA0-00RG Auto-tuning Control	200	1
Solid State Relay	8	1
Thermocouple wires and jacks	70	8
Metal parts	30	
Total	428	

Procedure

The units are turned on sufficiently far ahead to insure steady state conditions. The students use a digital thermometer to read the temperatures. This is done twice to help them develop a sense of reproducibility in measurements. They are given the k-value for the bottom cylinder, asked to calculate Q, and then using that Q-value to determine the k-value for the top cylinder. The laboratory procedure given to the students is reproduced in Appendix A.

Results

Examples of the data obtained are shown in Figures 2 and 3 for two hot end temperatures of 30°C and 40°C. Tables 3 through 6 show the data collected in the laboratory. Using the procedure for determining the k-value mentioned above, the data shown in Tables 4 and 5 have excellent agreement between the measured and the predicted k-value for aluminum. While for the other two examples, shown in Table 3 and 5, the agreement is not quite as good. The experience to date is that the larger the temperature gradient the better the calculated k will be.

Table 3. Data for 30°C.

	Temperature (C)	Position (cm)	Slope (dT/dx)	q = -k*(dT/dx)	k = -q/(dT/dx)	% Error
Thermocouple 1	30.1	0.0	-0.26000000	61.620000	249.8108108	5.4054054
Thermocouple 2	29.7	1.5				
Thermocouple 3	29.4	3.0				
Thermocouple 4	28.9	4.5				
Thermocouple 5	26.5	7.5	-0.24666667			
Thermocouple 6	26.2	9.0				
Thermocouple 7	25.8	10.5				
Thermocouple 8	25.4	12.0				

Table 4. Data for 30°C, second test.

	Temperature (C)	Position (cm)	Slope (dT/dx)	q = -k*(dT/dx)	k = -q/(dT/dx)	% Error
Thermocouple 1	30.1	0.0	-0.27333333	64.780000	237.0000000	0.000000000
Thermocouple 2	29.8	1.5				
Thermocouple 3	29.3	3.0				
Thermocouple 4	28.9	4.5				
Thermocouple 5	27	7.5	-0.27333333			
Thermocouple 6	26.5	9.0				
Thermocouple 7	26	10.5				
Thermocouple 8	25.8	12.0				

Table 5. Data for 40°C.

	Temperature (C)	Position (cm)	Slope (dT/dx)	q = -k*(dT/dx)	k = -q/(dT/dx)	% Error
Thermocouple 1	40	0.0	-0.44000000	104.280000	240.6461538	1.538461538
Thermocouple 2	39.3	1.5				
Thermocouple 3	38.7	3.0				
Thermocouple 4	38	4.5				
Thermocouple 5	30.9	7.5	-0.43333333			
Thermocouple 6	30.4	9.0				
Thermocouple 7	29.6	10.5				
Thermocouple 8	29	12.0				

Table 6. Data for 40°C, second test.

	Temperature (C)	Position (cm)	Slope (dT/dx)	q = -k*(dT/dx)	k = -q/(dT/dx)	% Error
Thermocouple 1	40	0.0	-0.54666667	129.560000	262.6216216	10.81081081
Thermocouple 2	39.3	1.5				
Thermocouple 3	38.3	3.0				
Thermocouple 4	37.6	4.5				
Thermocouple 5	32.6	7.5	-0.49333333			
Thermocouple 6	31.6	9.0				
Thermocouple 7	31.1	10.5				
Thermocouple 8	30.3	12.0				

Plots of the data listed in Tables 3 and 5 are shown in Figures 2 and 3 (after Bibliography). The difference between the calculated and the known value was 5.4% different for the data from Table 3, and 1.5% for the data from Table 5.

Currently, both of the cylinders are aluminum. The students use a given k-value, and determine the Q for the bottom cylinder, and then from that known Q, they can calculate the thermal conductivity of the top cylinder. The experiment will be used for the first time during the spring 98 semester, and results will be discussed during the conference.

In the design of the apparatus, we intended for the students to be able to ask what if questions. For example, the setup allows another material to be placed between the current aluminum cylindrical rods, and its thermal conductivity measured. The contact conductance may also be obtained, and the effect of pressure on the contact conductance may be determined. In addition, since the current classroom has an instructor's computer a data acquisition card for thermocouples is being purchased for connecting the setup to the instructor's machine and the students' will be able to see, in real time, the heating process required to achieve steady state conditions.

Conclusion

A thermal conductivity experiment has been developed as part of a new sophomore engineering program at Texas A&M University. The experiment helps in the integration of a materials science course and a continuum mechanics course. The experiment gives students an opportunity to make physical measurements and interpret the data with respect to the theory they are discussing in the classroom.

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[2] Griffin, R. B., Everett, L. J., Keating, P., Lagoudas, D., Tebeaux, E., Parker, D., Bassichis, W. and Barrow, D., "Planning the Texas A&M University College of Engineering Sophomore Year Integrated Curriculum," <u>Fourth World Conference on Engineering Education</u>, Oct. 95, St Paul, MN, vol. 1 pp. 228-232.
[3] Smith, K. A., "The Craft of Teaching Cooperative Learning: An Active Learning Strategy," 1989 Frontiers in Education Conference, ASEE, PP 188-192, 1989.
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[6] R. B. Griffin and L. R. Cornwell, "MeasurementOf the Modulus of Elasticity Using a Three-Point Bend Test," Conference, Seattle, WA, Oct. 1997.
[7] J. P. Schaffer, and et al., "The Science and Design of Engineering Materials," Chap. 13, 1^{st} ed. revised, Irwin, Chicago, 1995.
[8] D. R. Askeland, "The Science and Engineering of Materials," 3^{rd} ed., PWS Publishing Co., Boston, MA, 1994.
[9] S. C. Lau, MEEN 464 Heat Transfer Laboratory, Mechanical Engineering, Texas A&M University, 1997.

Figure 1. Schematic of thermal conductivity apparatus.

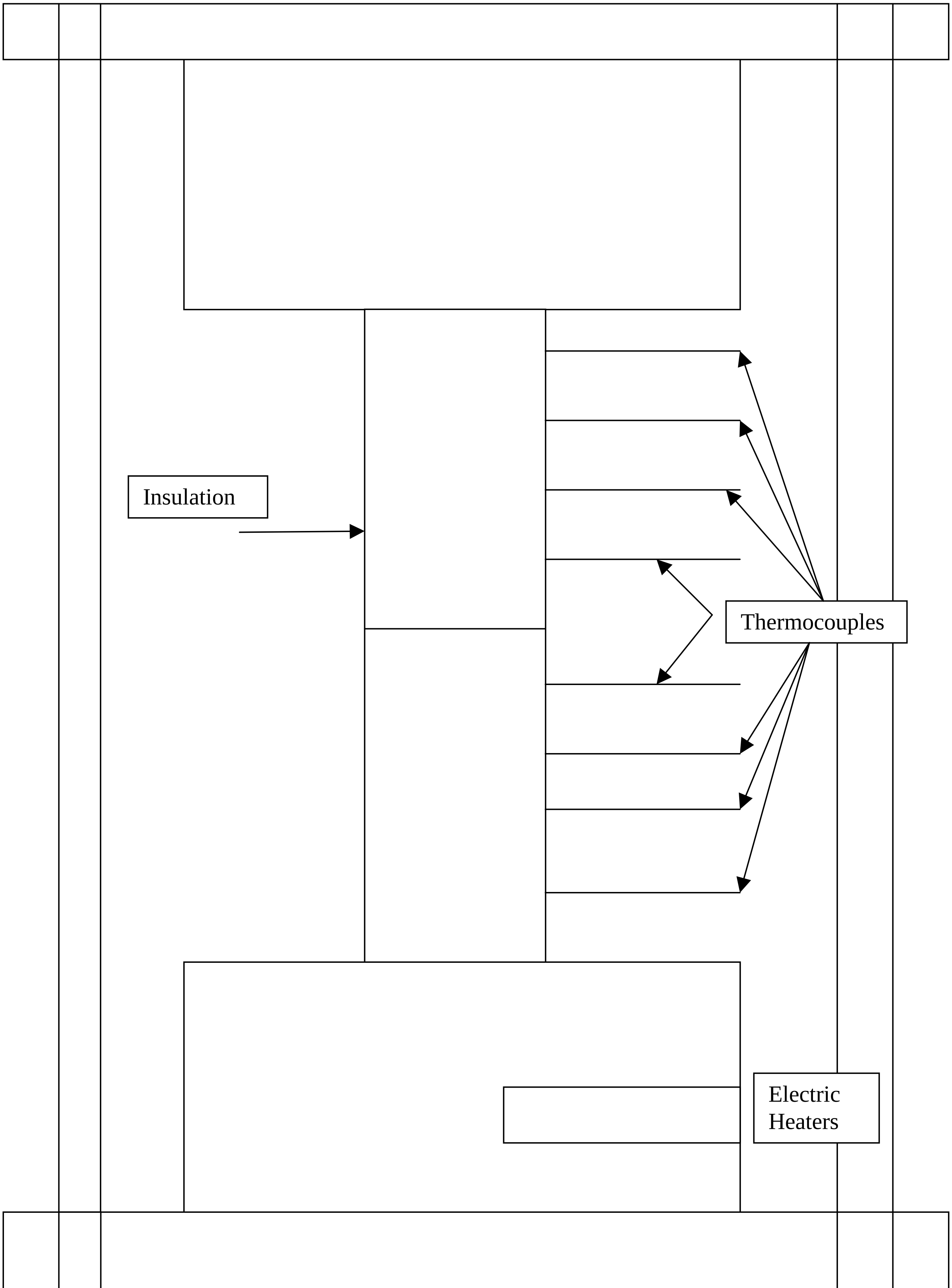


Figure 2. Temperature versus position for the data shown in Table 3.

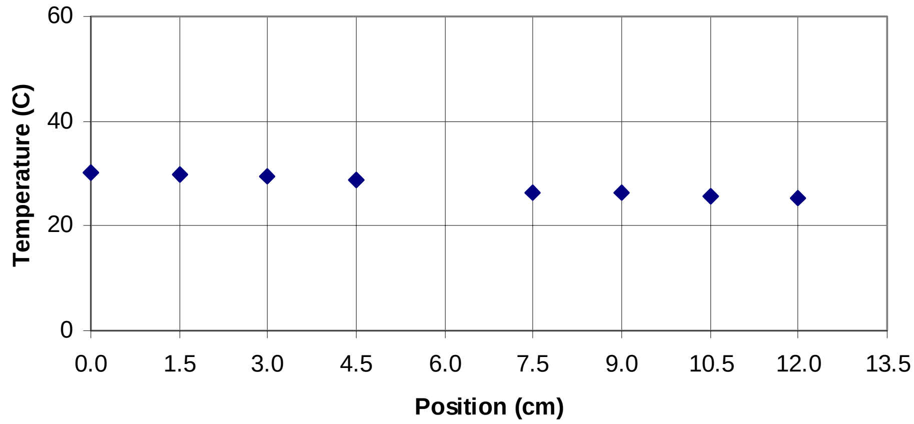
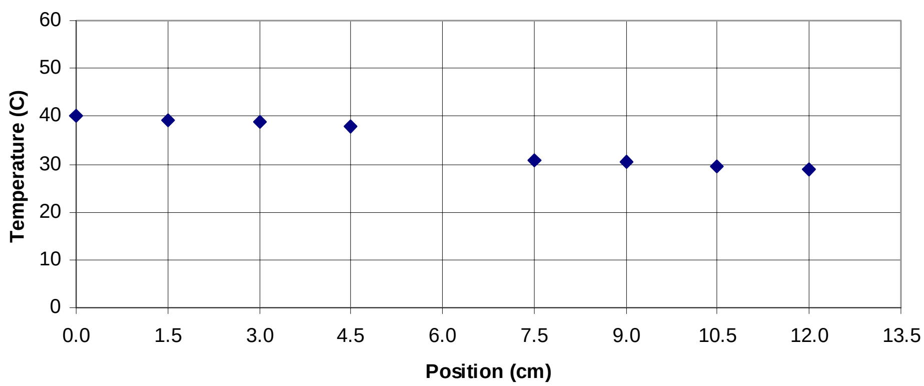


Figure 3. Temperature versus position for the data shown in Table 5.



DR. RICHARD B. GRIFFIN has been at Texas A&M University in the Department of Mechanical Engineering since 1977. He has taught materials related courses, and specialized in aqueous corrosion. For the past four years, he has been part of the NSF sponsored Foundation Coalition at A&M and Co-Team Leader for the Sophomore Year.

DR. DIMITRIS LAGOUDAS is a member of the Department of Aerospace Engineering at Texas A&M University. His teaching interests have been in mechanics, and his research interests are in the area of smart materials. He is part of the NSF Foundation Coalition and is Co-Team Leader for the Sophomore Year.

PRIYA RAGUPATHI was a graduate student (MS) in mechanical engineering. She twice helped as a teaching assistant in the NSF sponsored program. Currently, she works for Schlumberger in Houston, TX.

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ERIC JOHNSON is an undergraduate student in mechanical engineering at Texas A&M University.

Appendix A

EXPERIMENT: TO MEASURE THE THERMAL CONDUCTIVITY OF ALUMINUM

OBJECTIVE:

To demonstrate Fourier's Law of Conduction and how the value of thermal conductivity of a solid material may be determined.

DESCRIPTION:

The test apparatus consists of two coaxial vertical rods, one of aluminum and the other unknown. The end of the bottom rod is inside a brass block, which contains a heater equipped with a thermostat that controls the power input to the heater to maintain the set temperature. Thermocouples are installed along the centerline of each of the rod segments to give the axial temperature distribution. The test apparatus is insulated to maintain 1-D heat flow minimizing heat loss.

THEORY:

Heat is conducted by electrons and phonons from regions with higher temperature to those with lower temperature. Higher molecular kinetic energies correspond to temperatures. In the presence of a temperature gradient, heat must be transferred by conduction in the direction of decreasing temperature (application of Second Law of Thermodynamics). The rate at which heat is conducted through a material is characterized by the temperature gradient and the thermal conductivity of the material. Fourier's law states that:

$$\frac{\partial Q}{\partial t} = -\mathrm{kA}\frac{\partial T}{\partial x}$$

where **k** is the thermal conductivity, **Q** is the heat, **T** is the temperature along the x-axis, x is the position, and **A** is the cross-sectional heat transfer area.

In this experiment, the axial heat flux along each of the two rods may be determined using the thermal conductivity of one rod and the temperature gradient based on the temperatures in that rod. The value of the thermal conductivity of the other segment of each rod is then evaluated by using the Q-value determined above and substituting into the 1-D heat transfer equation along with the slope you measure, and then calculating a new k-value. In this experiment, the value of thermal conductivity for aluminum is 237 W/m-K.

PROCEDURE:

1. Record the temperatures along the two rods. Wait 10 minutes and repeat.

RESULTS:

1. Plot temperature vs. position.
2. Calculate **Q** for the bottom rod.
3. Calculate **k** for the top rod.
4. Compare the **given k** to the **calculated k**.

TRIAL 1:

	Temperature (C)	Position (cm)	Slope (dT/dx)	Q = -k*(dT/dx)	k = -Q/(dT/dx)
Thermocouple 1		0.0			
Thermocouple 2		1.5			
Thermocouple 3		3.0			
Thermocouple 4		4.5			
Thermocouple 5		7.5			
Thermocouple 6		9.0			
Thermocouple 7		10.5			
Thermocouple 8		12.0			

TRIAL 2:

	Temperature (C)	Position (cm)	Slope (dT/dx)	Q = -k*(dT/dx)	k = -Q*(dT/dx)
Thermocouple 1		0.0			
Thermocouple 2		1.5			
Thermocouple 3		3.0			
Thermocouple 4		4.5			
Thermocouple 5		7.5			
Thermocouple 6		9.0			
Thermocouple 7		10.5			
Thermocouple 8		12.0			

REPORTING PROCESS

1. Explain any difference in values between observed and given values.
2. Discuss any heat losses in the system.
3. Explain the temperature drop across the two bars.
   -What happens at the interface?
4. Check the units in the heat flux equation, and give the units for dQ/dt/A and k.
5. Include the plot of dT/dX.
6. Be sure to show your calculations.
7. Explain how the thermocouples measure temperature.
8. Think of another experiment that you might be able to suggest using the equipment you used today.