Laboratory/Demonstration Experiments in Heat Transfer: Thermal Conductivity and Absorptivity Measurement

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Abstract

One excellent method for reinforcing course content is to involve students in laboratory exercises or demonstrations which are designed to compare experimental data with data and/or correlations from the literature. As part of the requirements for CHEG 3143, Heat Transport, and CHEG 3232, Laboratory II, junior level chemical engineering students were required to perform simple heat transfer experiments using inexpensive materials that are readily available in most engineering departments. The design, implementation and analysis of two of these experiments are described in this presentation.

The thermal conductivities of polycarbonate, polystyrene and plywood were individually determined by sandwiching the test material between three 1 ½ in x 12 in x 18 in aluminum plates. After the center plate was heated to 70-80°C, the “sandwich” was assembled and insulated on all sides. The temperatures of the center plate and one of the outer plates were measured with time and used to calculate the rate of heat transfer and then the thermal conductivity. Finally, the experimental thermal conductivities were compared to values from the literature.

Radiative absorptivities were obtained for five metallic surfaces with different surface finishes in comparison to a matte black paint surface finish as the control. Metallic rods were first cooled to <18°C prior to inserting a thermocouple into the center end of the rod and then insulating the ends. A 1000W lamp was used to heat the rods while monitoring the temperature inside the rod as a function of time. Heat balances were then used to determine the surface absorptivity relative to the black matte finish. Finally, the experimental absorption coefficients were compared to values from the literature.

Introduction

A number of methods have been developed for reinforcing course content in order to enhance student learning including multimedia enhancement[1,2], active, problem-based learning[3], collaborative learning[4,5], and participation in cooperative education[6]. Another excellent method for reinforcing course content is to actively involve students in laboratory exercises or demonstrations which are designed to compare their experimental data with data or correlations from the literature. Hunkeler and Sharp[7] found that 42% of students in senior laboratory over a four year period were Type 3 learners, who are action-oriented "hands-on", common sense learners. This exercise has several benefits:

- It provides an opportunity for students to have additional "hands-on" experience;
- It demonstrates a physical application of the data or correlation; and,
- It helps to develop an appreciation for the limitations of the data or correlations.

As part of the combined requirements for CHEG 3143, Heat Transport, and CHEG 3232, Laboratory II, junior level chemical engineering students at the University of Arkansas were required to perform simple heat transfer experiments or demonstrations using inexpensive materials that are readily available in most engineering departments. The design, implementation and analysis of two of these experiments, a determination of the thermal conductivities of polycarbonate, polystyrene and plywood and a determination of the radiative absorptivities of five metallic surfaces with different finishes are described below.

Thermal Conductivity of Sheet and Granular Materials

Objective

Thermal conductivity is a quantitative measure of the ability of a material to conduct heat according to Fourier's law. Thermal conductivity varies from a low value of 0.026 W/m·°C for rigid foam urethane to 2,300 W/m·°C for diamond. In this experiment, a simple, inexpensive transient method was used for determining the thermal conductivity of low conductivity solid and granular materials. The objectives of this experiment were to:

1. Determine the thermal conductivities of various sheet materials, and
2. Compare the experimental thermal conductivities to literature values.

No attempts were made to include contact resistance due to air gaps and surface irregularities, which should be of relatively minor concern.

Experimental Equipment List

- Three mill finish aluminum plates (18 in x 12 in x 1½ in)
- Two Omega Model HH12 thermocouple readers

- Two 1/8 in dia x 12 in long sheathed thermocouples
- One Hair dryer (Hartman Protec Model 1600)
- One insulated (1/2 in Styrofoam®) heating box (23 in x 20 in x 13 in)
- Two Plexiglass® sheets (18 in x 12 in x 1/8 in)
- Two polystyrene foam sheets (18 in x 12 in x 9/40 in)
- Two plywood sheets (18 in x 12 in x 7/16 in)
- Insulation sheets of ½ in thick Styrofoam®
- One stopwatch

Experimental Procedure

The experimental apparatus is shown in the schematics of Figures 1 and 2 and the photographs of Figures 3 and 4.

Setup

1. Remove the heating box lid.
2. Place one aluminum plate in the heating box and replace the lid.
3. Insert the sheathed thermocouple into the aluminum plate.
4. Place the hair dryer in the hole on the top of the box and turn on the dryer to high speed.
5. While the plate is heating, place a layer of insulation on a table at room temperature.
6. On top of the insulation, place one of the room temperature aluminum plates.
7. Place a sheet of test material (plywood, Plexiglass®, polystyrene) on top of the aluminum plate so that the edges line up with the plate.
8. When the aluminum plate in the insulated box has reached a temperature of approximately 150°F, turn off the hair dryer, remove the box cover, and remove the hot plate from the heating box using gloved hands.
9. Place the heated aluminum plate (the second aluminum plate) onto the test sheet.
10. Quickly place a second sheet of test material on top of the hot aluminum plate.
11. Place the third and final room temperature aluminum sheet on top of the test material.
12. Place a layer of insulation on top of the uppermost aluminum plate.
13. Place insulation around the edges of the test sandwich.
14. Insert one sheathed thermocouple into the opening on the side of the hot center aluminum plate and another sheathed thermocouple into either the top or bottom room temperature plates.

Testing

1. Start the stopwatch when the sheathed thermocouples are placed in their

respective aluminum plates.

2. Record the plate temperatures with time, at 1°C increments of temperature, until the center plate has reached a temperature of 30°C.

Safety Concerns

1. Wear safety glasses at all times.
2. Be very careful when handling the aluminum plates since they each weigh 50 lb (14.35 kg), and can break bones if dropped.
3. Always wear gloves when handling the hot aluminum plates.

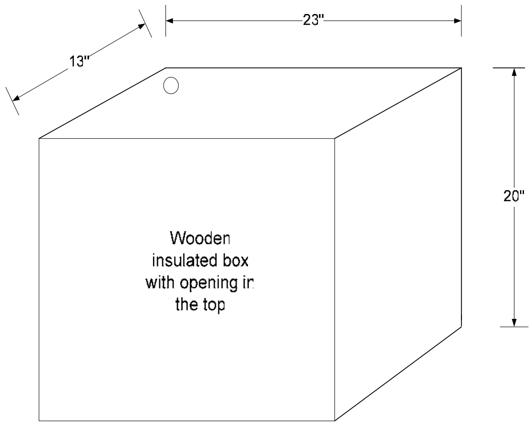

Figure 1. Insulated Wooden Box for Heating Aluminum Plate

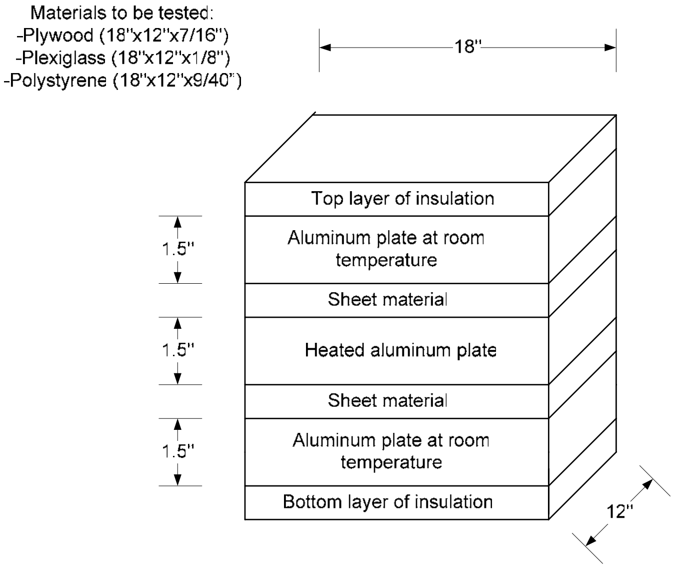

Figure 2. Schematic of Test Arrangement for the Plates and Test Materials

Figure 3. Photograph of Wooden Box used to Heat Aluminum Plate

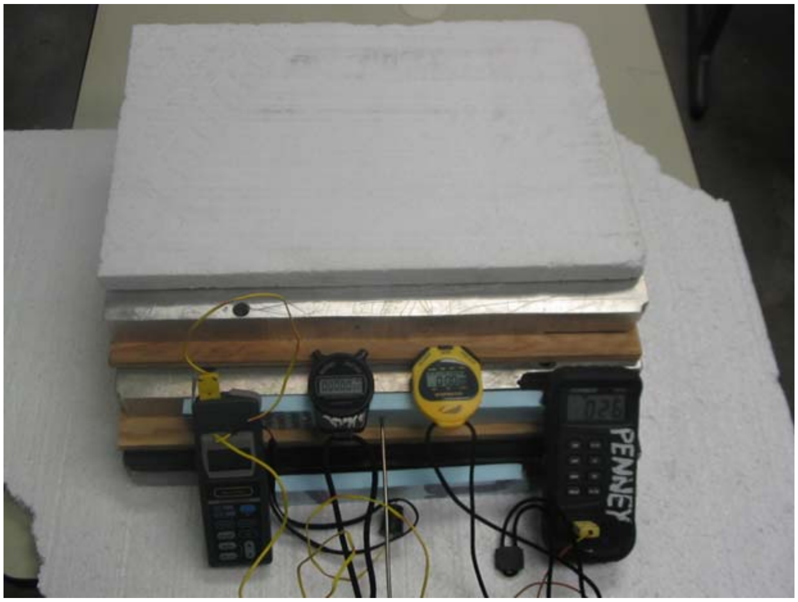

Figure 4. Photograph of Thermal Conductivity Apparatus Setup

Data Reduction

1. A heat balance on the center plate, with no heat generation within the plate, yields:

   $$-q_{out} = q_{acc} \tag{1}$$

2. The accumulation term for an individual aluminum plate is given by:

   $$q_{acc} = m\,Cp\frac{dT}{dt} \tag{2}$$

   and the heat transferred by conduction through the test specimens from the center to the outer plates is given by:

   $$-q_{out} = q_{cond} = -2kA\frac{\Delta T}{\Delta x} \tag{3}$$

3. Substituting Equations 2 and 3 into Equation 1, and solving for the temporal change of temperature with time for the center plate gives:

   $$\frac{dT_c}{dt} = \frac{-2kA\frac{\Delta T}{\Delta x}}{m_c C_p} \tag{4}$$

4. Analogous equations, which are identical because of symmetry, are written for the two outer plates, giving three differential equations.

5. The differential equations were inputted into a TK Solver 4th order Runga-Kutta routine for solving ordinary differential equations. Any other integration software could be used.
6. Using a known (literature) value of *k*, the transient temperatures of all plates were determined and the predicted temperatures were plotted vs. time.
7. The experimental data were inputted into the TK Solver data reduction program and were plotted on the same plot as the predicted temperatures.
8. The thermal conductivity, *k*, in the model was varied until the TK model predicted the best visual fit to the experimental data.

Comparison of Experimental Results with Values from the Literature

The temperatures recorded from the aluminum plates for each sheet materials tested are shown in Table 1. As an example of the procedure used to estimate the thermal conductivity, Figure 5 presents a transient plot of temperature as a function of time for the plywood sheet. The data points represent the experimental data from Table 1 and the curves show the best fit of model using a thermal conductivity of 0.12 W/m·°C.

Table 1. Experimental Temperatures Recorded from the Aluminum Plates

Plywood			Plexiglass®			Polystyrene Foam		
Time, sec	T_c, °C	T_o, °C	Time, sec	T_c, °C	T_o, °C	Time, sec	T_c, °C	T_o, °C
0	64.8	24	0	45.3	33	0	43.9	34
65	64		18	44		811	43	
120		25	84	43		1036		35
174	63		115		34	1692	42	
292	62		159	42		2701	41	
413		26	245	41				
424	61		298		35			
560	60		345	40				
702	59		467	39				
709		27	580		36			
854	58		627	38				
1010	57		845	37				
1050		28	1200	36				
1174	57							

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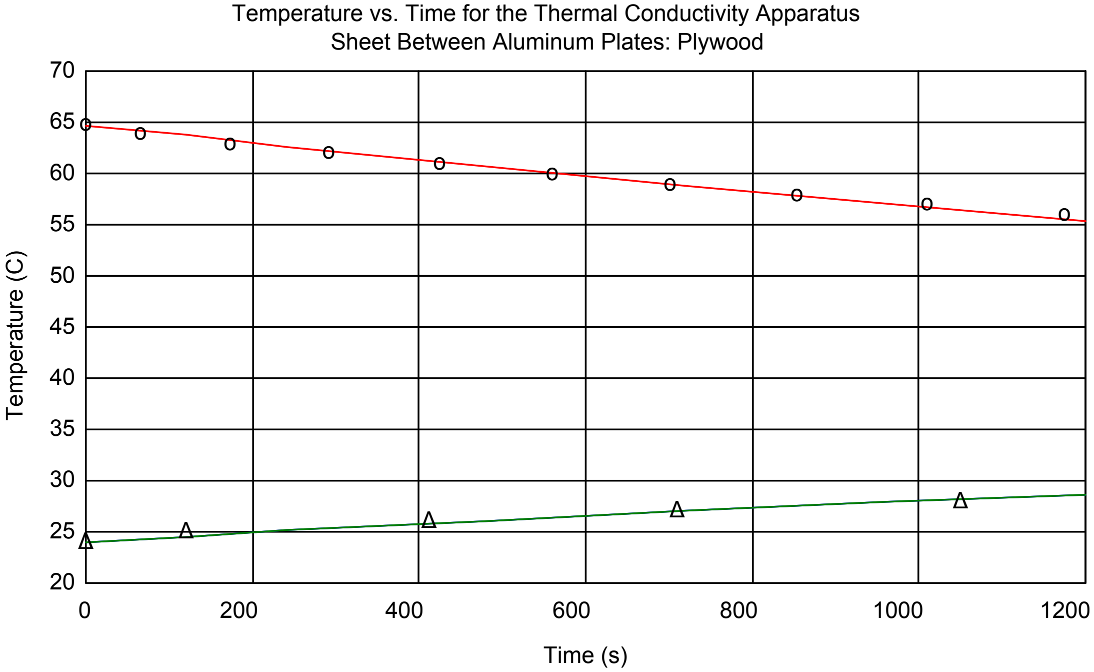

Figure 5. Transient Plate Temperatures with Plywood ($k = 0.12$ W/m·°C)
[Legend: Δ – outer plate; o – center plate; Lines – model predictions]

This procedure was repeated for the Plexiglass® and polystyrene foam test specimens.

Table 2 presents a comparison of the calculated experimental thermal conductivities and the literature values, as obtained from Cengel[8]. Very small errors (0-2.5%) were obtained for plywood and polystyrene, while the error for the Plexiglass® sheet was significantly larger but still reasonable. These errors demonstrate that this transient technique is best suited for materials of low thermal conductivity (< 0.19 W/m·°C), for which the plate temperatures do not decrease rapidly.

Table 2. Comparison of Calculated Experimental Thermal Conductivities and Literature Values for Plywood, Plexiglass® and Polystyrene

	k, W/m·°C		
Material	Experimental	Literature[8]	% Error
Plywood	0.12	0.12	0
Plexiglass®	0.24	0.19	26.3
Polystyrene Foam	0.039	0.04	2.5

Radiative Absorptivity of Metallic Surfaces

Introduction and Objective

The radiative absorptivity is defined as the fraction of incident irradiation absorbed by a surface. Dewitt and Touloukian[9] note that the radiative absorptivity: (1) is influenced by the "topographical, chemical and physical (structural) characteristics of the metallic surface", (2) is one of "the most important influences on the radiative properties arising from surface roughness and films (oxide growth)", (3) "the literature abounds with examples of test surfaces shown to be very sensitive to methods of preparation, thermal history, and environmental conditions," and (4) is "considerably dependent upon the energy spectrum". Thus, one does not expect to obtain good agreement with literature values for radiative absoprtivity experiments. The objective of this investigation was to experimentally determine the surface absorptivity of five metal surfaces relative to a matte black painted surface:

- A flat aluminum surface with a mill finish,
- A cylindrical aluminum surface with a mill finish,
- A cylindrical brass surface with mill finish,
- A cylindrical brass surface with an aluminum paint coating, and
- A cylindrical aluminum surface with a mechanically polished finish

Absoprtion of radiative heat from a quartz lamp by each test specimen was compared with absorption by the same test specimen painted matte black.

Experimental Equipment List

- One Craftsman heat lamp with 1000W and 500W settings.
- One Omega 1/8 in dia by 12 in long sheathed thermocouples.
- One Omega Model HH12 thermocouple reader.
- One stopwatch.
- A 'U' shaped wooden support frame (see Fig. 7). The vertical 2 in x 6 in supports are slotted to receive the 1/8 in sheathed thermocouple and the 1/8 in support rod.
- One 12 quart foam cooler, partially filled with ice cubes.
- One brass cylinder (3/4 in dia x 8 1/8 in long), mill finish.
- One brass cylinder (3/4 in dia x 8 1/8 in long), painted matte black.
- One brass cylinder (1 in dia x 8 1/8 in long), painted matte black.
- One brass cylinder (1 in dia x 8 1/8 in long), painted with aluminum paint.
- One aluminum cylinder (1 in dia x 8 1/8 in long), mill finish.
- One aluminum cylinder (1 in dia x 8 1/8 in long), polished.
- One aluminum rod (1 in x 1 ½ in x 8 3/16 in), with a mill finish side and a matte black painted side.
- Two ½ in thick Styrofoam® insulators for the ends of the test specimens.

Experimental Procedure

The experimental procedure for obtaining absorptivities involved heating each bar or rod *through* room temperature so that convective and radiative heat transfer to the surroundings were zero when the specimen passed through room temperatuare. Test materials of different sizes and shapes were used, along with a matte black version of the test material, to obtain the ratios of the absorptivities. The following procedure was used:

1. Cool the rods and bar (inside dry plastic baggies) in the cooler until the temperature is below 18°C.
2. Remove a test specimen from the cooler, insert a sheathed thermocouple and a support rod through ½ in thick Styrofoam® insulating washers and into the center drilled holes in opposite ends of the test specimen.
3. Rest the thermocouple sheath and the support rod into the notches in the upper ends of the 2 in x 6 in vertical support members.
4. Align the light so that it shines directly onto the test specimen.
5. Turn on the light.
6. Start the stopwatch before the specimen reaches 18°C, and record the time at each 1°C increment of temperature, to a final temperature of 30°C.

A schematic of the experimental apparatus is shown in Figure 6, and a photograph of the apparatus is shown in Figure 7.

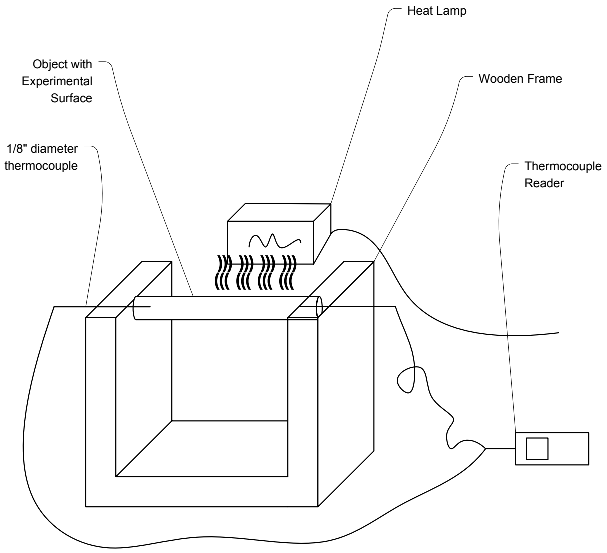

Figure 6. Schematic of Experimental Apparatus

Figure 7. Photograph of Experimental Apparatus

Safety Concerns

1. Wear safety glasses at all times.
2. Do not look directly into the lamp.
3. Do not place naked hand directly in front of the lamp.
4. Do not shine the lamp directly upon any object at short range.

Data Reduction

1. Prepare a plot of temperature, T, as a function of time, t, for each of the specimens tested. Determine the slope of the T vs. t curve when the specimen passes through room temperature. This determination is done at room temperature to eliminate convection and radiation to/from the surroundings.
2. A heat balance on the matte black specimen, at room temperature, yields:

$$\alpha_{\text{matte}}\ q_L'' A = m_{matte}\ C_{p,\text{matte}}(dT_{\text{matte}}/dt) \quad (5)$$

   where $\alpha_{\text{matte}} \approx 1$[8].

3. Similarly, a heat balance on the test specimen yields:

$$\alpha_{spec}\ q_L'' A = m_{spec}\ C_p(dT_{spec}/dt) \qquad (6)$$

4. The ratio of Equation 2 to Equation 1 yields the absorptivity of the test specimen:

$$\frac{\alpha_{matte}}{\alpha_{spec}} = \frac{m_{matte} C_{p,matte}\left(\frac{dT}{dt}\right)_{matte}}{mC_{p,spec}\left(\frac{dT}{dt}\right)_{spec}} \qquad (7)$$

If the masses, areas, and specific heats are the same, Equation 7 reduces to:

$$\frac{\alpha_{matte}}{\alpha_{spec}} = \frac{\left(\frac{dT}{dt}\right)_{matte}}{\left(\frac{dT}{dt}\right)_{spec}} \qquad (8)$$

Comparison of Experimental Results with Values from the Literature

The temperatures recorded for the specimens as a function of time are shown in Table 3. A second order polynomial regression was performed on each data set. The derivatives of the appropriate equations, at room temperature, gave the data needed to use Equation (8) to obtain ($\alpha_{matte}/\alpha_{spec}$). With $\alpha_{matte} \approx 1$, α_{spec} was obtained. Table 4 shows a comparison of the calculated experimental absorptivities and the literature values, as obtained from Dewitt and Touloukian[8]. The errors, which ranged from 0-60% for all materials, are acceptable given the scope of this experiment and the difficulty in comparing data that are obtained for different light sources. This difficulty in comparing data is illustrated in the literature values for the absorptivity of polished aluminum, which differ by a factor of 3.5 (0.1-0.35[8]). Thus, the experiment was a success in demonstrating how contrasting material surfaces alter the absorptivity of a substance.

Table 3. Specimen Temperature as a Function of Time ($T_{room} \approx 23$ C)

Painted Matte Black Aluminum Rectangular Prism (1 in x 1 ½ in x 8 3/16 in)

t, sec	*T*, °C	*t,* sec	*T*, °C	*t,* sec	*T*, °C
0	18	128	23	235	28
29	19	151	24	255	29
57	20	172	25	273	30
81	21	193	26		
104	22	215	27		

Painted Matte Black Brass Cylinder (1 in dia x 8 1/8 in long)

t, sec	*T*, °C	*t,* sec	*T*, °C	*t,* sec	*T*, °C
0	18	125	23	234	28
25	19	149	24	255	29
53	20	171	25	274	30
78	21	192	26		
102	22	214	27		

Brass Cylinder with Aluminum Paint (1 in dia x 8 1/8 in long)

t, sec	*T*, °C	*t,* sec	*T*, °C	*t,* sec	*T*, °C
0	18	263	23	493	28
56	19	310	24	538	29
111	20	357	25	580	30
161	21	405	26		
211	22	450	27		

Polished Aluminum Cylinder (1 in dia x 8 1/8 in long)

t, sec	*T*, °C	*t,* sec	*T*, °C	*t,* sec	*T*, °C
0	18	372	23	745	28
74	19	446	24	822	29
150	20	519	25	901	30
221	21	593	26		
300	22	669	27		

Painted Matte Black Brass Cylinder (3/4 in dia x 8 1/8 in long)

t, sec	*T*, °C	*t,* sec	*T*, °C	*t,* sec	*T*, °C
0	18	105	23	198	28
21	19	125	24	215	29
44	20	144	25	231	30
64	21	162	26		
85	22	180	27		

Mill Finish Brass Cylinder (3/4 in dia x 8 1/8 in long)

t, sec	*T*, °C	*t,* sec	*T*, °C	*t,* sec	*T*, °C
0	18	158	23	296	28
33	19	187	24	322	29
68	20	226	25.4	349	30
98	21	242	26		
129	22	270	27		

Mill Finish Aluminum Cylinder (1 in dia x 8 1/8 in long)

t, sec	*T*, °C	*t*, sec	*T*, °C	*t*, sec	*T*, °C
0	18	195	23	378	28
39	19	233	24	415	29
80	20	270	25	451	30
119	21	305	26		
158	22	343	27		

Mill Finish Aluminum Rectangular Prism (1 in x 1 ½ in x 8 3/16 in)

t, sec	*T*, °C	*t*, sec	*T*, °C	*t*, sec	*T*, °C
0	18	298	23	577	28
62	19	356	24	633	29
123	20	412	25	688	30
182	21	466	26		
241	22	523	27		

Table 4. Comparison of Calculated Experimental and Literature Absorptivities

	Absorptivity		
Material	Experimental	Literature	% Error
Brass, painted aluminum	0.39	0.4-0.5[8]	-3 to -28
Polished aluminum	0.22	0.1-0.35[8]	54 to -59
Mill finish al. cylinder	0.50	0.50[9]	0
Mill finish brass	0.66	0.6[8]	9
Mill finish al. bar	0.37	0.50[9]	-35

Conclusions

Two simple experiments were developed for obtaining (1) thermal conductivities of sheet and granular materials and (2) radiative absorptivities of metal surfaces, which help to illustrate some of the concepts taught in undergraduate heat transfer. Very small errors (0-2.5%) in thermal conductivity were obtained for plywood and polystyrene, while the error for the Plexiglass® sheet was significantly larger but still reasonable. These errors demonstrate that this transient technique is best suited for materials of low thermal conductivity (< 0.19 W/m·°C), where the resulting plate temperatures change relatively slowly with time.

Absorptivity errors, which ranged from 0-60% for all materials, are acceptable given the scope of this experiment and the inherent variability of radiative absorptivities properties with surface topographical, chemical and structural characteristics and radiation energy spectrum. All the absorptivity experiments were successful in demonstrating how contrasting material surfaces alter the absorptivity of the surface.

Nomenclature

A	Heat transfer surface area, m²
C_p	Specific heat of test specimen, J/kg·K
k	Thermal conductivity, W/m·ºC
m	Mass of test specimen, kg
q_{acc}	Heat rate accumulated within a control volume, W
q_{cond}	Heat transfer conduction, W
$q_L^{''}$	Radiative heat flux incident on test specimen surface, W/m^2
q_{out}	Heat rate leaving a control volume or surface, W
t	Time, sec
T	Temperature, °C
T_c	Temperature of the center (hot) aluminum plate, °C
T_o	Temperature of the outer (cold) aluminum plate(s), °C
x	Linear dimension, m

Greek Symbols

α_{matte}	Absorptivity of matte black specimen
α_{spec}	Absorptivity of test specimen
ΔT	Temperature difference between center and outside plates

References

1. Ellis, T., 2004, "Animating to Build Higher Cognitive Understanding: A Model for Studying Multimedia Effectiveness in Education," *Journal of Engineering Education*, Vol. 93, No. 1, pp. 59-64.
2. Wise, M., Groom, F.M., 1996, "The Effects of Enriching Classroom Learning with the Systematic Employment of Multimedia" *Education*, Vol. 117, No. 1, pp. 61-69.
3. Grimson, J., 2002, "Re-engineering the Curriculum for the 21st Century," *European Journal of Engineering Education*, Vol. 27, No. 1, pp. 31-37.
4. Bjorklund, S.A., Parente, J.M., Sathianathan, D., 2004, "Effects of Faculty Interaction and Feedback on Gains in Student Skills," *Journal of Engineering Education*, Vol. 93, No. 2, pp. 153-160.
5. Colbeck, C.L., Campbell, S.E., Bjorklund, S.A., 2000, "Grouping in the Dark: What College Students Learn from Group Projects," *Journal of Engineering Education*, Vol. 71, No. 1, pp. 60-83.
6. Blair, B.F., Millea, M., Hammer, J., 2004, "The Impact of Cooperative Education on Academic Performance and Compensation of Engineering Majors," *Journal of Engineering Education*, Vol. 93, No. 4, pp. 333-338.

7. Hunkeler, D., Sharp, J.E., 1997, "Assigning Functional Groups: The Influence of Group Size, Academic Record, Practical Experience, and Learning Style," *Journal of Engineering Education*, Vol. 86, No. 4, pp. 321-332.
8. Cengel, Y.A., 2003, Heat Transfer: A Practical Approach, McGraw-Hill Book Company, New York.
9. Dewitt, D.P., Touloukian, Y.S., 1970, "Thermophysical Properties of Matter," The TPRC Data Series: Thermal Radiative Properties of Metallic Elements and Alloys, IFI/Plenum, New York.

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Mr. Marrs, Ms. Park, Mr. Scalia and Mr. Weston are junior-level chemical engineering students at the University of Arkansas. All four students participated with their classmates (in groups of two) in performing experimental exercises as part of the requirements for CHEG 3143, Heat Transport, and CHEG 3232, Laboratory II.