Laboratory/Demonstration Experiments in Heat Transfer: Free Convection

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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 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 three of these experiments are described in this paper.

Experimental free convection heat transfer coefficients were determined from hot upward-facing horizontal plates, hot vertical plates and the cylindrical bulbs on mercury-in-glass thermometers. In each case, the preheated object was allowed to cool in ambient room air or in a hood, while recording temperature as a function of time. The experimental heat transfer correlations were then determined by numerically integrating the heat balance using a 4th order Runga-Kutta integration, while varying the correlation coefficients to give the best fit to the experimental data. Finally, the experimental correlations were compared to literature correlations.

The literature correlations were multiplied by a constant factor to obtain the best fit of the experimental data. For the geometries tested, the experimentally determined multiplying factors were:

GEOMETRY	MULTIPLYING FACTOR (h_{exp}/h_{theory})
1. Cooling, Upward-Facing Horizontal Plate	1.4
2. Cooling Vertical Plate	1.0
3. 4.1 mm Cooling Mercury-in-glass Thermometer Bulb	1.8
4. 6 mm Cooling Mercury-in-glass Thermometer Bulb	2.2

Unavoidable forced convection (with limited resources) caused the correction factors to be > 1 for the horizontal plate and the horizontal mercury-in-glass thermometer. Any effect of forced convection on the vertical plate was offset by a lowering of the convection coefficient, since the lower edge of the plate was close to a horizontal table top, and this retarded the free convection flows relative to an isolated vertical plate suspended in a very large room.

Introduction

A number of methods have been developed for enhancing student learning including multimedia developments[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, that is, "kinesthetic" or "tactile" learners.

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 three free convection experiments (the cooling of an upward-facing plate, the cooling of a vertical plate and the cooling of a horizontal cylinder) are described below. This exercise has several benefits:

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

Experiment 1. Free Convection Heat Transfer from an Upward Facing Horizontal Plate

Objective

Free convection heat transfer is encountered in many practical applications, including heat transfer from pipes, transmission lines, baseboard heaters and steam radiators. Correlations are available for predicting free convection heat transfer coefficients from many different geometries. One of the important geometries is the upward facing horizontal heated surface or plate, the subject of this investigation. The objectives of this experiment were to:

1. Determine the experimental free convection heat transfer coefficient for the top surface of a horizontal hot plate exposed to air, and
2. Compare these results with results generated from the appropriate correlation of Churchill and Chu[8].

Experimental Equipment List

- Hartman Pro-Tech Model 1600 hair dryer, 1600 watts
- 25 ¼ in x 22 in x 16 in cardboard heating box, used for heating the plates
- 1 3/16 in thick Styrofoam® insulation, lining the cardboard box

- Wooden stand to hold and elevate the aluminum plate
- 18 in x 12 in x 1 ½ in aluminum plate, with a black painted finish
- Omega HH12 thermocouple reader
- 1/8 in diameter x 12 in long sheathed thermocouples
- Stopwatch, graduated in 0.01 s time intervals
- 1 3/16 in thick Styrofoam® sheet insulation

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. Determine the weight of the aluminum plate and the surface area of the 12 in x 18 in face of the plate.
2. Make sure the air conditioning systems and fume hoods are off to isolate the apparatus from room air disturbances.
3. After placing the aluminum plate inside the insulated heating box, place the nozzle of the hair dryer into the hole in the lid, and heat the plate to ~150°F.
4. Using insulated gloves, set the aluminum plate on a sheet of Styrofoam® insulation, and wrap the two 12 in x 1 ½ in and two 18 in x 1 ½ faces with insulation as well
5. Connect the sheathed thermocouples to the thermocouple reader and insert them into the plate.

Testing

1. Start the stopwatch as soon as the temperature changes 1°C from its original temperature.
2. Record the time at each successive 1°C change in temperature.
3. Repeat the experiment as necessary.

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 cause serious foot injury if dropped.
3. Always wear heat resistant gloves when handling the hot aluminum plates.
4. Avoid standing in water when working with electrical appliances.

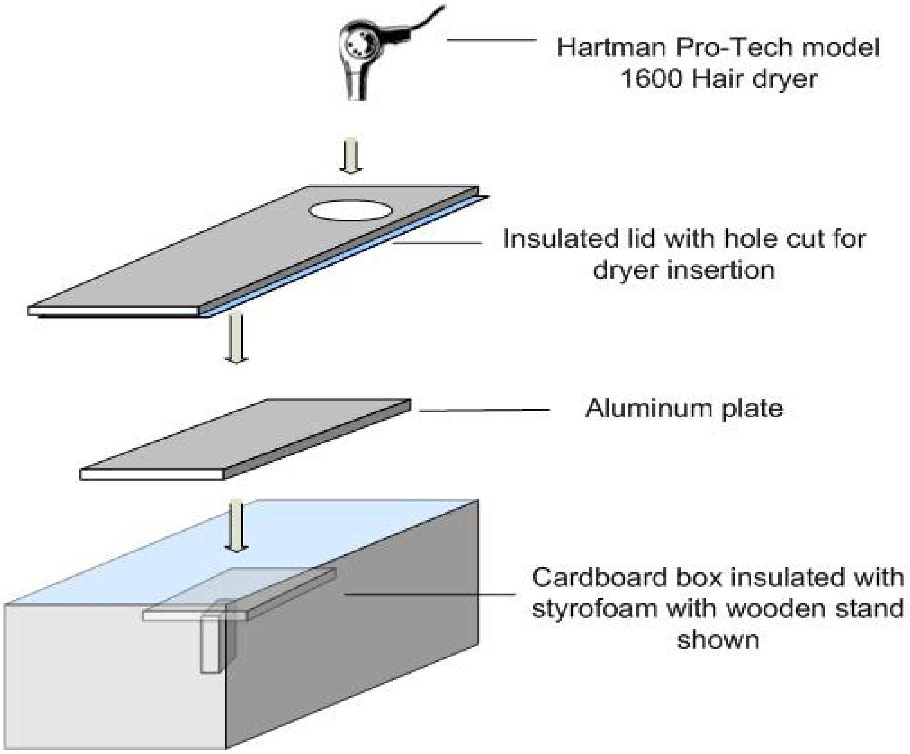

Figure 1. Insulated Wooden Box for Heating the Aluminum Plate

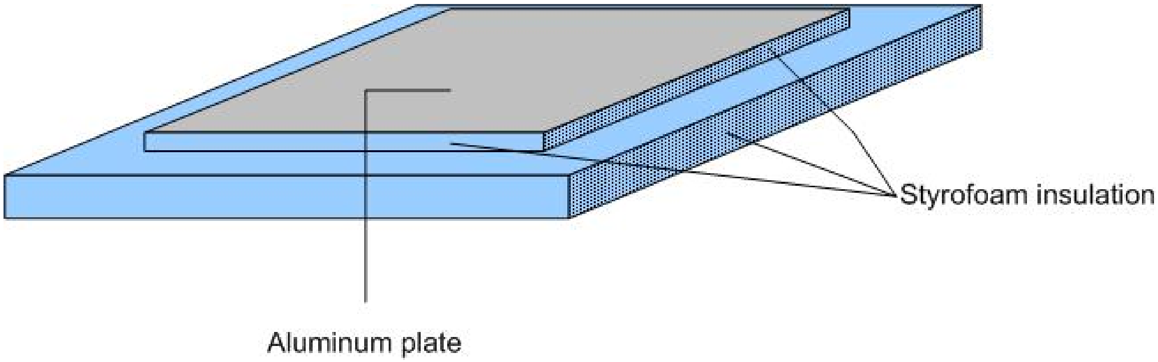

Figure 2. Experimental Setup for Cooling the Horizontal Insulated Plate

Figure 3. Photograph of Wooden Box used to Heat the Aluminum Plate (note—the lid is open)

Figure 4. Photograph of Apparatus for Cooling the Insulated Horizontal Plate

Data Reduction

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

$$-q_{OUT} = q_{ACC} \tag{1}$$

2. The plate is cooled by free convection and radiation as follows:

$$q_{OUT} = q_{CONV} + q_{RAD} = hA_S(T_{SURFACE} - T_\infty) + \varepsilon\sigma A_S(T_{SURFACE}^4 - T_\infty^4) \tag{2}$$

3. The plate accumulates heat with an inverse relationship to time as it cools back to room-temperature:

$$q_{ACC} = m(C_p)\frac{dT}{dt} = \rho V(C_p)\frac{dT}{dt} \tag{3}$$

4. Thus, the heat balance of Equation 1 becomes:

$$-\left(hA_S(T_{SURFACE} - T_\infty) + \varepsilon\sigma A_S(T_{SURFACE}^4 - T_\infty^4)\right) = \rho V(C_P)\frac{dT}{dt} \tag{4}$$

5. Experimental data of temperature vs. time were used to determine the “best fit” experimental heat transfer coefficient by integrating Equation 4 numerically using a TK Solver 4th order Runga-Kutta integration.

6. The heat transfer coefficient from the literature was determined using the correlation for free convection from a horizontal heated, upward-facing plate[8]:

$$Nu = 0.54Ra^{1/4} \qquad 10^4 < Ra < 10^7 \tag{5a}$$

$$Nu = 0.15Ra^{1/4} \qquad 10^7 < Ra < 10^{11} \tag{5b}$$

where the Rayleigh number is calculated as:

$$Ra = \frac{g\beta(T_{SURFACE} - T_\infty)L^3}{\nu^2}\mathbf{Pr} \tag{6}$$

In Equation 6, the length of the plate is the characteristic length in free convection and, for a horizontal flat plate, L = A_S/P. Assuming that the surrounding air is an ideal gas, the volumetric expansion coefficient may be calculated as:

$$\beta = \frac{1}{T} \tag{7}$$

7. Finally, h_{CORR} may be calculated from the Nusselt number as:

$$h_{CORR} = \frac{kNu}{L} \tag{8}$$

8. The experimental coefficient will not agree with the literature correlation since it is extremely difficult to remove all outside interferences and achieve free convection only. Thus, a factor times the theoretical coefficient was used to obtain the best fit of Equation 4 to the experimental data.

Comparison of Experimental Results with Values from the Literature

Figure 5 shows a plot of the experimental temperature as a function of time, as well as a curve showing a numerical integration of Equation 4 using the “best fit” experimental heat transfer coefficient. The emissivity (ε) of the black painted surface was assumed to be 0.98. The experimental heat transfer coefficient was 8 W/m^2K at a surface temperature of 352 K, while the coefficient based on the Churchill/Chu relationship was 5.6 W/m^2K. Thus, a correction factor of 1.4 was needed in order to match the experimental data with the correlation. The need for this correction arises from introduced forced convection. It is very difficult to obtain and keep an ideal, free convection atmosphere due to existing air currents. However, isolating the apparatus in an enclosed space, turning off all air conditioning systems, and preventing any disturbances caused by movement of any kind kept these air currents to a minimum.

Figure 5. Temperature vs. Time Experimental Data (+) and Predicted by Equation 5 Multiplied by a Factor of 1.4 (h_{EXP} = 8 W/m^2K at T_s = 352 K)

Experiment 2. Free Convection Heat Transfer from a Vertical Plate

Objective

Another important geometry for free convection heat transfer is the vertical heated surface or plate, the subject of this investigation. The objectives of this experiment were to:

1. Determine the experimental free convection heat transfer coefficient for the top surface of a vertically oriented hot plate exposed to air, and
2. Compare these results with results generated from the appropriate correlation of Churchill and Chu[8].

Experimental Equipment List/Experimental Procedure/Safety Concerns

With the exception of a plate stand to orient the plate in a vertical fashion, the equipment, procedures and safety concerns were the same as in the previous experiment. It is highly recommended that the base be constructed in a fashion to prevent a tipping hazard. The experimental apparatus is shown in the schematic of Figure 6 and the photograph of Figure 7.

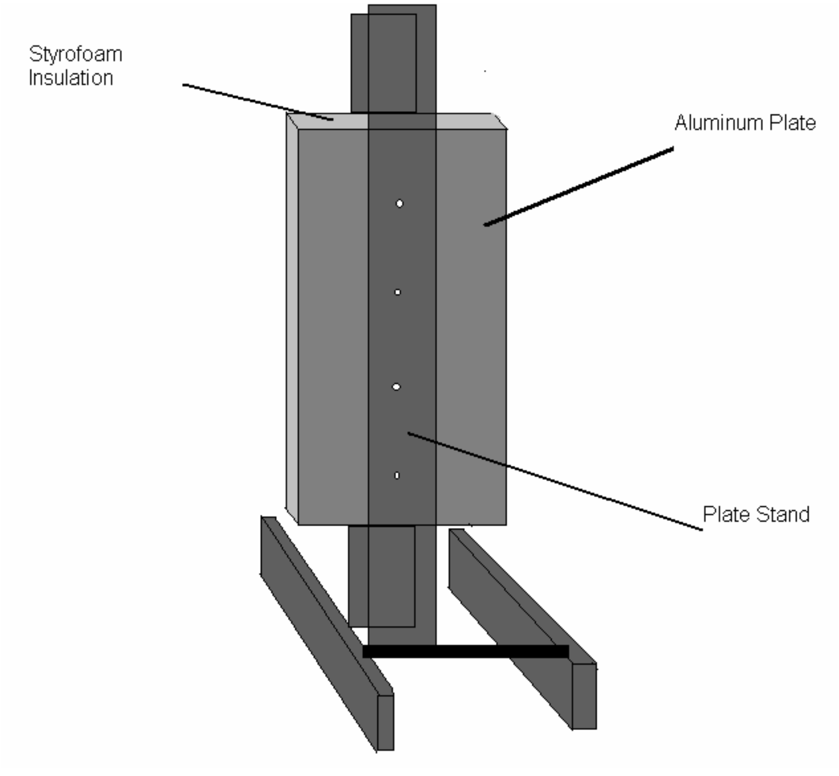

Figure 6. Schematic of Vertical Cooling Apparatus

Figure 7. Photograph of Vertical Cooling Apparatus

Data Reduction

Equations 1-4 were used to model the transient cooling of the plate as in the previous experiment. The heat transfer coefficient from the literature was determined using the Churchill/Chu correlation for free convection from a vertical plate[8]:

$$Nu = \left\{ 0.825 + \frac{0.387\boldsymbol{Ra}^{1/6}}{\left[1 + \left(0.492/\mathrm{Pr}\right)^{9/16}\right]^{8/27}} \right\}^2 \qquad \textbf{(9)}$$

Comparison of Experimental Results with Values from the Literature

Figure 8 shows a plot of the experimental temperature as a function of time, as well as a curve showing a numerical integration of Equation 4 using the "best fit" experimental heat transfer coefficient. The experimental heat transfer coefficient was 4.7 W/m^{2}K at a surface temperature of 324.25 K, and the coefficient based on the Churchill/Chu relationship was also 4.7 W/m^{2}K. Thus, the correction factor needed in order to match the experimental data with the correlation was 1.0. The experiment was carried out in a still storage room that had no air circulation and was completely isolated from traffic. However, the table top on which the experiment was performed retarded heat flow a bit. An emissivity (ε) of 0.5 was assumed based on literature data. Suggestions for improving the experiment are to use polished aluminum plates or aluminum painted surfaces, and to move the plate further from the table surface.

Figure 8. Temperature vs. Time for Cooling of a Vertical Plate: Experimental Data (+)
and Prediction by Equation 9 with a Multiplication Factor of 1
($h_{EXP} = 4.7$ W/m^{2}K, $T_s = 324.25$ K)

Experiment 3. Free Convection Cooling of the Bulb of a Mercury/Glass Column

Objective

Still another geometry for free convection heat transfer is a cylinder, in this case a cylinder of mercury enclosed in a thin glass vessel (a simple mercury-in-glass thermometer). The objectives of this experiment were to:

1. Determine the experimental free convection heat transfer coefficient for two different size cylinders of mercury (two different size thermometers), and
2. Compare these results with results generated from the appropriate correlation of Churchill and Chu[8].

Experimental Equipment List

- Two mercury thermometers, one with a diameter of 6 mm and a length of 1.5 cm and the other with a diameter of 4.1 mm and a length of 1.4 cm
- Hot tap water
- Stop watch, graduated in 0.01 s time intervals

Experimental Procedure

Set up and Testing

1. Record the initial temperatures on the thermometers (room temperature).
2. Heat the thermometers in hot water to a temperature of approximately 70°C.
3. Suspend the thermometers without disturbing them, and allow the thermometers to cool in still, ambient air.
4. Record the temperature as a function of time in 0.5°C increments.

Safety Concerns

1. Wear safety glasses at all times.
2. Be careful not to drop the thermometers, and know the spill clean up procedures for mercury in your facility.
3. Take care in transporting hot water.

Data Reduction

Equations 1-4 were once again used to model the transient cooling of the cylinder. The literature heat transfer coefficient was determined using the Churchill/Chu correlation for free convection from a long horizontal cylinder[8]:

$$Nu = \left\{0.60 + \frac{0.387\boldsymbol{Ra}^{1/6}}{\left[1+\left(0.559/\mathrm{Pr}\right)^{9/16}\right]^{8/27}}\right\}^2 \qquad \textbf{(10)}$$

Comparison of Experimental Results with Values from the Literature

Figures 9 and 10 show plots of the experimental temperatures as a function of time, as well as a curve showing a numerical integration of Equation 4 using the “best fit” experimental heat transfer coefficients. The experimental heat transfer coefficient for the smaller 4.1 mm thermometer at 309.2 K was 10 W/m^2K, while the coefficient based on the Churchill/Chu relationship was 5.6 W/m^2K. The experimental heat transfer coefficient for the larger 6 mm thermometer at 315 K was 9 W/m^2K, while the coefficient based on the Churchill/Chu relationship was 4.1 W/m^2K. Thus, a correction factor of 1.8-2.2 was needed in order to match the experimental data with the correlation. The need for the correction once again arises from introduced forced convection. It is very difficult to obtain and keep an ideal, free convection atmosphere due to existing air currents. However, isolating the apparatus in an enclosed space, turning off all air conditioning systems and fume hoods, and preventing any disturbances caused by movement of any kind kept these air currents to a minimum.

Figure 9. Temperature vs. Time Experimental Data for a 4.1 mm Diameter Mercury/Glass Thermometer Cooling in Ambient Air. The solid line is the Predicted Transient Profile using Equation 10 with a Multiplication Factor = 1.8 and the Experimental Data are indicated as: (+, Experiment 1; o, Experiment 2) (h_{EXP} = 10 W/m^{2}K at T_s = 309.2 K)

Figure 10. Temperature vs. Time Experimental Data for a 6 mm Diameter Mercury/Glass Thermometer Cooling in Ambient Air. The solid line is the Predicted Transient Profile using Equation 10 with a Multiplication Factor = 2.2 and the Experimental Data are indicated as: (+, Experiment 1; o, Experiment 2) ($h_{EXP} = 9$ W/m^{2}K at $T_s = 315$ K)

Conclusions

Three simple free convection heat transfer experiments were developed for determining heat transfer coefficients from an upward-facing, cooling horizontal plate, a cooling vertical plate and a cooling mercury/glass thermometer bulb. In determining the experimental free convection heat transfer coefficient for the top surface of a horizontal hot plate exposed to air, a correction factor of 1.4 was needed in order to match the experimental data with the correlation. The need for this correction arises from introduced forced convection. In determining the experimental free convection heat transfer coefficient for the top surface of a vertically oriented hot plate exposed to air, no correction factor was needed in order to match the experimental data with the correlation; any effects of forced convection were offset by the flow retarding effects of the table on which the vertical plate was mounted. Finally, in determining the experimental free convection heat transfer coefficient for two different size cylinders of mercury (two different size thermometers), a correction factor of 1.8 (for the 4.1 mm bulb) and 2.2 (for the 6 mm bulb) was needed in order to match the experimental data with the correlation. The need for the correction once again arises from introduced forced convection.

Although the effects of these experiments on student learning has not yet been quantified, anecdotally students remarked, *after* the completion of the exercise, that they really learned a lot from these assignments. It is planned to offer this exercise again this fall, at which time the students will be surveyed relative to the value of the exercise.

Nomenclature

A_S	area for convection, m^2
C_p	specific heat of the aluminum plate or cylinder, J/kg K
g	gravitational constant, m/s^2
h	convection heat transfer coefficient, $W/m^2 K$
h_{CORR}	correlated heat transfer coefficient, $W/m^2 K$
h_{EXP}	experimental heat transfer coefficient, $W/m^2 K$
k	fluid thermal conductivity, W/mK
L	length of the plate or cylinder, m
m	mass of the plate or cylinder, kg
Nu	Nusselt number
P	Perimeter of rectangular plate, m
Pr	Prandtl number of the fluid
q_{OUT}	heat transfer out of the system, W
q_{ACC}	heat accumulated in the system, W
q_{CONV}	heat transfer by convection, W
q_{RAD}	heat transfer by radiation, W
Ra	Rayleigh number of the fluid
T_∞	temperature of the surroundings, K
$T_{SURFACE}$	temperature at the surface of the plate or cylinder, K
V	volume of the plate or cylinder, m^3
β	volumetric expansion coefficient, K^{-1}
ε	emissivity of the surface
μ	dynamic viscosity of air, Ns/m^2
ν	kinematic viscosity of air, m^2/s
ρ	density of the aluminum plate or cylinder, kg/m^3
σ	Stefan-Boltzmann constant, W/m^2K^4

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Mr. Colville, Ms. Dunn, Mr. El Qatto, Ms. Hall, Mr. Schulte and Mr. von der Mehden are either current or former 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.