MEEG346 Thermal Laboratory

Laboratory Problem X1 – Heat Transfer from an extended surface Teams A & B

Objective

1. Observe two of the three fundamental modes of heat transfer – conduction and natural convection (radiant excluded for now).
2. Compare measurements to an equation for the temperature distribution developed from basic principles.
3. Determine the surface heat transfer coefficient h.
4. **Design Objective:** Predict surface temperature based on your measurements for other environmental conditions for a company installing marine instruments. Recommend design changes to the rod and rod installation that would lower surface temperature and protect cabling that might contact it.

Design Objective:

With GPS satellites now universal, commercial ships are required to install an automatic identification system (AIS). (www.marinetraffic.com/en/ais) The owners of a cargo ship, believing it to be sailing from the UK to Portland, Oregon, via the summer Arctic route north of Canada, checked AIS. AIS gave its location to be Lat 39.68 N, Long 75.75 W. This was not reasonable, and the owners blamed the new AIS, not the ship captain.

You are an employee of the company who installed the AIS. After long investigation, thermal damage to a ribbon cable is suspected. In particular, in a narrow passage near the ship's engine spaces it was found that instrument wiring was supported overhead using a series of structural rods inserted into a hot wall, bracing a colder insulated bulkhead across the passage. It is hypothesized that these braces became hot enough by conduction to damage a 60 mm wide ribbon cable draped over it. The cable manufacturer specifies a maximum temperature in use of 115 C.

A sample brace rod has been removed and provided to you, instrumented with thermocouples along its length. By experiment you are to determine how hot the surface of this rod will be under varying circumstances.

The ship's engineering officer estimates the hot wall temperature can vary from normal 60 C to 160 C at flank speed, and that the ambient temperature in the passage can be as high as 40 C. Your test equipment is limited for safety to a maximum test temperature of 100 C. You must extrapolate your results to answer the question: Can the rod get hot enough to damage the cable? Based on your measurements and analysis you are make design recommendations for practical changes to the rod that will keep the surface temperature below critical.

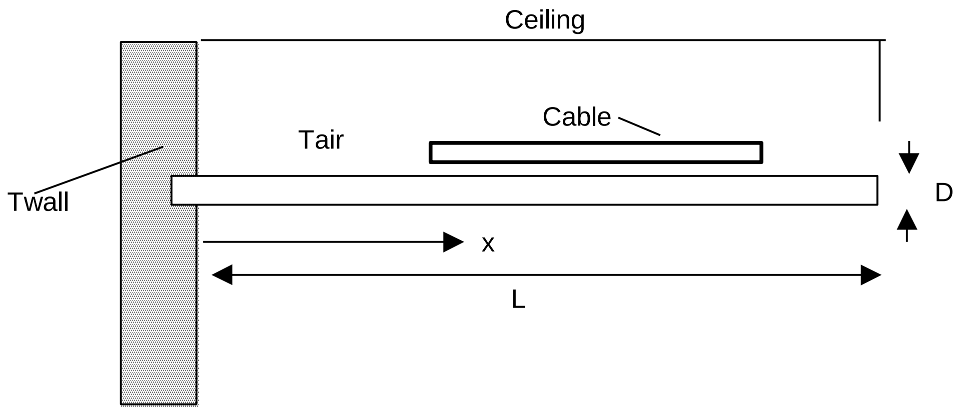

Figure 1 – Rod heated at one end

Theoretical Considerations

This is typical of what is called an "extended surface." A colloquial name is "fin." Fins can take varying shapes in cross section (recall flat fins around the cylinder head on a small air-cooled gasoline engine).

You will be shown during the next weeks in lecture how fins of many shapes are analyzed. A straight fin with circular cross section is one of the simpler examples. In this laboratory exercise, we are simply measuring the temperature and heat transfer performance, and accepting for the moment the theoretical solution.

As shown in Figure 1, the cylindrical rod, made of brass, is heated at its base by an electrical heater simulating the hot engine room wall, and cooled by surrounding air, assumed to be stagnant. So thermal energy is conducted along the rod and convected into the surrounding air. The fin is instrumented with thermocouples along its length to obtain the temperature T as a function of distance x along the fin.

It is possible to relate T(x) to the base temperature Twall, the ambient temperature Tair, fin geometry, material conductivity, and surface heat transfer coefficient h. Each quantity in this relation, except h, can be directly measured or looked up in a handbook (e.g., Table A.1 in your textbook).

The heat transfer coefficient is not a material property, but rather an empirical function of a specific situation. Our goal is to compare the measured distribution with the theoretical one, and thus extract the heat transfer coefficient for this system. (You recall in Fluids Lab finding the C_d of an orifice discharging to make theoretical match actual).

You will study more general and complex correlations for determining h later in your heat transfer lecture course. However, all of them ultimately are the result of careful experiments similar to this one.

One can derive an expression for the temperature profile in the rod from principles found in Chapters 1 and 2 of your heat transfer text. The starting point is the Fourier heat conduction law**, Eqn 1.1 or 2.1 in your text** by Incropera and DeWitt.

$$Q(x) = - k_s A_c \, dT/dx \qquad (1)$$

where Q(x) is the heat conducted through the rod cross section at a point x, A_c is the cross sectional area, and k_s is the thermal conductivity of the rod material.

Convection heat transfer is the mode by which heat is convected from a surface to an ambient fluid, in this case air. The general relationship is given by **Eqn 1.3a in your textbook.**

$$Q_c = hA_s (T_s - T_{air})$$

In this particular case, we might expect the surface temperature T_s to vary with x as heat is convected, so that more formally we should write this expression as a differential.

$$dQ_c = h \, Pdx \, [T(x) - T_{air}] \qquad (2)$$

where dQ_c is the heat convected into the air from a differential rod length of dx, and P is the perimeter of the rod. You can guess that h depends on many factors, including the speed with which the fluid is passing over the rod and physical surroundings. If there is no forced flow, then the heat of the rod induces what is called free convection, where heated air is rising because of buoyancy from differential density. This is the approximate situation in our experiment.

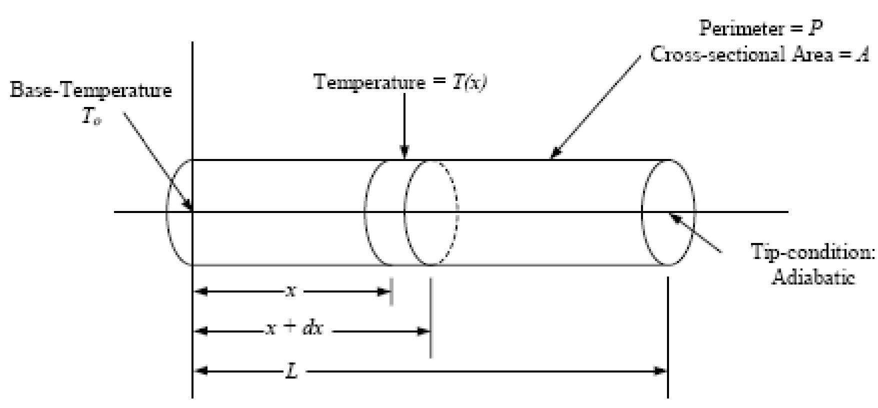

Figure 2: Schematic of heated fin in cross-flow

An energy balance equation can be written using the equations above and differential calculus. The result however, is a second order differential equation

$$d^2T(x)/dx^2 = m^2\,[T(x) - T_{air}] \qquad (3)$$

where $m^2 = hP/k_sA_c$. (m here is not mass flow). In this case the solution to the differential equation is

$$\frac{T(x) - T_{air}}{T_{wall} - T_{air}} = \frac{\cosh(m(L-x))}{\cosh(mL)} \qquad (4)$$

You are **NOT** required to derive this for the report. You will do later in lecture class.

The total heat Q transferred to the air by the rod must equal the heat conducted into the rod at x = 0. Agree? Therefore, we could use the equation above to compute dT/dx and along with Fourier's equation obtain (Eqn 3.81 in textbook 6^{th} ed.)

$$Q = M \tanh(mL) \qquad (5)$$

$$\text{where } M = \text{sqrt}(hPkA_c) * (T_{x=0} - T_{air})$$

Procedure

The equipment provided consists of (1) the rod to be tested with heat source at one end and eight attached thermocouples; (2) a combination thermocouple readout and power supply unit; (3) a computer with software to record all data. The necessary data can be recorded manually or remotely with the computer. This is the team's choice.

Familiarize yourself with the equipment components.

The data you leave with must include the following for each of two power levels. You should come to the lab with a data sheet prepared:
Heater voltage
Heater current
Temperatures at steady state for each power level:
T1 at x=0 (the heated end)
T2 at x=50mm
T2 at x=100mm
T3…T7 etc.
T8 at x= 350 mm (the cold end)
T9 = ambient temperature

The length of the rod is 350 mm; the diameter is 10 mm; the material is brass.

1. Record the initial temperatures on the instrumented rod with no power applied. Also record room temperature. Slight differences may suggest experimental error. The Voltage setting controls the power levels. Some time is required for the rod

temperatures to reach steady state. Time can be minimized by initially heating the rod to about 80 C at x=0, then adjusting voltage downward to the levels required.

2. Set the heater voltage to 20 Volts, using the software to control voltage and observer rod temperature. If operating the unit Manually then adjust the VOLTAGE CONTROL potentiometer to give a reading of 20 volts on the top panel meter with the selector switch set to position V.
3. Monitor temperature T1 regularly using the software screen or the lower selector switch. When T1 reaches 80 C reduce the heater voltage to the highest power level of the two you have chosen to use. For example 18 volts if you have chosen 14 and 18 volts to test). Allow the temperatures to stabilize. Monitor the temperatures using either the software screen or the lower selector switch meter.
4. When stabilized, record all temperatures. Then set the heater voltage control to the next power level and repeat.

Analysis

1. Plot T(x) vs x data for all trials using Excel or similar. For highest temperature case, also plot the curve provided by Equation 4. (How do you do that when m is unknown? Pick a value. Hint: m will probably be in the range of 5 to 15 in SI units).The guessed value of m must be adjusted to minimize the error between experimental temperature and theoretical. This can be done by eye, but is best done by a least squares fit. This was demonstrated in Lab Discussion.
2. Knowing m, calculate a value for h using the other known parameters in the definition of m.
3. For a broader range than tested of possible values of T_{wall} and $T_{ambient}$ plot temperature profiles for the rod using your derived h.
4. What are the circumstances (wall and air temperatures) where the rod temperature could damage a contacting ribbon cable?

Discussion

1. Comment on how well the temperature and theoretical profiles matched, and list possible reasons for differences.
2. A key assumption in the theoretical derivation is that h is a constant value along the rod, and for varying external circumstances. Does your data imply that this a reasonable assumption?
3. Comment on the test conditions. Are we accounting for all of the heat transfer mechanisms possibly involved? Are there heat losses in addition to the rod surface? (Suggestion: calculate Q from equation (5) for one of your power levels and compare to measured Volts*Amps at that level).
4. You were not given the exact circumstance of position on the ship. Suppose the rod was near the ceiling, as sketched in Figure 1. Would you expect your lab results would still apply? Why or why not?
5. You are required to make design recommendations relative to keeping the rod at a lower temperature. Assume that changes in material, attachment, or construction are allowed, but the bracing has to remain for structural reasons. Assume that relocating

the instrument cable, while an obvious solution, is not possible for other reasons. Make three practical and reasonable suggestions based on engineering principles.

6. Calculate the effect on temperature of somehow making a change that would increase the value of h that you measured by 50%. How does that affect your recommendations?

Error Analysis

For this experiment only do the following. For one of your runs, compare your measured temperature values with your theoretical calculation of temperature at the same point: Calculate the difference at each point and square that difference. Sum the differences and compute the square root of the sum of the squares. This scheme is sometimes called the root-mean-square estimate, and implies a worst case error value. Comment on the value. Do you believe your measurement uncertainties were more or less than this?

Summary

Write a short letter to the ship's owners with your findings and recommendations.

Worldwide Car Carriers
201 Harbor Street
Wilmington, DE