Lab 3 Heat Transfer

Mech 306 Lab Section 35

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Abstract

In this lab, we conducted an experiment to measure heat transfer through convection and radiation from two aluminum rods to the surrounding environment. The objective was to determine key coefficients for the two forms of heat transfer present in this experiment, emissivity (ε) for radiation and the heat transfer coefficient (h) for convection. The calculation of these key coefficients allows us to first compare the two materials through their convection properties and then analyze the effects of exterior colour on radiation from the body. One of the rods was painted black while the other had a polished aluminum surface. To experimentally determine the heat transfer coefficient of the material and the emissivity of the two rods, we inserted an electrical heating cartridge into one end of the rods to create heat conduction via electrical resistance within the material while running heated air over the rods. The electrical heat generation allowed us to take measurements in a controlled environment and record how the temperature of the rod was affected. We then heated the rods with the electrical current only and measured the energy transfer. This provided data that included heat radiation to input into our thermodynamic model, which allowed us to calculate the emissivity for the rods. The two rods differed only by the colour of their exterior, as demonstrated by the calculated equivalent heat transfer coefficients, which can be correlated to the emissivity results. We found that emissivity in the black rod was greater than that of the polished rod; therefore, black bodies radiate more heat energy than grey bodies.

Introduction

Heat transfer plays an important role in most fields of engineering; being able to maximize or minimize heat transfer can greatly improve the overall efficiency of a system. It is common to have multiple mechanisms of heat transfer active at one time, which makes the system difficult to manipulate for an engineer unless they have a clear representation for each form of heat transfer present. The results from this experiment define two key factors that influence radiation and convection heat transfer:

- Emissivity (radiation) - mainly impacted by the material composition and the surface characteristics.
- The Heat Transfer Coefficient (convection) - based on the shape of the object and the dynamic state and properties of the fluid that surrounds it (the factors that influence convection are very similar to those that influence drag).

With these constants defined, an engineer can use these values to determine how the rods would respond when exposed to different conditions.

Methods

Setup

The objective of this experiment was to determine the emissivity and heat transfer coefficients of a polished aluminum rod, and a black-painted aluminum rod. To determine these values, we needed to control the thermal inputs and outputs of the system. Before beginning to collect experimental data, we recorded data that may be relevant to the experimental process; this data can be found in Appendix A.

The thermal outputs, radiation and convection, were controlled by regulating the airflow and air temperature around the rod. We achieved this by placing the aluminum rod on a mount in front of a heated fan, so that the curved side directly faces the airflow. The air velocity and temperature were recorded using a probe placed at the same distance from the fan as the rod.

To create an isolated and consistent thermal input, we used an electrical heating cartridge placed in one end of the rod with power supplied by a variac. We measured the temperature of the rod over time by using four thermocouples (in equally spaced positions, recorded by a Data Acquisition System).

Techniques

The first technique we used relied on a steady state system. The fan was set to it's low setting, to provide a consistent air temperature and velocity. The rod was heated by a steady power input from the variac. We then waited until the temperature of the rod and fan reached a steady state (around 10 minutes), and recorded the average temperature of the rod over the period of a minute. The advantage of this method is that the system has reached a steady state, therefore the internal energy of the rod is constant and can be removed from the energy balance. Consequently, the energy from the electrical input directly balances with the energy lost through radiation and convection.

The second technique involved shutting off the electrical power supply and recording the decay in temperature of the rod. Electrical power is removed as a thermal input, leaving the loss in internal energy of the rod as the main source of energy for heat transfer. This method was convenient because we had to shut off the power supply following the conclusion of the first technique and wait for the rod to cool before dismantling the experiment and this allows us to verify our results from the first technique.

The technique employed to obtain emissivity was similar to the first technique in obtaining the heat transfer coefficient. We placed thermocouples into the rods and measured the energy input to the rod at thermodynamic steady state using an electrical source. We then calculated the emissivity using the same thermodynamic energy balance equation in the first technique; however, this method does not eliminate radiation from the equation. This means that we can calculate the emissivity of each rod using the heat transfer coefficient that was calculated in the first section of this experiment.

Results

Our results for the steady state trials can be found in Table 1 below. We compared the theoretical value, found in Table 2, that we calculated using Whitaker's equation with our experimental numbers and concluded that the results are comparable to the theoretical model provided based on sources of error. The error in our experimental results can be attributed to human error in both setup and measurement as well as time constraints in obtaining sufficient data, thermocouple inconsistency, electrical source fluctuation and inaccuracy, and the inability to completely remove all radiation effects during the first technique. Error is further discussed below. The heat transfer coefficients were obtained by averaging the temperature of the rod in steady state across the rod's temperature gradient using the equations found in Appendix B and analyzing the data in MatLab using the code found in Appendix C.

Table 1: Technique 1 Trial Results

Results from Steady State Trials	
Emissivity of Black Rod	-0.55
Emissivity of Polished Rod	-2.64
Heat Transfer Coeff. Black ($W/m^2/K$)	51.56
Heat Transfer Coeff. Polished ($W/m^2/K$)	53.36

Table 2: Whitaker Equation Heat Transfer Coefficient

Whitaker Calculation (with Air as fluid at 35ºC)	
Heat Transfer Coeff. 9mm Rod ($W/m^2/K$)	52.34

The results for the decay experiment can be found below in Table 3. The results for the Heat Transfer Coefficient agree with the results from the steady state trials, as well as the Whitaker equation.

Table 3: Temperature Decay Results

Results from Decay Trials	
Heat Transfer Coeff. Black ($W/m^2/K$)	51.47
Heat Transfer Coeff. Polished ($W/m^2/K$)	54.05

Our results for emissivity, found in Table 4, are clearly incorrect because they are negative (should be a value between 0 and 1). Our results cannot be taken as conclusive; however, the emissivity of the polished rod was consistently lower than the black rod, which agrees with the typical expectation for emissivity.

Table 4: Emissivity Calculation Results

Results from Emissivity Experiment	
Emissivity of Black Rod	-0.55
Emissivity of Polished Rod	-2.64

Analysis and Discussion

Steady State Analysis

After the system reaches steady state with the heat source active, the temperature of the rod stabilizes and the governing equation of energy balance is:

$$q_{elec} = q_{rad} + q_{conv}$$

$$IV = \varepsilon\sigma A(T_s^{\,4} - T_f^{\,4}) + hA(T_s - T_f)$$

where A, the surface area of the rod is described by: (see lab manual for descriptions of other parameters).

$$A_{Surf} = \pi dL + 2\pi \frac{d^2}{4}$$

To calculate the emissivity and heat transfer coefficient, we took the IV and T experimental values (See Table A.4), and interpolated it to get the coefficients. The coefficient for the T^4 terms is $\varepsilon\sigma A$, and since we know Stefan-Boltzmann constant and area, it is easy to solve for emissivity. A similar method was applied to the coefficient for the T terms (coeff. = A) to get the heat transfer constant. Since there are multiple possible solutions when interpolating, we wrote a MATLAB code (see Appendix B) that iterates to find a solution. We then compared the heat transfer coefficients to the number calculated from Whitaker's equation . Whitakers equation is given below:

$$h = k / d * [\ (0.4Re^{0.5} + 0.06Re^{2/3})Pr^{0.4}(\mu_f/\mu_w)^{0.25}\ ]$$

Our heat transfer coefficients were very close to the value given by Whitaker. For emissivity, some iterations provided values outside the range of emissivity (between zero and one), but the code provided answers within one order of magnitude. Additionally, the emissivity of the black rod is consistently larger than the emissivity of the unpainted rod, which agrees with the expectations for the emissivity of a dark object. These errors are likely from the sources of error discussed below.

Decay Analysis

During the cool down process, the energy balance is described by:

$$q_{rod} = q_{rad} + q_{conv}$$

$$mC\frac{dT}{dt} = \varepsilon\sigma A(T_s^{\,4} - T_f^{\,4}) + hA(T_s - T_f)$$

Similar to the results for the steady state analysis, we used Matlab to interpolate values to obtain the coefficients. The results from the decay experiment for the heat transfer coefficient agree with our results from the steady state trials and Whitakers equation.

Sources of Error

A significant source of error in our experiment was power loss through the electrical system, such as components in the variac or the resistance of the wires. This energy loss was not accounted for which means the recorded energy outputs of convection and radiation are likely higher than the actual values. In our MATLAB code, we added a multiplier and an adding factor to account for the resistance, but time and course scope limits us from finding the reasonable range of values to account for the losses.

Another potential source of error is the fact that we assumed the stream of air from the fan has uniform properties. The temperature and pressure gradient of the air current is likely to have some variance, and because we measured temperature at one specific point in the airstream, it is not a good representation of the overall flow.

The resolution uncertainties of the tooling are also present, but these are likely negligible compared to the larger sources of error we've described.

An important note is that the magnitude of convection heat transfer is around 10x greater than the magnitude of heat transfer from radiation. This means that any errors that impacted the experiment will have a small impact on the heat transfer coefficient, but a very large effect on emissivity. This helps to explain why our heat transfer coefficient results are relatively consistent and close to the predicted value from Whitaker, and why our result for emissivity was incorrect.

Conclusions

The results from our experiment showed somewhat reliably that the heat transfer coefficient for the rods in the controlled environment is around ~52 $W/m^2/K$. Our results for emissivity are inconclusive as our calculated values do not fall within the specific range of 0 to 1. However, the expectation that the emissivity of the black rod would be higher than the polished rod was supported.

Our results from this lab seem to show that it is hard to measure convection and radiation at the same time due to the differences in magnitude and the number of variables involved. There are are likely more accurate ways to work out the objective variables than the procedure we followed in this lab. For example, if the lab were conducted with the rod in a vacuum, convection would essentially be removed and we could get a more accurate value for emissivity. Then with a confident value for emissivity, we could find a more accurate for the heat transfer coefficient.

This lab made us question how values surrounding heat transfer are calculated in industry. Do companies mainly use experimental values from other research, or do they conduct thorough tests on their own to determine these values? Getting accurate results for these values would probably be a labour and cost intensive process due to the difficulty of measurement.

Appendix A: Recorded Data

Table A1: Aluminum Rod Dimensions

Aluminum Rod Dimensions		
	Polished	**Black**
Length, L (mm)	157	158
Diameter, d (mm)	9	9
Mass, m (g)	30	31
Surface Area (m2)	*4.57e-03* m^2	*4.60e-03* m^2

Table A2: Whitaker Equation Values

Properties of Air at 35℃ for Whitaker Equation	
Density, p	1.145 kg/m^3
Thermal Conductivity, k	0.02625 W/m/K
Thermal Diffusivity, α	$2.277*10^{-5}$ m^2/s
Dynamic Viscosity, μ	$1.895*10^{-5}$ kg/m/s
Prandtl number, Pr	0.7268
Far/Wall field ratio, [μ_f / μ_w]	1

Table A3: Airflow Properties

Airflow Properties from Fan	
Velocity, v	2.16 m/s
Temperature, T	33.5 C

Table A4: Individual Trial Data for Steady State

Data for Each Steady State Trial				
Trial	**Rod**	**Voltage (V)**	**Current (A)**	**Avg. Temp(℃)**
1	Black	0.99	0.05	39.46
2	Black	4.00	0.26	42.22
3	Black	7.00	0.46	49.53
4	Black	10.01	0.65	60.18
5	Polished	4.00	0.26	43.64
6	Polished	7.00	0.46	51.99

Appendix B: Temperature Gradient Charts

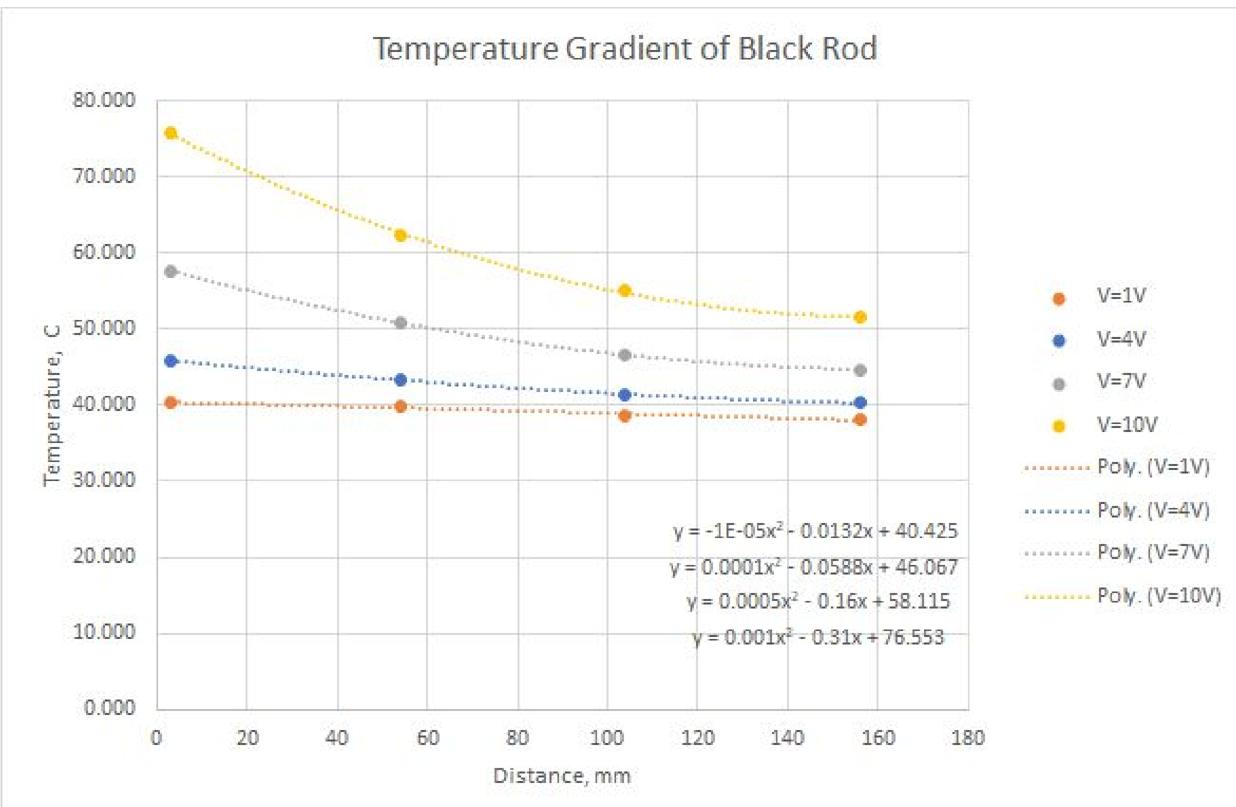

Figure B1: Temperature Gradient for Black Rod at Different Voltages

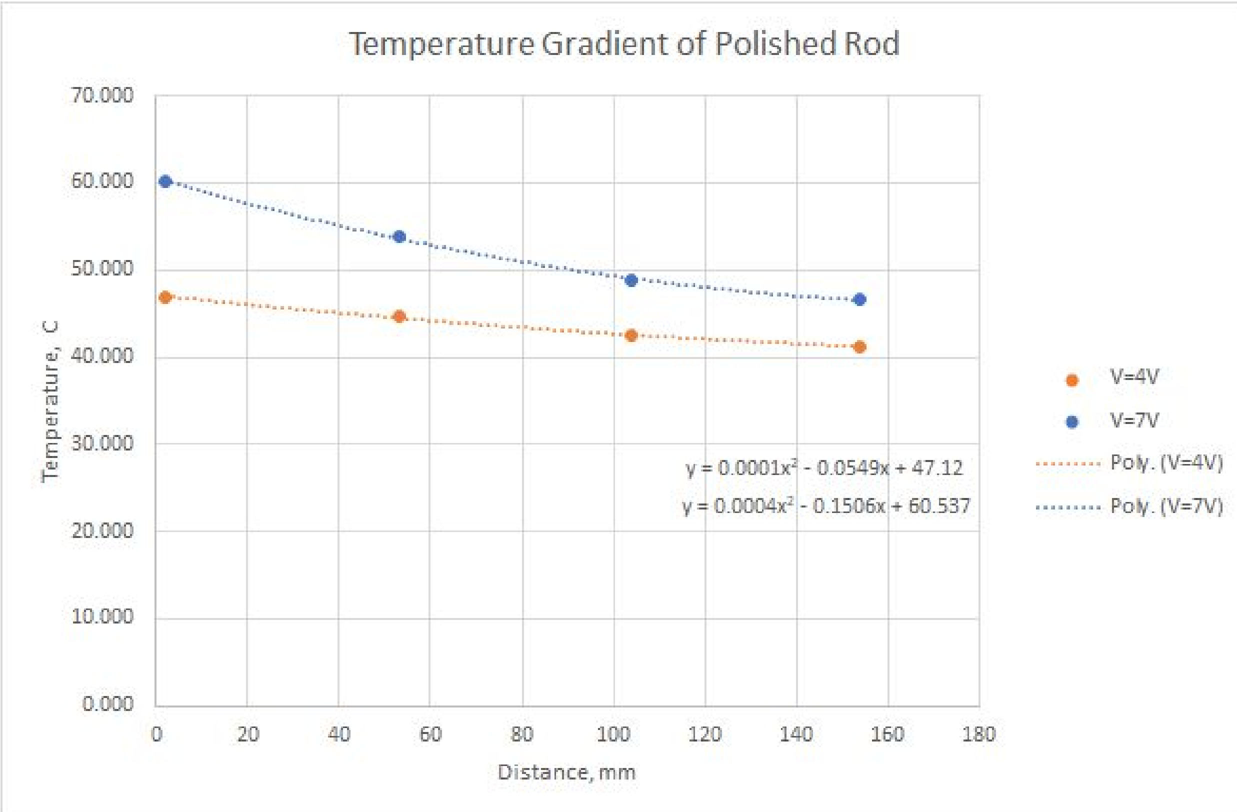

Figure B2: Temperature Gradient for Polished Rod at Different Voltages

Appendix C: MATLAB Calculation Code

```
function [a, b, c, d, e, f, g, h] = mech306_lab3b()
    clear
    clf
    %format long
    format short

    PlossMultiplier = 1;
    PlossAdd = 0;

    l1= .158; %black rod, len, m
    d1 = .009; %diam, m
    l2 = .157; %silver rod, len, m
    d2 = .009; %m
```

```
%black paint, low fan
v = 2.16; %m/s
T = [39.458 42.220 49.531 60.179]; %C
T = T+273.15;
Tsurr = 33.5+273.15; %C
V = [.99 4 7 10.01]; %V
V = PlossMultiplier*V;
V = V+PlossAdd;
i = [.05 .26 .46 .65]; %A
A1 = d1*l1*pi+2*pi*((d1/2)^2); %surface area of rod, m^2,

%{
Since dT/dt = 0, we can simplify our equation to:
q{elec} = q{radiation} + q{convection}
(I)(V) = (epsilon)(sigma)(A)(T^4 - Tsurr^4) + (h)(A)(T - Tsurr)
this can be simplified to:
(I)(V) = (a)(T^4) - (a)(Tsurr^4) + (b)(T) - (b)(Tsurr)
%}

%func getCoeff solves for a & b, given a set of IV, a set of T, and Tsurr
CoeffSet = getCoeffSet(T, i.*V, Tsurr);

%NOTE that our y = IV, x = T is very linear,
%so trying to make it fit a n=4 polynomial is either going to give you:
%1. weird a & b
%2. weird theoretical plot (r value is low)

%NOTE that the way matlab interpolate plots, there can be multiple values
%run this code multiple times and compare h to h from Whitaker approximation

%func CoeffSetToValSet solve (a) = (epsilon)(sigma)(A) and (b) = (h)(A)
%for epsilon and h, respectively, and output them in a matrix
ValSet = CoeffSetToValSet(CoeffSet, A1);

%func getBestVal compares 100 e&h's to h from Whitaker approximation and returns the closest matching pair
```

```
    [a, b] = getBestVal(ValSet);

    %silver metal / no paint
    T = [43.64 51.99]; %C
    T = T+273.15;
    Tsurr = 33.5+273.15; %C
    V = [4 7]; %V
    V = V*PlossMultiplier;
    V = V+PlossAdd;
    i = [.26 .46]; %A
    A2 = d2*l2*pi+2*pi*((d2/2)^2); %surface area of rod, m^2

    CoeffSet2 = getCoeffSet(T, i.*V, Tsurr);
    ValSet2 = CoeffSetToValSet(CoeffSet2, A2);
    [c, d] = getBestVal(ValSet2);

    %Decay calculations

    BlackRodDecay = GetDecayTemp('BlackRodDecay.csv');
    dy = diff(BlackRodDecay(:,2))./diff(BlackRodDecay(:,1));
    x = BlackRodDecay(:, 2);
    CoeffSet3 = getCoeffSet(x(2:end)', dy', Tsurr);
    ValSet3 = CoeffSetToValSet(CoeffSet3, A1);
    [e, f] = getBestVal(ValSet3);

    PlainRodDecay = GetDecayTemp('PlainRodDecay.csv');
    dy = diff(PlainRodDecay(:,2))./diff(PlainRodDecay(:,1));
    x = PlainRodDecay(:,2);
    CoeffSet4 = getCoeffSet(x(2:end)', dy', Tsurr);
    ValSet4 = CoeffSetToValSet(CoeffSet4, A1);
    [g, h] = getBestVal(ValSet4);
    %}
  end

function DataMatrix = GetDecayTemp(s)
    filename = s;
```

```
    fileID = fopen(filename);
    Data = textscan(fileID, '%s %s');
    fclose(fileID);

    timeStep = 2; %sec/measurement

    DataMatrix = zeros(length(Data{1}), length(Data));
    for j = 1:length(Data)
        DataCol  = Data{j};
        for i = 1:length(Data{j})
            DataMatrix(i, j) = str2double(DataCol{i});
        end
    end

    DataMatrix(1, 1) = 0;
    DataMatrix(:, 1) = DataMatrix(:, 1).*timeStep;
end

function ValSet = CoeffSetToValSet(CoeffSet, A)
    [r, c] = size(CoeffSet);
    ValSet = zeros(r, c);
    for i = 1:r
        [e, h] = solveForEpiAndHFromCoeff(CoeffSet(i, 1), CoeffSet(i, 2), A);
        ValSet(i, 1) = e;
        ValSet(i, 2) = h;
    end
    %disp(ValSet);
end

function CoeffSet = getCoeffSet(T, y, Tsurr)
    CoeffSet = zeros(100, 2);
    for f = 1:100
        [a, b] = getCoeff(T, y, Tsurr);
        CoeffSet(f, 1) = a;
        CoeffSet(f, 2) = b;
    end
```

```
    %disp(CoeffSet);
end

function [coeff1, coeff2] = getCoeff(T, y, Tsurr)

    x = T';
    y = y';

    ft = fittype( @(a,b,c,d,x) a*x.^4+b*x+a*c+b*d, 'problem', {'c', 'd'});
    [fitobj,~,~,~]=fit(x,y,ft, 'problem', {-(Tsurr^4), -Tsurr}); %[fitobj, goodness, output, convmsg]=fit(x,y,ft)
    coeff1=fitobj.a;
    coeff2=fitobj.b;

     yfit=coeff1*x.^4+coeff2*x-coeff1*(Tsurr^4)-coeff2*Tsurr;     %Remember dot notation

end

function [bestE, bestH] = getBestVal(coeffSet)

    whitakerH = 52.3406; %number from Cole

    set = coeffSet(1, :);
    bestE = set(1);
    bestH = set(2);
    for f = 1:100
        set = coeffSet(f, :);
        a = set(1);
        b = set(2);
        if (abs(whitakerH - bestH) > abs(whitakerH - b))
            %disp(bestH);
            bestE = a;
            bestH = b;
        end
    end
    %disp(bestH);
end
```

```
function [ep, h] = solveForEpiAndHFromCoeff(a, b, A)
    ep = a/(5.67*10^(-8)*A);
    h = b/A;
end
```