New York Institute of Technology

MENG343: Thermofluids Laboratory
Lab#3: Heat Transfer Experiment

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Lab Performed:
10/9/2019, 10/16/2019 & 10/18/2019
Submitted:
10/23/2019

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Abstract

The first part of this lab was conduction heat transfer. There were multiple purposes of the lab. First, we calculated the thermal conductivity of brass and stainless steel. The brass samples tested had 2 different diameters, so we were able to determine the effect that the cross sectional area has on the thermal conduction. Based on the electrical circuit analogy, we were able to determine the gap conductance. Finally, we determined the RC constant so that it can be used to determine the time to steady state. Conduction heat transfer is important to understand because it is the most efficient means of heat transfer. It is the passing of heat between materials that are making physical contact through one another.

Based on our experimental results, the thermal conductivity of the 13 mm and 25 mm brass came out to be 110 WmºC, while the actual thermal conductivity of brass was found to be 110 WmºC. This results in a 0% error. It would be expected that the thermal conductivity should be the same, regardless of the cross sectional area. This is because the thermal conductivity is a material property and does not depend on the dimensions. The next material was stainless steel, which our experiment showed had a thermal conductivity of 21WmºC. Based on actual values, the thermal conductivity of stainless steel is 25WmºC. This gives us a 16% error. The gap conductivity was calculated to be 32WmºC at the hotter end and 29WmºCat the colder end. The thermal conductivities strongly suggest the material is not purely air since air's conductivity is approximately 20E-3WmºCat the operating temperature. As it was demonstrated in the experiment, there was white sticky material between the cylinders. Thus, the conductivity is for that material.

For conduction, we know that 5RC is equal to steady state. Using this information, we calculated that steady state should take about 1 hour to achieve for stainless steel sample, 35 minutes for the 13 mm brass sample, and 24 minutes for the 25 mm brass sample. Using this RC constant, we determined that we have reached steady for the 25 mm brass and the 13 mm brass samples, but not the stainless steel sample even though we had more than 3.3 time constants meaning about 96% "charged" which implies closeness to steady-state.

The second part of this experiment involved observing convection heat transfer. Convection heat transfer is important because this is the way that liquids and gases typically exchange heat. This is seen in heat exchangers, where fluids move across surfaces that can carry away heat. There are multiple purposes of the lab. First, we attempted to show the effect of free vs. forced convection. Next, we showed the effects of an increased surface area (plate vs plate with fins) under forced convection. Finally, we validated the predicted heat transfer coefficient against the experimental results for forced convection by calculating the heat transfer rate, Q. In this portion of the lab, we were unable to calculate quantitative results for free convection. This is because the sensor was unable to detect an airflow without the aid of a fan.

For the pin-fin case, the heat transfer through the D-B and energy methods are 2.0245 W and 94.792 W, respectively. The errors for both are 86.746% and 520.57%, as heat loss from the surroundings was not taken into consideration. For the flat plate case, the heat transfer is 8.0566 W and 76.563 W and the errors are 47.256% and 394.68%, respectively. Regarding the heat transfer for the fin, it is recorded to be 5.8562 W and 1.1381 x 10-2W respectively.

The final part of this experiment involved observing radiation heat transfer. Radiation heat transfer is important because it is the process of which thermal energy is exchanged between two surfaces which are not directly in contact with each other, and are separated in space. This is able to happen through the process of electromagnetic radiation.

Based on our results, we were able to graphically express that the radiation heat transfer dependence on temperature is to the fourth power. It is expected that a log log graph of irradiance and temperature should result in a slope of 4. Our experimental results showed a relationship of temperature to the 4.412 power. This is a 10% error.

Theory:

Conduction in 1D

The heat between hot and cold surfaces always travel from the hot to the cold surface according to thermodynamic laws. The concept of conduction is when the material is present between the hot and cold surfaces and is motionless. The heat flow rate across materials is dependant on the geometry of the material such as cross-sectional area, A, and length, L, the temperature across each end of the material, ΔT, and the material's ability to transfer heat, k. The exact relationship is represented mathematically for a one-dimensional-steady heat transfer in the equation below.

In 1D in steady state one obtains:

$$q=(kA/L)\Delta T$$

Where:

k = coefficient of conduction (BTU/hr ft $^{\circ}$F) or (W/m*K)
ΔT = difference in temperature ($^{\circ}$F) or (K)
q = heat transfer rate (BTU/hr) or (W)
A = cross sectional area of surface (ft^2) or (m^2)
L = length of surface (ft) or (m)

Circuit analogy: to help understand and simplify the heat transfer solving method.

L/kA in heat transfer is equivalent to the resistance in the circuit analogy. Then, one can use a circuit analogy.

$$V = IR$$
$$\Delta T= qR$$

That is the driving potential for heat flow is the temperature difference in heat transfer which is conceptually equivalent to the voltage difference being the driving potential in circuit analogy.

Therefore, the solving of the resistance of each material is easier when more than one material is present since it is simplified using the circuit analogy. For instance, if you have multiple materials in series you add the resistances to get an equivalent resistance as you would in circuit analysis and if they are in parallel you divide their product by their sum

$R_{eq\text{-}series} = \Sigma R_i$ $R_{eq\text{-}parallel}=(\Sigma R_{i\text{-}1})_{\text{-}1}$

Then, $\Delta T = R_e q$

For the instrumented sample one can determine the gap conductance for the two gaps and then use that to help determine the conductivity of the stainless steel sample.

RC constant in circuit analogy: meaning in a Resistor and Capacitor circuit, the voltage will not be steady across components and their steady time depends on the resistance and capacitance.

The transient solution to this problem is now mostly done by computer, but the circuit analogy is a very good check.

That analogy is a function of the Resistance/Capacitance time constant, or RC time constant.

R is the resistance we have been discussing which should be R_{eq} for the whole system of heat transfer.

C is equivalent to $c_p \rho V$ the product of the heat capacitance, density and nodal volume.

It takes 5 time constants (RC time constants) to fully charge the capacitor (63% in 1 RC, 86% in 2 RC, 95% in 3 RC, 98% in 4 RC, 99% in 5 RC).

The percent charge is determined using: 1- exp(-coefficient_of_time_constant) as indicated in the graph below.

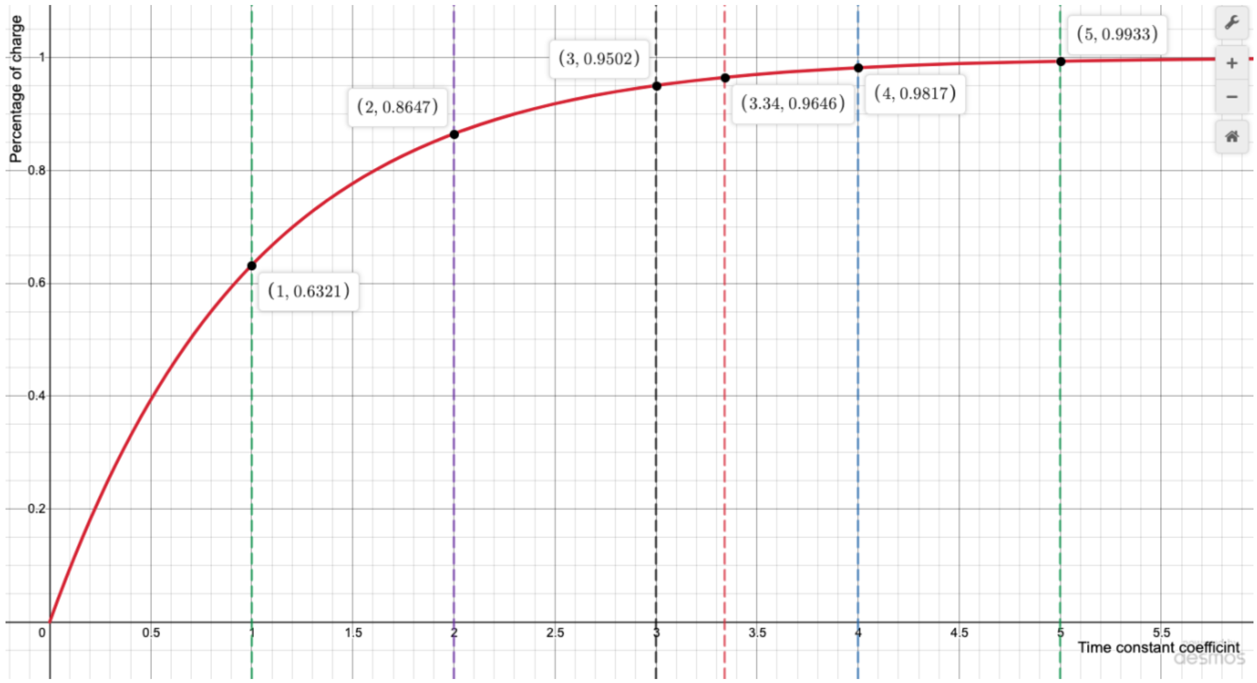

Figure 1: Time constant vs percentage charge for RC.

Convection

According to thermodynamic laws, energy of heat transfers from hotter to cooler objects. When the ambient fluid is present but naturally moving without any external forces, it is called natural/free convection. However, when the fluid is moving, it is called forced convection. Heated surfaces loses its heat to a cooler environment.

$$q=hA\Delta T$$

Where:

h = convective heat transfer coefficient

A is the surface area of contact between the fluid and object

ΔT is temp difference between the heated surface and the bulk cooling air.

For turbulent flow one can use the Dittus- Boelter equation to obtain the convective heat transfer coefficient: (Tong, p.195, or http://en.wikipedia.org/wiki/Heat_transfer_coefficient)

$$hDk = 0.023(DG)^{0.8}(cpk)^{0.4}$$

Here:
D = hydraulic diameter (**4 times the cross sectional area divided by the perimeter= hydraulic diameter**)
k = thermal conductivity of fluid
c_p = specific heat of fluid

G = mass velocity (#/(hr- ft squared))
μ = fluid viscosity (#/(hr- ft))
These are taken at the bulk conditions of the fluid.

OR even better use the FE Handbook to determine the convective heat transfer coefficient for both laminar, turbulent and natural convection. (FE HBK pp. 118, 119, 121)

Thermodynamics Energy equation:

$$Qsupplied=m'cpT - Qloss$$

For the heat transfer of a fin, a first law analysis states that:

$$q_x = q_{x+dx} + dq_{conv}$$

Expanding the q_{x+dx} term and recognizing that q_x= $-kA_c dT/dx$(Fourier's Law) yields

$$d_2T/dx_2 – m_2 = 0 \qquad \text{where m2 hPkAc and =Ts- T.}$$

This is a second order, homogenous, differential equation. Two boundary conditions are required for a unique solution. Such conditions are

$$h(L) = -k(d/dx)$$

(can be derived from an energy balance at the end of the fin) and

$$(0) = T_b\text{-}T = \theta_b$$

where Tbis the temperature of the base of the fin. The general solution to the differential equation is

$$(x) = C1e_{mx}+C2e_{-mx}$$

Applying the boundary conditions mentioned before yields the temperature profile

$$\theta (x) = \theta_b (\cosh m(L-x) + (h/mk) \sinh m(L-x)/\cosh mL + (h/mk) \sinh mL)$$

Employing Fourier's Law onto the temperature profile evaluated at x=Lyields the heat transfer of the fin:

$$q =\theta_b(hPkA)_{1/2(}\sinh(mL) + (h/mk) \cosh(mL)\cosh(mL) + (h/mk) \sinh(mL))$$

(Incropera, 141-143). The four thermocouples attached at different points of the fin should validate the temperature distribution of the fin, as well as the total heat transfer of the fin.

Radiation HT (See FE HBK p. 122)

The heat transfers from hot to cold surfaces according to the thermodynamic laws. Radiation happens regardless of presence of material/medium between the hot and cold surfaces.

Stefan-Boltzmann's law is confirmed by plotting the measured values on log-log diagram in a similar manner to the figure below, and determining the slope. The thermopile is measuring only the radiation of the heat source EH, but the equation there must be used the total Radiation ES, including the ambient radiation Eamb:

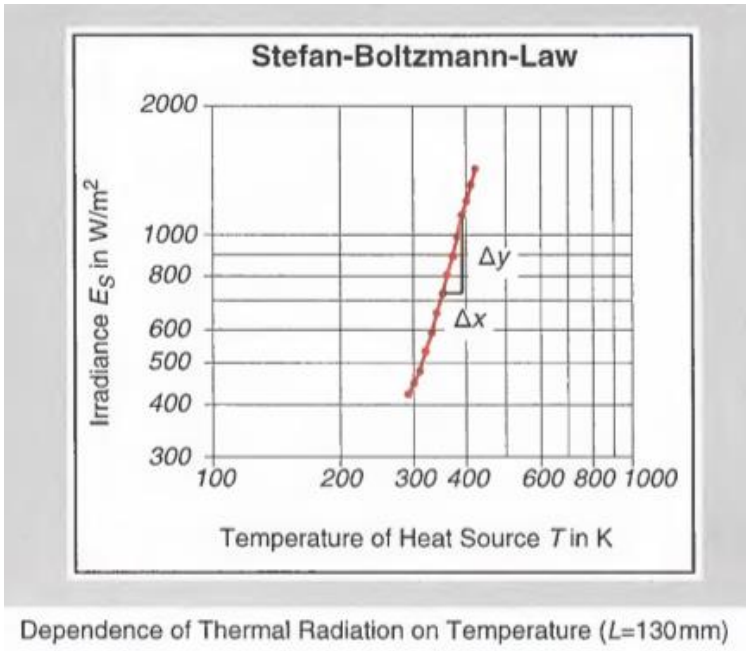

Figure 2: Radiation equation (Stefan-Boltzmann) validation.

$E_s = E_H + E_{amb}$

The ambient radiation results from the ambient temperature:

$E_{amb} = C_s * ((273.15+T_{amb})/100)^4$

The emission coefficient results from the radiation of the heat source and the theoretical radiation:

$\varepsilon = (E_s/E_{theo})*100\%$

$E_{theo} = C_s * ((273.15+T_{amb})/100)^4$

Plotting the measured values in a log-log diagram and determining the slope of the equalising curve results in a slope of

$a = \Delta Y/\Delta X$

$E_s = T^4$

This is evidence of the law of Stefan Boltzmann.

$Q' = es\, FAT_4$

Where:
e = emissivity
s = Boltzmann constant
A = body surface area
F = shape factor

Equipment

Conduction

Major components

-1-D Conduction apparatus with heat supply, cooling water, 3 samples (1 instrumented)

Controls:

- Water cooling flow valve: This allows water to flow through the cold region of the conduction apparatus resulting in temperature difference across the material to drive the heat transfer.
- Heat input supply: This supplies the heat to the hot region of the conduction experiment that allows the transfer of heat throughout the system since heat transfers from high to low temperatures.

Sensors:

- 3 thermistors on each bookend: These determine the entering and leaving temperatures of the sample as well as in between.
- 2 thermistors on instrumented sample: These will determine the temperature within the sample to help calculate the conductivity of brass.
- Time: Time is to be taken to determine the total time of the run to reach steady state

DAQ:

Temperatures: temperature of each thermistor. Eight temperatures for the instrumented sample and 6 for the other samples.

Voltage: since the heating is done using electricity, the voltage driving the electricity in the hot region is displayed.

Current: since the heating is done using electricity, the current going through the material is calculated. The current and voltage gives us the power or heat rate across the material.

Convection

Major components:

-Vertical rectangular duct with air flow control & heated samples consisting of Flat Plate & Finn.

Controls:

-Air cooling flow control: This knob can be turned to allow more airflow through the convection apparatus
-Heat supply: This supplies the heat to the conduction experiment that allows the transfer of heat throughout the system

Sensors:

-Flow: This sensor reads the actual airflow throughout the system in m/s
-Heat source: This will provide the voltage and current outputs, which can then be translated into a power
-Movable temperature indicator; before and after heated sample, contact with pin fin ± 0.5°C
-Temp sensor to heated sample ± 0.5°C

DAQ:

Temperatures: temperature of each thermistor. Three temperatures, for inlet, outlet, and plate surface.

Voltage: since the heating is done using electricity, the voltage driving the electricity in the hot region is displayed.

Current: since the heating is done using electricity, the current going through the material is calculated. The current and voltage gives us the power or heat rate across the material.

Radiation

Major components:

-Thermal Radiation Unit: This unit will provide a power that can sense temperature and irradiance

Controls:

-Thermopile Separation Distance ± 2mm

-Power Regulator ±3%

Sensors:

-Temperature Sensor ± 0.5°C

-Irradiance Sensor ± 0.38 W/m^2

DAQ:

There is no DAQ for radiation.

Procedure

Conduction

Before conducting the experiment, it is important to read the lab equipment manual to ensure proper set up and safety is completed.

1. Insert the 25 mm brass sample into the apparatus.
2. Set the voltage, and check the resulting current as to make the power about 5 Watts.
3. With a timestamp, turn the knob to take readings for all 8 temperatures.
4. Repeat this process until the device has seemed to reach steady state. Steady state can be observed when the 8 temperatures are essentially not varying with time anymore.
5. When the temperatures are stable, record the following 8 temperatures as the last set of data.
6. From the 25 mm brass, a gap conductance can be calculated, and it will be assumed to be the same throughout the entirety of the experiment.
7. Repeat steps 2-5 for the 13 mm brass sample and the stainless steel sample.

Radiation

Before conducting the experiment, it is important to read the lab equipment manual to ensure proper set up and safety is completed.

1. Mount the thermopile at a separation of L= 130mm from the heat source, connect to the measuring amplifier ('Strahlung/Radiation' connector). Remove all other fittings in between.
2. Connect up the heat source ('Last/Load' connector and 'Temperature 1' connector).
3. Switch on the measuring amplifier, note the offset displayed (background radiation).
4. Switch on the heat source.
5. Set the power regulator on the measuring amplifier to 70. The temperature climbs slowly.
6. Take the series of measurements by noting the temperature and the irradiance indicated every 10 K.

Natural Convection

Before conducting the experiment, it is important to read the lab equipment manual to ensure proper set up and safety is completed.
Free Conduction

1. Set the voltage on the power supply and take note on the current. This power should be set to about 15 W.
2. Open up the valve to allow airflow to run through the system, leaving the fan off to allow for free convection.
3. With the plate inserted, note the airflow of the system for free convection.
4. Checking the inlet, outlet, and sample temperatures over time, keep taking values throughout a period of time until steady state is achieved.

5. Repeat steps 2-4 for the pin fin. Note: The pin fin has 4 probe temperatures, located at the plate surface, and 3 throughout the length of the pins.

Forced Convection

1. Set the voltage on the power supply and take note on the current. This power should be set to about 15 W.
2. Open up the valve to allow airflow to run through the system, turning the fan on to allow an airflow of 5 m/s for forced convection.
3. Checking the inlet, outlet, and sample temperatures over time, keep taking values throughout a period of time until steady state is achieved.
4. Repeat steps 2-4 for the pin fin. Note: The pin fin has 4 probe temperatures, located at the plate surface, and 3 throughout the length of the pin.

Results

Conduction Calculated Data

Table 1: Calculated data for conduction.

Parameter	**Value ± Propagation of Error**
Power	4.8 ± 0.1 W
Brass Thermal Conductivity	110 ± 19 Wm°C
Stainless Steel Conductivity	21 ± 2 Wm°C
Colder Gap Resistance	0.48 ± 0.08 °CW
Hotter Gap Resistance	0.52 ± 0.09 °CW
Hotter Gap Conductivity	32 ± 7 Wm°C
Colder Gap Conductivity	29 ± 5 Wm°C
Brass 25mm Resistance	0.3 ± 0.2 °CW
Brass 13mm Resistance	2.1 ± 0.2 °CW
Stainless Steel 25mm Resistance	2.9 ± 0.2 °CW
Time to reach steady state Brass25mm	24 min
Time to reach steady state Brass13mm	35 min
Time to reach steady state Stainless Steel	60 min

Figure 3: The circuit analogy employed into heat transfer.

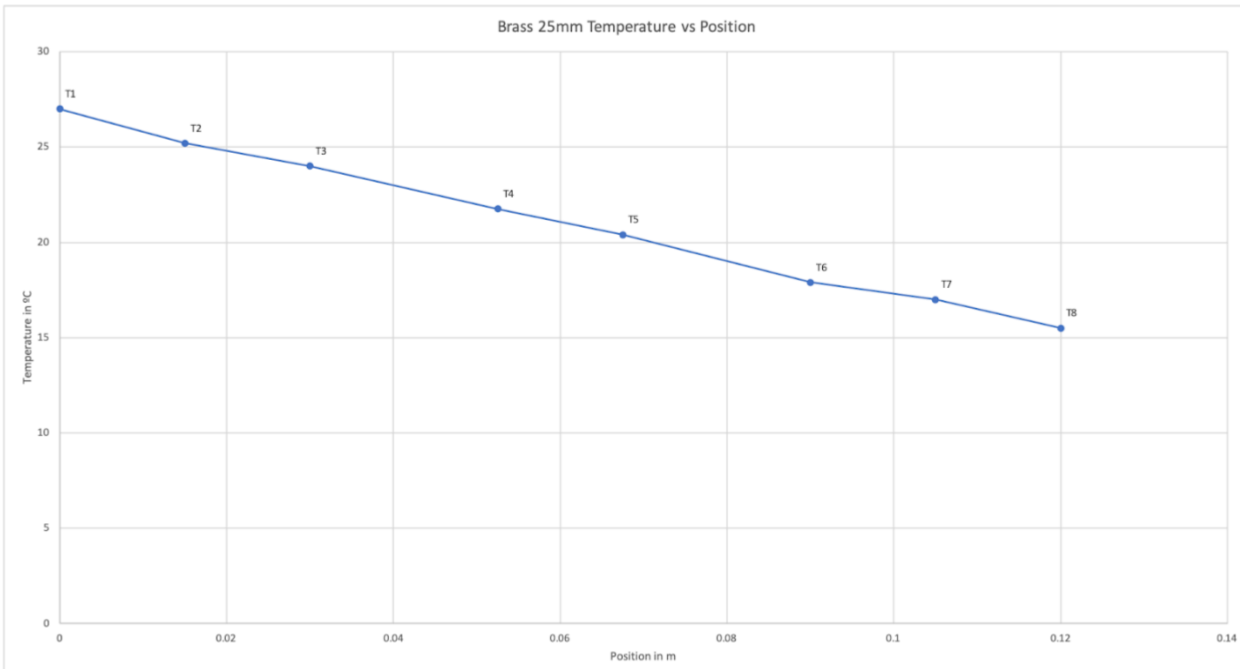

Figure 4: Temperature vs position of sample specimen.

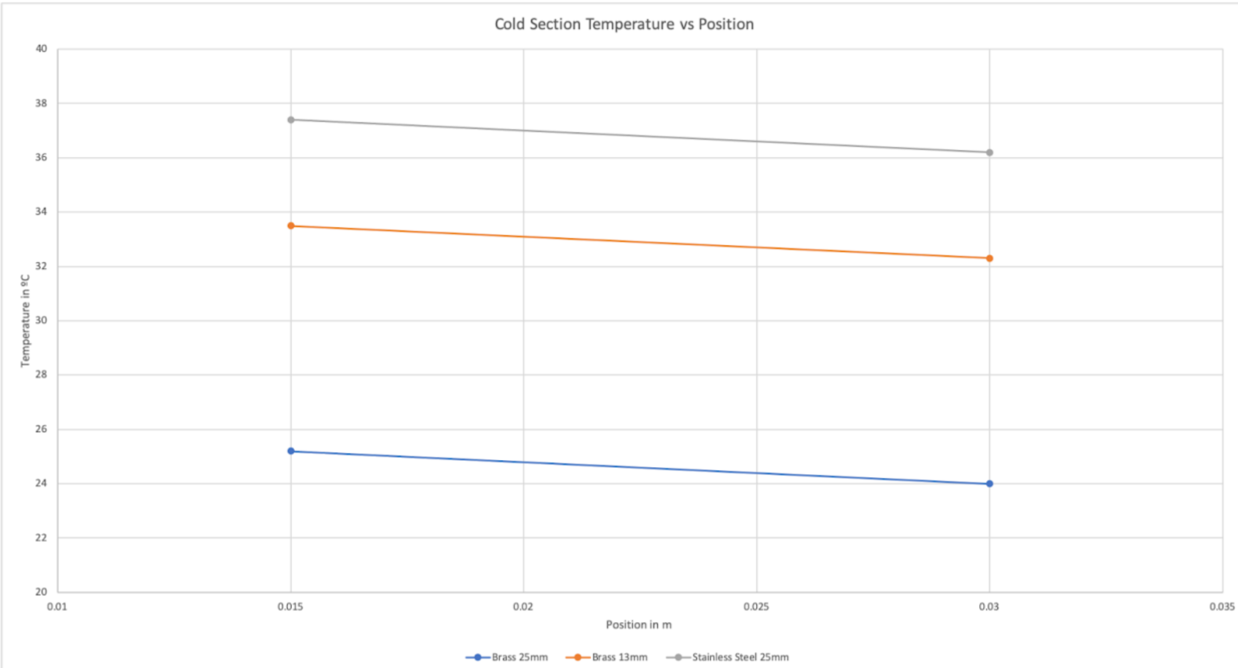

Figure 5: Temperature vs position of the hot section of different specimens at the same heat input.

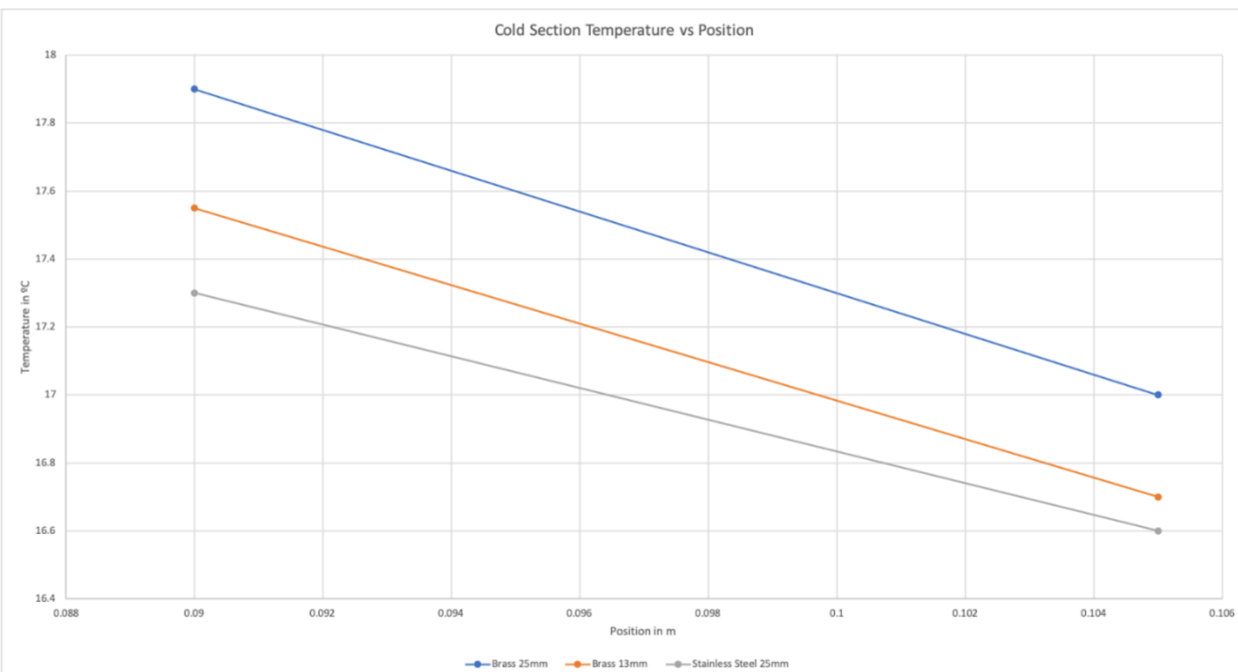

Figure 6: Temperature vs position of the cold section of different specimens at the same heat input.

Convection Calculated Data

Table 2: Calculated data for convection.

Parameter	**Value ± Propagation of Error**
Power	15 ± 0.2 W
Convective Heat Transfer Coefficient (D-B)	17.7 ± 0.3 W/m^{2}K
Experimental Heat Transfer Coefficient	30 ± 0.9 W/m^{2}K
Heat Loss	36 ± 0.2 W/m^{2}K
Hydraulic Diameter	0.222 ± 0.007 m

Convection Pin Fins Temperature Profile

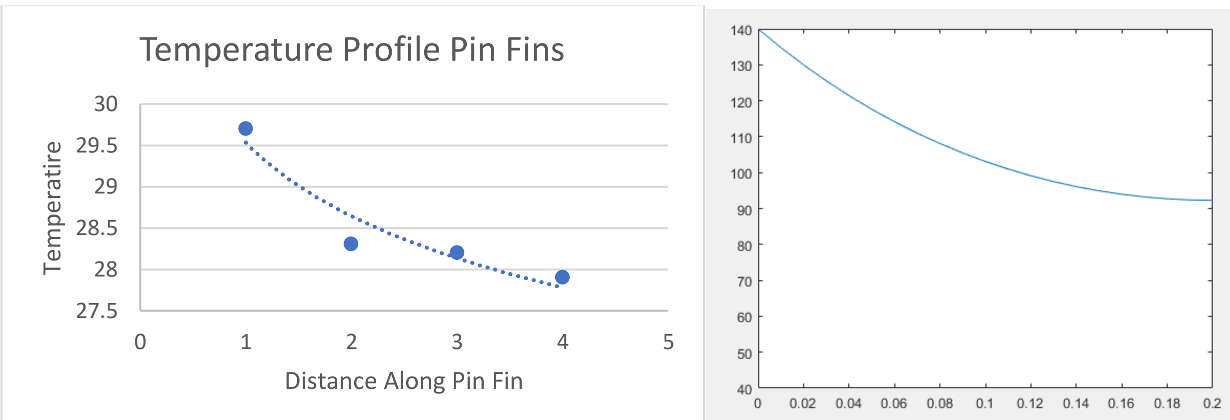

Figure 7: Temperature profile along fin.

On figure 7, the left shows the temperature distribution along the pin fins from the experimental data and the right shows what the actual temperature distribution should look like along the pin fins. This similarity displays that we were able to replicate what the actual temperature distribution should be along the length of the fins.

Radiation Calculated Data

Table 3: Calculated data for radiation.

Temperature (C)	EH (W/m^2)	Etheo (W/m^2)	Epsilon	ES (W/m^2)
20	1	417.8818804	100.2388521	418.88
30	18	477.9182037	91.20389151	435.88
40	46	544.2023453	85.24035297	463.88
50	100	617.1534317	83.9143029	517.88

60	160	697.2041972	82.88533005	577.88
70	230	784.8009843	82.55341328	647.88
80	306	880.4037434	82.22136781	723.88
90	389	984.4860328	81.95951727	806.88
100	477	1097.535019	81.53543938	894.88
110	572	1220.051476	81.13428156	989.88
120	679	1352.549787	81.09719956	1096.88
130	791	1495.557942	80.83137176	1208.88
140	915	1649.617539	80.79933489	1332.88
150	1053	1815.283785	81.02755128	1470.88

Table 4: Calculated data for radiation log-log relationship.

Log Temperature	Log Irradiance
5.6801726	0
5.7137328	2.8903718
5.74620191	3.828641396
5.777652323	4.605170186
5.80814249	5.075173815
5.837730447	5.438079309
5.866468057	5.723585102
5.894402834	5.963579344
5.92157842	6.167516491
5.948034989	6.349138991
5.973809612	6.520621128
5.998936562	6.673297968
6.023447593	6.818924065

6.047372179	6.959398512

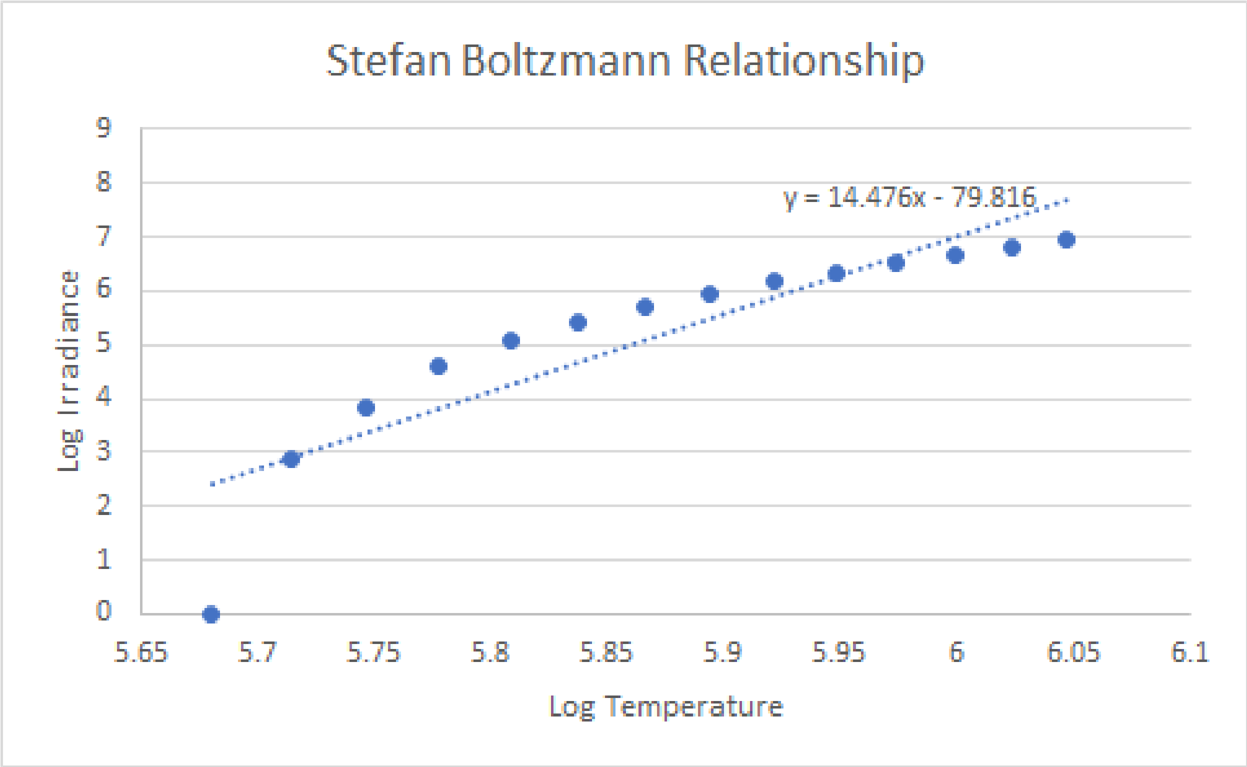

Figure 8: Radiation equation log-log plot of temperature vs irradiance of all points.

This graph represents the slope of the log-log curve including for all the points. However, we eliminated the first couple points for optimization, which gave us a much more accurate result.

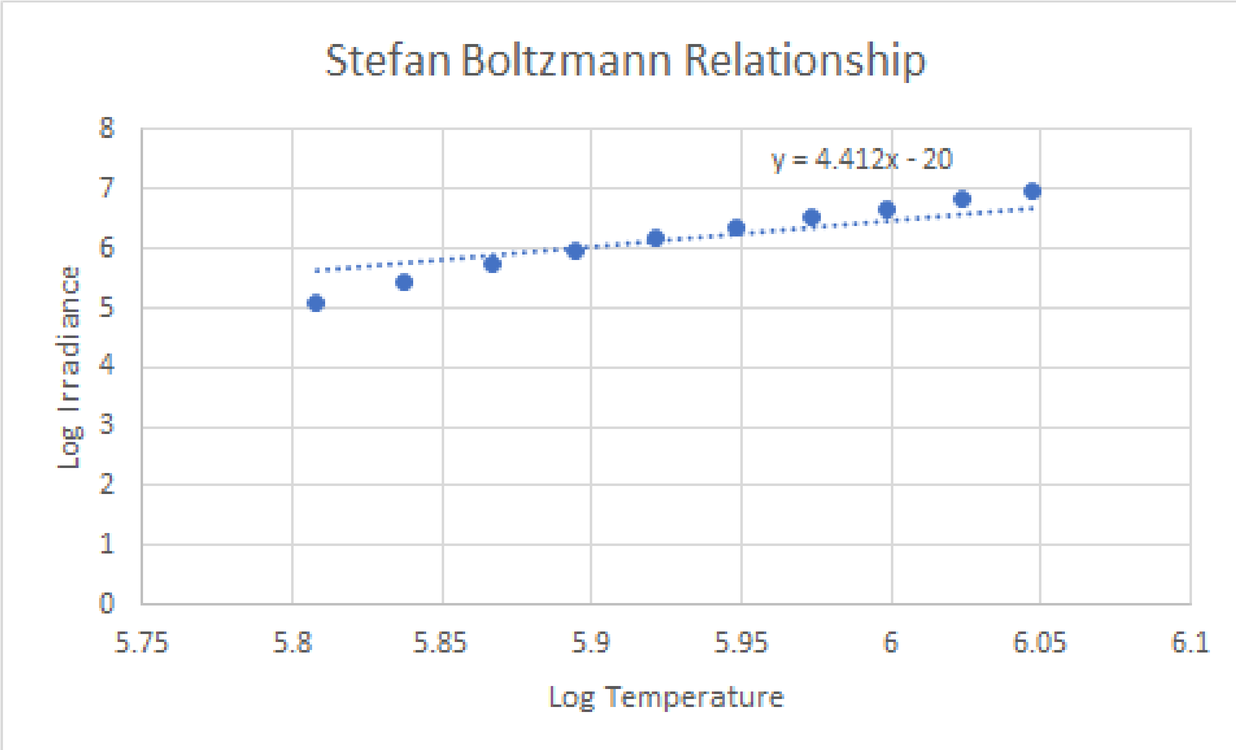

Figure 9: Radiation equation log-log plot of temperature vs irradiance of all best-fit points.

Conclusion

The first part of this lab was conduction heat transfer. Based on our experimental results, the thermal conductivity of the 13 mm and 25 mm brass came out to be 110 ± 19 Wm°C , while the actual thermal conductivity of brass was found to be 110-128 Wm°C. This results in a 0% error. It would be expected that the thermal conductivity should be the same, regardless of the cross-sectional area. This is because the thermal conductivity is with respect to the material. The next material was stainless steel, which our experiment showed had a thermal conductivity of 21± 2Wm°C. Based on actual values, the thermal conductivity of stainless steel is 25Wm°C. This gives us a 16% error. The gap conductance was calculated to be 32 ± 7Wm°C at the hotter end and 29 ± 5Wm°Cat the colder end. Based on our results, we think that the gap conductivity is for the white sticky material on the surface of the cylinders. The experimental values for both brass samples (13 mm and 25 mm) were accurate, due to the fact that we had enough time to reach steady state. According to our results from the stainless steel sample, we have a 16% percentage error. A reason for this occurring, as discussed in the next paragraph, was that we did not have enough time to reach steady state. In order to allow for more time to reach steady state, a suggestion to better this experiment would be to provide another heat source so that the convection and conduction experiments can be completed simultaneously or making each experiment in a different session.

In an attempt to show general outcomes of the conduction experiment, we learned multiple consequences of changing one parameter while keeping the rest constant in the conduction equation. We fixed the heat input for all the 3 samples and learned: First, with regards to the diameter difference between the brass samples, we noticed that the resistance of the brass sample increased in the smaller diameter as compared to the larger one. Second, the temperature difference will increase as the diameter decreases when using the same material. Third, changing the material will affect the temperature difference when the diameters are consistent. The temperature difference increases as the thermal conductivity decreases which we learned from the stainless steel sample compared to the brass sample of the same diameter. Overall, our experimental data agrees with the conductivity equationq=kAdTdx or q= dTR where R=dxkA. Unfortunately, we have a large propagation of error for the brass conductivity since the resistance was 0.3 with a 0.2 uncertainty, which makes the uncertainty extremely high percentage wise, 67%.

For conduction, we know that 5RC is the time needed to reach steady state. Using this information, we calculated that steady state should take about 1 hour to achieve for stainless steel sample, 35 minutes for the 13 mm brass sample, and 24 minutes for the 25 mm brass sample. Using this RC constant, we determined that we have reached steady for the 25 mm brass and the 13 mm brass samples, but not the stainless steel sample. For our experiment, we ran our 13 mm brass sample for 42 minutes, our 25 mm brass sample for 48 minutes, and our stainless steel sample for 40 minutes. From this information, we are able to tell that we reached steady state for both brass samples. However, we were unable to reach steady state for the stainless steel sample due to a lack of time. This is why the stainless steel sample gave us a 16% difference in our experimental value when compared to the actual value. On the other hand, we spent 40 minutes out of 60 minutes which corresponds to 3.34RC resulting in 96% steady state.

The second part of this experiment involved observing convection heat transfer. There were multiple purposes of the lab. First, we attempted to show the effect of free vs. forced convection. Next, we showed the effects of an increased surface area (plate vs plate with fins) under forced convection. Finally, we validated the predicted heat transfer coefficient against the experimental results for forced convection by calculating the heat transfer rate, Q.

For free convection, we wanted to test the effects on the heat transfer at the room air flow without the aid of a fan. However, the sensor was unable to detect an airflow without the aid of the fan. Therefore, we were unable to complete calculations for this portion of the lab. A reason for the lack of a reading for airflow is that the airflow in the room was slow, and the placement of the apparatus was underneath an air diffuser. Therefore, the airflow through the apparatus could have either been too slow to read, or that the diffuser was pushing air in the opposite direction, therefore having an effect on the reading, which would explain why the airflow was detected as a small negative number.

For the pin-fin case, the heat transfer through the D-B method is 2.0 ± 0.1W and 95 ±32 W, not taking into account heat loss from the surroundings. For the flat plate case, the heat transfer is 8.1 ±0.2 W and 77 ±6.0 W, respectively. The power input of the system is 15.257 W, which is much different in comparison to the theoretical results.

The massive error refers to the readings of the airflow velocity. It has been shown after repeated recordings to be very inaccurate, and thus the measured 5 meters per second may not be the actual presented velocity. Additionally, heat loss to the environment was not considered for this analysis. Part of the energy balance method involves utilizing heat loss from the surroundings to gain an accurate reading of the heat transfer. Since it is difficult to predict how much heat is lost to the environment, it was excluded from the analysis. This contributes to the massive propagation error with the heat transfer, as in theory, all the electrical work input should be converted to heat transfer through a temperature gradient formed through the air velocity.

For this case, the increased surface area of the pin-fin had less heat transfer than the flat plate, as a greater temperature gradient is required for more heat transfer and the gradient has more area that must be gone through. This can also be shown with the heat transfer of the pin-fin fin being much smaller in comparison to the heat transfer of the flat plate fin. Although the experiment was not performed for free convection, in general the forced convection case will induce greater heat transfer than the free convection case, as the inertial effects are considered and applied which causes are larger temperature gradient.

The final part of this experiment involved observing radiation heat transfer. Based on our results, we were able to graphically express that the radiation heat transfer dependence on temperature is to the fourth power. It is expected that a log-log graph of irradiance and temperature should result in a slope of 4. Our experimental results showed a relationship of temperature to the 4.412 power. This is a 10% error. This is seen on the graph provided. At first, the slope of the curve including all the points was reading that the radiation has a relationship of temperature to the 14th power. However, eliminating the first couple of data points gave us the more accurate slope of the curve. The reason for eliminating the first couple of data points is because they appeared to be causing an exponential curve. A reason for this could be a system start-up that took some time to read the data accurately. We noticed this may be an issue since on start-up the machine was reading a value of -15 W/m^2 for the irradiance. Therefore, if we were to repeat the experiment, we would turn the apparatus on and wait some time for the values to settle.

Appendices

Conduction Raw Data (**Bold signifies steady state data points)**

V= 6.7 V ± 0.1 V

I= 0.72 ±0.01 A

P= V*I= (6.7 V)*(0.72 A)= 4.8 ± 0.1 W

Table 5: Raw data for conduction.

Time (HH:MM)	T1 (°C) ±0.2°C	T2 (°C) ±0.2°C	T3 (°C) ±0.2°C	T4 (°C) ±0.2°C	T5 (°C) ±0.2°C	T6 (°C) ±0.2°C	T7 (°C) ±0.2°C	T8 (°C) ±0.2°C
Instrumented Brass 25 mm								
5:15 pm	18.4	18.0	17.9	17.3	16.8	16.0	15.5	14.8
5:30 pm	25.8	24.3	23.1	21.0	19.8	17.6	16.7	15.4
5:35 pm	26.3	24.7	23.5	21.3	20.0	17.7	16.6	15.3
6:18 pm	**27.0**	**25.2**	**24.0**	**21.8**	**20.4**	**17.9**	**17.0**	**15.5**
Small Brass 13 mm								
6:23 pm	26.5	25.3	24.6	X	X	16.2	15.8	14.9
6:30 pm	31.0	29.5	28.5	X	X	16.8	16.2	15.1

6:40 pm	33.7	32.2	30.9	X	X	17.3	16.5	15.3
6:51 pm	34.8	33.2	32.0	X	X	17.5	16.6	15.3
7:00 pm	**35.2**	**33.5**	**32.3**	**X**	**X**	**17.6**	**16.7**	**15.4**
Stainless Steel 25 mm								
7:05 pm	34.4	32.9	32.0	X	X	16.5	16.0	15.0
7:15 pm	37.3	35.7	34.6	X	X	16.9	16.3	15.2
7:20 pm	Power shutdown, resumed at 7:23 pm							
7:23 pm	34.0	32.8	32.1	X	X	16.9	16.3	15.2
7:30 pm	37.0	35.4	34.4	X	X	16.9	16.3	15.2
7:40 pm	38.6	36.9	35.8	X	X	17.2	16.5	15.3
7:45 pm	**39.0**	**37.4**	**36.2**	**X**	**X**	**17.3**	**16.6**	**15.4**

Convection Raw Data **(Pin Fin vs. Plate)**

Area Top Opening= 3 in x 4 13/16 in

Area Plate= 4 15/16 in x 3 15/16 in

Area Pin Fins= Area Plate+ 17 pins*0.466in*pi*2.655 in … 0.466 in diameter… 2.655 in length

Free Convection

V= 6.5 V

I= 2.35 A

Table 6: Raw data for natural convection.

Sample	Power W	Inlet Temp(°C)	Outlet Temp(°C)	Sample Temp (°C)	IRT	Flow rate	Probe Temp Loc 1	Probe Temp Loc 2	Probe Temp Loc 3
Plate									
8:04	15.275	24.4	29.3	90.9		0			

Since there was no flow rate detected, we were unable to perform the free convection portion of the experiment

Forced Convection

V= 6.5 V

I= 2.35 A

Table 7: Raw data for forced convection (plate).

Sample	Power	Inlet temp(°C)	Outlet Temp(°C)	Sample Temp (°C)	IRT	Flow Rate (m/s)	Probe Temp Loc 1	Probe Temp Loc 2	Probe Temp Loc 3
Plate									

8:11 pm	15.275 W	24.9	83.5	27.2		5			
8:20 pm	15.275 W	24.9	70.2	26.3		5			
8:25 pm	**15.275 W**	**25.3**	**66.1**	**26.7**		**5**			

Forced Convection

V = 6.5 V

I = 2.35 A

Table 8: Raw data for forced convection (fin).

Sample	Power	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)	T5 (°C)	T6 (°C)	Flow Rate (m/s)
12:42 PM	15.275	24.5	25.8	33.5	30.6	30.1	30.1	5
12:50 PM	15.275	25.0	25.1	29.1	27.7	27.4	27.5	5
1:00 PM	15.275	25.0	25.3	29.2	27.8	27.5	27.7	5
1:10 PM	15.275	25.7	25.9	29.6	28.3	27.9	28.1	5
1:20 PM	15.275	25.5	25.8	29.7	28.3	27.9	28.2	5

Pin-Fin (Recorded on Friday, October 18th, 2019)

Radiation Data Table
Power= 70 W
L= 130 mm ± 0.05mm

Table 9: Raw data for radiation.

Temperature (°C)	Irradiance (EH in W/m^2)
20	1
30	18
40	46
50	100
60	160
70	230
80	306
90	389
100	477
110	572
120	679
130	791
140	915
150	1053

Convection Calculations

Flat plate

Q = hAΔT
Where h = (K/D)(.023)(DG/μ)^.8(cpμ/K)^.4
G = pv, D = 4A/P
ΔT = T3-((T1-T2)/2)

ΔT= 66.1 °C - ((26.7°C - 25.3°C)/2)
ΔT= 40.1°C = 40.1 K since ΔTC °C) = ΔT(k)
Properties of air at T3 = 299.0 K:
P = 1.1661 kg/mg^3, cp = 1.0070 kJ/kg K , μ = 184.10 x 10^-7 N s/ m^2
K = 26.220 x 10^-3 W/mK
G = (1.1661 kg/m^3)(5m/s)= 5.8305 kg/m^2s
A = (4.8125 in)(3.00 in)(6.415 x 10^6 m^2/1in) = 9.3145 x 10^-3 m^2
P = (2)(4.8125 in +3 in)(25.4 x 10^3m/1in) = .39688 m
Then D = ((4)(9.3145 x 10^-3 m^2)/ .39688 in)) = 9.3877 x 10^-2 m
h = (26.220 x 10^-3 J/smK/9.3877 x 10^-2 m)*(0.023)*(9.3877 x 10^-2 m)(5.8305 kg/m^2s)/(184.10 x10^-7Ws/m^2)^.8*(1.0070 kJ/kg K)(184.10 x 10^-7 Ws/m^2)/26.220 x 10^-3 W/mK)
H = 21.995 W/m^2K
ΔT = 66.1°C -(26.7°C + 25.3°C)/2 = 40.1°C =40.1K
Q= (21.995 W/m^2K)(9.3145x10 ^-3 m^2)((40.1K)
Q = 8.0566 W

b.) q = mcpΔTamb
M = pvA
M= (1.611kg/m^3)(5m/s)(9.3145 x 10^-3m^2)
M = 5.4308 x 10^-2 kg/s
ΔTamb =26.7°C - 25.3°C = 1.4°C = 1.4 K
Q = (5.4038 x 10^-2 kg/s) (1.0070 kj/kg K)(1.4 K) (100W/1 kj/s)
Q = 76.563 W

Pin Fin

Tamb = (25.5°C + 26.8°C) /2 = 25.65°C = 298.65 K
Tm= 29.7°C , Ua = 5 m/s, V = 6.5 V, I = 2.35 A
Conv heat transfer
Q = hAΔT
ΔT = 29.7°C - 35.65 °C = 4.05 °C = 4.05 K
Where h = (K/D)(.023)(DG/μ)^.8(cpμ/K)^.4
G = pv, D = 4A/P
Properties of air at T3 = 298.65 K:
P = 1.1677 kg/mg^3, cp = 1.0070 kJ/kg K , μ = 183.10 x 10^-7 N s/ m^2
K = 26.220 x 10^-3 W/mK
G = (1.1661 kg/m^3)(5m/s)= 5.8305 kg/m^2s
A = (4.375 in)(3.9375 in)+ 17(pie)(.466in)(2.655 in)
A= .053744 m^2
P = (pie)(.466 in)(25.4 x 10^3m/1in) = .037185 m
Then D = ((4)(0.053744 m^2)/ .037185 in)) = 5.7183 m
h = (26.192 x 10^-3 J/smK/5.7183 m)*(0.023)*(5.7813m)(5.8305 kg/m^2s)/(183.93 x10^-7Ws/m^2)^.8*(1.0070 kJ/kg K)(183.93 x 10^-7 Ws/m^2)/26.192 x 10^-3 W/mK)
H = 9.3028 W/m^2K
Q= (9.3028 W/m^2K)(.053744 m^2)(4.05 K)

Q =2.0245 W

b.) q = mcpΔTamb
M = pvA
M= (1.677 kg/m^3)(5m/s)(.053744 m ^2)
M = .31378 kg/s
ΔTamb =25.8°C - 25.5°C = .3°C = .3 K
Q = (.31378 kg/s) (1.0070 kj/kg K)m = .31378 kg /s
(.3 K)(100 W/1kj/s)
Q = 94.792 W

Radiation (Sample Calculation for 30 °C)

E_H= 18 W/m_2
E_{amb}= C_S*((273+T_{amb})/100)^4= 5.67*((273+20)/100)^4= 417.88 W/m_2
E_S= E_H+E_{amb}= 18 W/m_2+417.88 W/m_2= 435.88 W/m_2
E_{theo}= C_S*((273+T_{amb})/100)^4=5.67*((273+30)/100)^4= 477.41 W/m_2
ε= E_S/E_{theo}*100%= 435.88 W/m_2/477.41 W/m_2*100%= 91.3%

Reference

https://theengineeringmindset.com/density-of-metals/
https://www.aksteel.com/sites/default/files/2018-01/304304L201706_1.pdf
Incropera, Frank. "Heat Transfer of Extended Surfaces." *Fundamentals of Heat and Mass Transfer*, edited by Joesph Hayden, NY, Wiley, 2007, (141-143).