ME 320 Heat Transfer Experiment:
Free vs. Forced Convection Coefficient Comparison

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Introduction

Free convection is the natural heat transfer from a material to its surroundings, while forced convection is this transfer under the influence of air flow acting on the object. The greater the air flow keeping all other conditions the same, the greater the rate of temperature change and the greater the heat flux. This experiment determines how significant of an impact forced convection air flow has on the convection coefficient of different material samples. Using a scenario of free convection compared to two scenarios of different forced convection air flow speeds, this experiment compares the convection coefficients to quantify the impact of forced convection on material convective properties. Each material starts at an initial temperature significantly above room temperature, and this experiment records how the temperature changes over time as it dissipates heat to its surroundings. This rate of temperature change is used to calculate the convection coefficient for each of the material and air flow speed scenarios.

Research Question: What is the impact of forced convection air flow speed on a material's convection coefficient? How does this compare to the material's free convection coefficient, and is this relationship similar or different when evaluated for different materials?

Experimental Methods

For three different materials, the specimen is heated to an initial temperature far above the room air temperature. This specimen is then placed in the path of a wind tunnel with one of the faces of the cube facing the direction of air flow. As the material experiences heat loss to the surroundings via free or forced convection, a thermocouple is used to measure and record its changing temperature in increments of 20 seconds. Time is the independent variable while our dependent variable is the set of changing temperature data (dT_s/dt) needed to calculate the convection coefficient. Air speed is also an independent variable, as this creates a comparison between the calculated convection coefficient of free vs forced convection. The volume and surface area of each material specimen are constant as well as the direction of air flow from the wind tunnel.

Materials Needed:

- 0.025 m side length cubes of stainless steel, copper, and aluminum
- Material heating oven
- Wind tunnel
- Thermocouple for material sample temperature measurement
- Temperature monitor
- Spreadsheet to record temperature values at time iterations

Experimental Setup:
Both free convection and forced convection are evaluated using the setup shown below with a heated material specimen placed on a thermocouple and in the path of a wind tunnel.

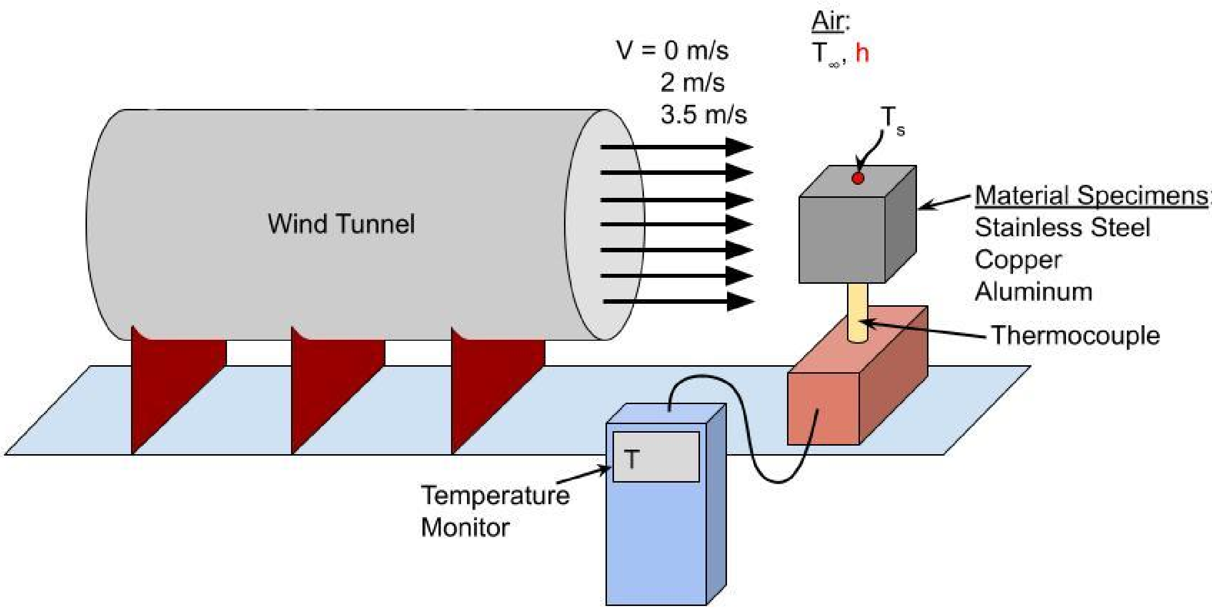

Figure 1: Setup / Schematic

Experimental Procedure:

Free convection

1. Set up experimental materials
    a. Connect the thermocouple to the temperature monitor
2. Heat cube of stainless steel to an initial surface temperature
3. Attach the heated cube to thermocouple
4. Monitor and plot continuous data for the surface temperature
    a. Every 20 seconds starting at t = 0, record the thermocouple temperature measurement and record it in a spreadsheet
    b. Stop collecting data at t = 580 seconds
5. Calculate the average convection coefficient using Equation 5 in the calculation methods section
6. Confirm that the lumped capacitance method is valid using Equation 6
7. Repeat steps 1-6 for copper and aluminum

Forced convection

1. Set up experimental materials
    a. Connect the thermocouple to the temperature monitor
    b. Turn on the wind tunnel
    c. Use a wind speed measurement instrument at the output of the wind tunnel

    d. Adjust the voltage input to the wind tunnel until the measured wind speed is at V = 2 m/s
2. Heat cube of stainless steel to an initial surface temperature
3. Attach the heated cube to thermocouple and make sure one face of the cube is facing the wind tunnel output
4. Monitor and plot continuous data for the surface temperature
    a. Every 20 seconds starting at t = 0, record the thermocouple temperature measurement and record it in a spreadsheet
    b. Stop collecting data at t = 580 seconds
5. Calculate the average convection coefficient using Equation 5 in the calculation methods section
6. Confirm that the lumped capacitance method is valid using Equation 6
7. Repeat steps 1-6 for copper and aluminum
8. Repeat steps 1-7 for V = 3.5 m/s

<u>Assumptions</u>:
1. Steady-state conditions
2. For each material and flow speed condition, the convection coefficient h is constant throughout the heat dissipation process
3. Radiation is negligible
4. Air flow from the wind tunnel is laminar

<u>Calculation Methods</u>:

Convection heat transfer is represented by this formula. The convection coefficient h is constant per material, but increases with air flow for cases of forced convection.

<u>Equation 1</u>:

$$q = hA_c(T_s - T_\infty)$$

Heat transfer is also a function of the change of temperature over time dT/dt that we measure in this experiment as well as the specific heat and mass of the material.

<u>Equation 2</u>:

$$q = -mc_p(dT/dt)$$

The lumped capacitance method is expressed in Equation 3 below and can be used to solve for h as shown by Equation 4.

Equation 3:

$$hA_c(T_s - T_\infty) =- mc_p(dT/dt)$$

Equation 4:

$$h =- mc_p(dT/dt) \,/\, A_c(T_s - T_\infty)$$

Values that remain constant throughout the experiment are the change in time dt = 20 seconds, the surface area of the block A_c = 0.000625 m^2, and the surrounding room temperature T_∞ = 21.67 C. We can therefore substitute these values into Equation 4 to create Equation 5. Mass m is dependent on the material specimen. The values that vary with time are the temperature of the block T_s, the change in temperature of the block over 20 seconds dT_s, and the specific heat of the cube material as temperature changes. Density and specific heat must be found at the corresponding evaluated T_s.

Equation 5:

$$h =- mc_p(dT/20) \,/\, 0.000625(T_s - 21.67)$$

To confirm that this lumped capacitance method calculation of h is valid, this calculated convection coefficient h and the material conduction coefficient k as well as side length L must be used to calculate the Biot number. If Bi ≤ 0.1, the lumped capacitance method is valid.

Equation 6:

$$Bi = hL/k$$

Results and Discussion

Specimen mass, conduction coefficient and dimensions of each material are needed for calculations. These properties are shown in Table 1 below.

Table 1: Material Properties

Material	k [W/(m*K)]	Mass (g)	Side Length (m)	A_c (m^2)
Stainless Steel	25	122	0.025	0.000625
Copper	398	131.5	0.025	0.000625
Aluminum	237	41.8	0.025	0.000625

The experimental procedure yielded temperature change vs time data for all three materials at each of the flow speeds as shown in Table 2. Figures 2 through 4 show plots of this temperature change for all nine scenarios organized by air flow speed. The rate of temperature change dT/dt for each material and wind speed scenario slowly reduces as the block temperature T_s becomes closer to the surrounding temperature T_∞. The rate of change dT/dt at the same T_s value is greater, however, the higher the wind velocity V. This is also expected behavior, as forced convection causes greater heat dissipation. These plots also show us differences between the evaluated materials in that aluminum appears to have the highest temperature change rate (dT/dt) compared to the other materials under the same conditions while stainless steel has the lowest. This is true for each of the scenarios of free vs forced convection.

Table 2: Temperature Change over Time Experimental Data

	Temperature (C)								
Time (s)	Stainless Steel			Copper			Aluminum		
	0 m/s	**2 m/s**	**3.5 m/s**	**0 m/s**	**2 m/s**	**3.5 m/s**	**0 m/s**	**2 m/s**	**3.5 m/s**
0	83.8	115.3	136.5	109.7	116	127.2	94.9	92.9	105.1
20	83.1	112.3	130.3	108.7	112.1	120	94.2	89.4	97.6
40	82.3	109.2	124.1	107.2	108.3	113.6	93	85.5	91.3
60	81.4	106.1	118.3	105.7	104.7	107.3	91.5	82	85.1
80	80.6	103.3	113.1	104.3	101.1	101.4	90.1	78.8	79.8
100	79.8	100.1	107.9	102.9	97.7	96	88.8	75.5	74.6
120	79	97.4	103	101.5	94.3	91.1	87.6	72.8	70.1
140	78.2	94.7	98.3	100.1	91.2	86.4	86.3	69.9	66.1
160	77.4	92.2	94.2	98.7	88.2	82.2	85	67.2	62.3
180	76.7	89.8	90	97.4	85.5	78.1	83.9	64.8	58.7
200	75.9	87.4	86.3	96	82.6	74.3	82.6	62.7	55.8
220	75.1	85	82.5	94.8	80.1	70.8	81.4	60.3	52.9
240	74.4	82.7	79.2	93.6	77.5	67.6	80.3	58.1	50.3
260	73.7	80.5	76	92.3	75.1	64.5	79.1	56.2	47.9
280	73	78.5	73	91.1	72.8	61.7	78	54.4	45.9
300	72.3	76.4	70.2	90	70.7	59.2	76.9	52.6	43.9
320	71.6	74.5	67.5	88.8	68.5	56.6	75.7	51	42.2
340	70.9	72.6	65	87.7	66.4	54.4	74.7	49.4	40.6
360	70.3	70.8	62.6	86.6	64.5	52.4	73.6	48	39.2
380	69	69.1	60.3	85.6	62.7	50.5	72.3	46.6	37.9
400	69	67.3	58.1	84.5	60.9	48.6	71.5	45.3	36.7
420	68.3	65.6	56.3	83.5	59.2	46.9	70.3	44.1	35.6
440	67.7	64.1	54.3	82.4	57.5	45.3	69.4	42.9	34.5
460	67.1	62.6	52.6	81.5	56	43.9	68.3	41.8	33.7
480	66.5	61.1	50.9	80.4	54.4	42.6	67.7	40.8	32.9
500	65.9	59.7	49.4	79.4	53	41.3	66.7	39.9	32.2
520	65.4	58.3	47.9	78.5	51.6	40.2	65.9	38.9	31.6
540	64.7	57	46.5	77.6	50.3	39.1	65.2	38.1	31
560	64.2	55.7	45.2	76.7	49	38.1	64.4	37.2	30.4
580	63.6	54.4	44	75.8	47.8	37.2	63.6	36.5	30

Since the temperature of the block T_s, the change in temperature of the block dT_s, and the specific heat of the material specimen change with time, the convection coefficient can be calculated for each time step using Equation 5. Tables 3 through 5 show these calculations for free convection, V = 2 m/s, and V = 3.5 m/s. The calculated coefficient experiences slight variation at each time step due to error factors. It should not experience a trend of increase or decrease with progressing time, however, because it is assumed to be a constant given the experimental conditions. These convection coefficient calculations were performed in Excel using the determined constants, the time-varying components calculated at each step, and Equation _ at each step. The calculated average convection coefficient h_{avg} in each scenario is the experimentally-determined value for the tested material. Since variation of the calculated coefficient at each time step is an indicator of error, this is quantified by the calculated standard deviation as addressed in the uncertainty analysis section.

Free Convection Coefficient Calculations:

Figure 2 plots the temperature change over time for the three free convection scenarios. This data, among the constants, is used to calculate the convection coefficient via the lumped capacitance method. These convection coefficients are shown in Table 3.

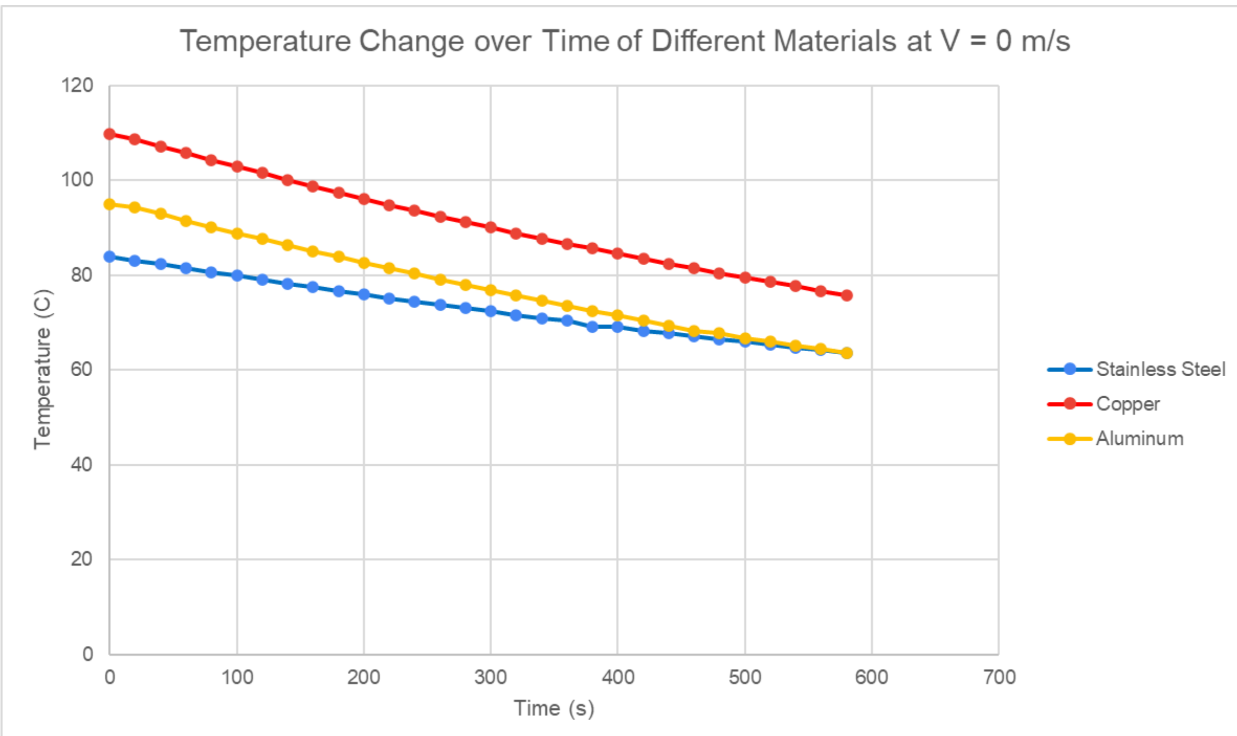

Figure 2

Table 3

Time (s)	Stainless Steel dT_s/dt	Stainless Steel Biot	Stainless Steel Specific Heat [J/(kg*K)]	Stainless Steel h [W/(m^2*K)]	Copper dT_s/dt	Copper Biot	Copper Specific Heat [J/(kg*K)]	Copper h [W/(m^2*K)]	Aluminum dT_s/dt	Aluminum Biot	Aluminum Specific Heat [J/(kg*K)]	Aluminum h [W/(m^2*K)]
	Convection Coefficient Calculations at V = 0 m/s											
0	0.7	0.0510	464.1	51.03	1	0.0030	394.9	47.20	0.7	0.0032	934.2	29.86
20	0.8	0.0589	463.7	58.94	1.5	0.0045	394.8	71.58	1.2	0.0054	933.7	51.66
40	0.9	0.0671	463.3	67.13	1.5	0.0046	394.6	72.81	1.5	0.0069	933.2	65.62
60	0.8	0.0605	463.0	60.52	1.4	0.0043	394.5	69.14	1.4	0.0066	932.7	62.53
80	0.8	0.0613	462.6	61.29	1.4	0.0044	394.3	70.29	1.3	0.0062	932.2	59.22
100	0.8	0.0621	462.2	62.08	1.4	0.0045	394.2	71.47	1.2	0.0059	931.7	55.69
120	0.8	0.0629	461.8	62.90	1.4	0.0046	394.1	72.70	1.3	0.0065	931.1	61.40
140	0.8	0.0637	461.4	63.73	1.4	0.0046	393.9	73.97	1.3	0.0066	930.6	62.60
160	0.7	0.0565	461.0	56.52	1.3	0.0044	393.8	69.91	1.1	0.0057	930.1	54.02
180	0.8	0.0654	460.7	65.36	1.4	0.0048	393.6	76.55	1.3	0.0069	929.6	64.94
200	0.8	0.0663	460.3	66.27	1.2	0.0042	393.5	66.83	1.2	0.0065	929.1	61.19
220	0.7	0.0588	459.9	58.81	1.2	0.0043	393.3	67.90	1.1	0.0060	928.6	57.19
240	0.7	0.0595	459.5	59.54	1.3	0.0047	393.2	74.76	1.2	0.0067	928.1	63.52
260	0.7	0.0603	459.1	60.29	1.2	0.0044	393.0	70.25	1.1	0.0063	927.5	59.41
280	0.7	0.0611	458.8	61.06	1.1	0.0041	392.9	65.48	1.1	0.0064	927.0	60.54
300	0.7	0.0619	458.4	61.85	1.2	0.0046	392.7	72.56	1.2	0.0071	926.5	67.32
320	0.7	0.0627	458.0	62.67	1.1	0.0043	392.6	67.68	1	0.0060	926.0	57.31
340	0.6	0.0544	457.6	54.43	1.1	0.0043	392.5	68.78	1.1	0.0068	925.5	64.20
360	1.3	0.1193	457.2	119.29	1	0.0040	392.3	63.56	1.3	0.0082	925.0	77.43
380	0	0.0000	456.8	0.00	1.1	0.0045	392.2	70.99	0.8	0.0052	924.5	48.85
400	0.7	0.0659	456.5	65.89	1	0.0041	392.0	65.64	1.2	0.0078	923.9	74.41
420	0.6	0.0573	456.1	57.28	1.1	0.0046	391.9	73.34	0.9	0.0060	923.4	57.15
440	0.6	0.0580	455.7	57.97	0.9	0.0038	391.7	61.07	1.1	0.0075	922.9	71.13
460	0.6	0.0587	455.3	58.69	1.1	0.0048	391.6	75.74	0.6	0.0042	922.4	39.69
480	0.6	0.0594	454.9	59.43	1	0.0044	391.4	70.12	1	0.0071	921.9	66.97
500	0.5	0.0502	454.5	50.15	0.9	0.0040	391.3	64.17	0.8	0.0058	921.4	54.74
520	0.7	0.0710	454.2	70.95	0.9	0.0041	391.1	65.17	0.7	0.0051	920.9	48.74
540	0.5	0.0515	453.8	51.46	0.9	0.0042	391.0	66.19	0.8	0.0060	920.4	56.56
560	0.6	0.0624	453.4	62.43	0.9	0.0042	390.9	67.25	0.8	0.0061	919.8	57.59
			h_avg	60.27			**h_avg**	68.73			**h_avg**	59.02
			st. dev.	16.63			**st. dev.**	5.63			**st. dev.**	9.59

All of the Biot numbers associated with the calculated h at each time step are less than 0.1, so the lumped capacitance method used to calculate h for the case of V = 0 m/s is valid. The experimental results are therefore likely to be accurate aside from any sources of bias or precision error. These convection coefficient results are displayed in Table 6, along with the results for the two forced convection scenarios.

<u>Forced Convection Coefficients at V = 2 m/s</u>:

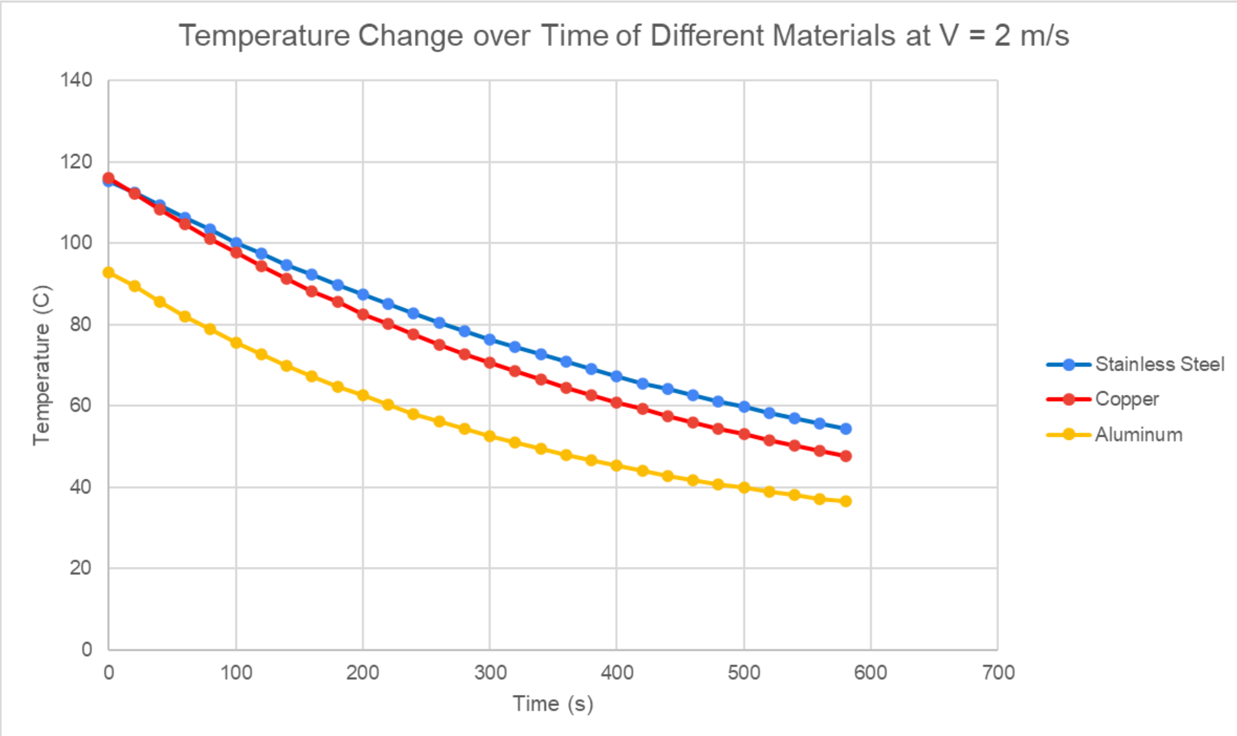

Figure 3

Table 4

Time (s)	Convection Coefficient Calculations at V = 2 m/s											
	Stainless Steel				Copper				Aluminum			
	dT_s/dt	Biot	Specific Heat [J/(kg*K)]	h [W/(m^2*K)]	dT_s/dt	Biot	Specific Heat [J/(kg*K)]	h [W/(m^2*K)]	dT_s/dt	Biot	Specific Heat [J/(kg*K)]	h [W/(m^2*K)]
0	3	0.1504	480.8	150.36	3.9	0.0108	395.7	172.10	3.5	0.0162	933.3	153.36
20	3.1	0.1600	479.2	159.99	3.8	0.0110	395.3	174.73	3.9	0.0189	931.8	179.42
40	3.1	0.1651	477.7	165.12	3.6	0.0108	394.8	172.60	3.5	0.0180	930.3	170.58
60	2.8	0.1541	476.1	154.11	3.6	0.0113	394.4	179.89	3.2	0.0174	928.8	164.74
80	3.2	0.1816	474.6	181.57	3.4	0.0111	394.0	177.41	3.3	0.0189	927.3	179.11
100	2.7	0.1589	473.0	158.93	3.4	0.0116	393.5	185.14	2.7	0.0164	925.7	155.27
120	2.7	0.1641	471.5	164.05	3.1	0.0111	393.1	176.51	2.9	0.0185	924.2	175.29
140	2.5	0.1570	469.9	157.00	3	0.0112	392.7	178.24	2.7	0.0182	922.7	172.73
160	2.4	0.1557	468.7	155.65	2.7	0.0105	392.4	167.51	2.4	0.0171	921.7	162.47
180	2.4	0.1607	467.4	160.71	2.9	0.0118	392.1	187.38	2.1	0.0158	920.7	149.91
200	2.4	0.1661	466.2	166.14	2.5	0.0106	391.7	169.09	2.4	0.0190	919.7	179.89
220	2.3	0.1648	465.0	164.82	2.6	0.0115	391.4	183.23	2.2	0.0185	918.7	174.95
240	2.2	0.1632	463.8	163.16	2.4	0.0111	391.1	176.87	1.9	0.0169	917.6	160.04
260	2	0.1535	462.5	153.47	2.3	0.0111	390.8	176.97	1.8	0.0169	916.6	159.78
280	2.1	0.1664	461.3	166.37	2.1	0.0106	390.5	168.72	1.8	0.0178	915.6	168.39
300	1.9	0.1560	460.3	155.97	2.2	0.0116	390.3	184.21	1.6	0.0167	914.9	158.27
320	1.9	0.1612	459.4	161.24	2.1	0.0116	390.0	183.99	1.6	0.0176	914.3	166.78
340	1.8	0.1581	458.4	158.12	1.9	0.0109	389.8	174.18	1.4	0.0163	913.6	154.24
360	1.7	0.1545	457.4	154.48	1.8	0.0108	389.6	172.23	1.4	0.0171	912.9	162.32
380	1.8	0.1691	456.4	169.07	1.8	0.0113	389.3	179.69	1.3	0.0168	912.3	159.08
400	1.7	0.1656	455.5	165.62	1.7	0.0111	389.1	177.39	1.2	0.0163	911.6	154.80
420	1.5	0.1515	454.5	151.47	1.7	0.0116	388.9	185.31	1.2	0.0172	910.9	162.97
440	1.5	0.1565	453.6	156.52	1.5	0.0108	388.7	171.18	1.1	0.0166	910.4	157.74
460	1.5	0.1620	452.8	161.95	1.6	0.0120	388.5	190.47	1	0.0159	909.9	151.16
480	1.4	0.1566	451.9	156.61	1.4	0.0110	388.3	174.72	0.9	0.0151	909.4	143.07
500	1.4	0.1621	451.1	162.07	1.4	0.0115	388.1	182.43	1	0.0176	908.9	166.73
520	1.3	0.1559	450.2	155.95	1.3	0.0111	387.9	177.24	0.8	0.0149	908.4	141.04
540	1.3	0.1614	449.4	161.38	1.3	0.0116	387.7	185.19	0.9	0.0175	907.9	166.31
560	1.3	0.1672	448.5	167.22	1.2	0.0112	387.5	178.98	0.7	0.0144	907.4	136.77
			h_avg	160.66			**h_avg**	178.06			**h_avg**	161.63
			st. dev.	6.40			**st. dev.**	5.95			**st. dev.**	11.24

As expected, the convection coefficient calculations of each material increase with forced convection air flow. This means that the Biot numbers have increased, so it is important to confirm that the lumped capacitance method is still valid. Bi < 0.1 for copper and aluminum, so this method is valid for both of these materials. For stainless steel, however, the Biot numbers are slightly above 0.1 so a different method is needed to find a more accurate convection coefficient.

Forced Convection Coefficients at V = 3.5 m/s:

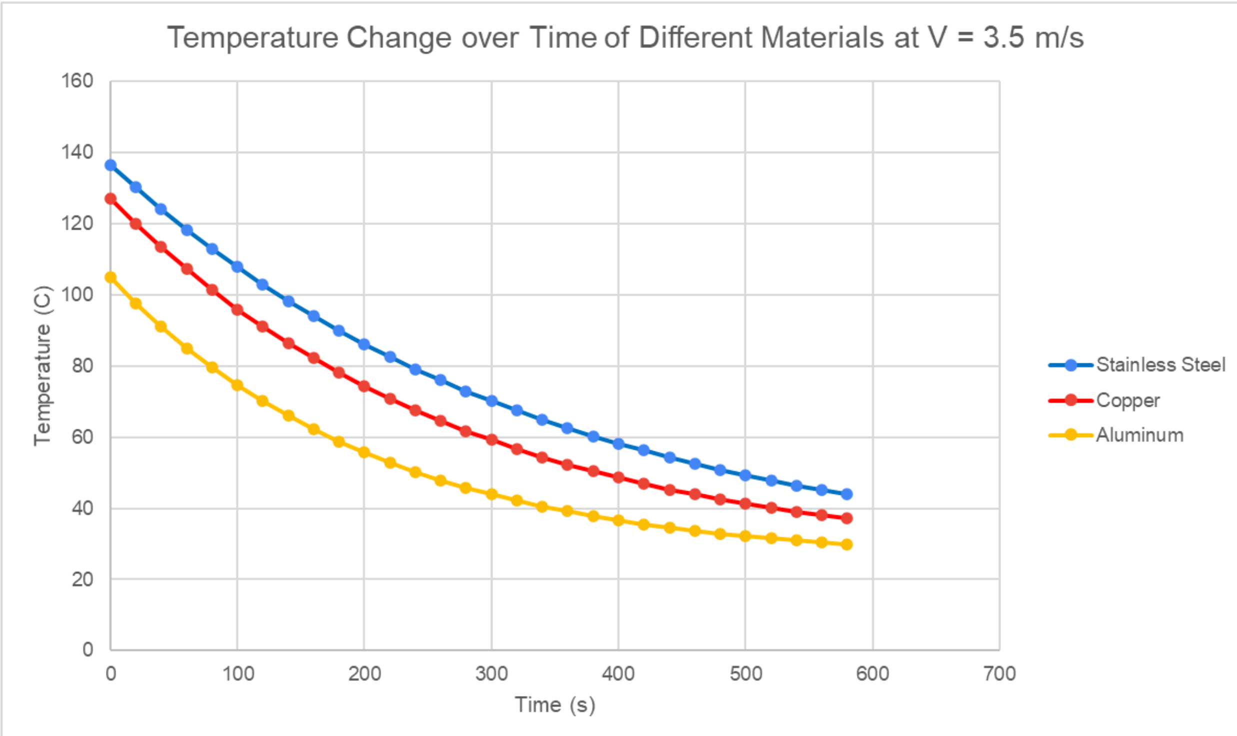

Figure 4

Table 5

	Convection Coefficient Calculations at V = 3.5 m/s											
Time (s)	Stainless Steel				Copper				Aluminum			
	dT_s/dt	Biot	Specific Heat [J/(kg*K)]	h [W/(m^2*K)]	dT_s/dt	Biot	Specific Heat [J/(kg*K)]	h [W/(m^2*K)]	dT_s/dt	Biot	Specific Heat [J/(kg*K)]	h [W/(m^2*K)]
0	6.2	0.2584	490.4	258.44	7.2	0.0179	397.0	284.95	7.5	0.0298	938.9	282.25
20	6.2	0.2717	487.8	271.71	6.4	0.0170	396.3	271.35	6.3	0.0274	936.4	259.80
40	5.8	0.2681	485.1	268.09	6.3	0.0179	395.6	285.20	6.2	0.0293	933.8	278.05
60	5.2	0.2534	482.4	253.39	5.9	0.0180	394.9	286.24	5.3	0.0274	931.3	260.21
80	5.2	0.2663	479.8	266.33	5.4	0.0176	394.2	280.87	5.2	0.0293	928.7	277.81
100	4.9	0.2646	477.1	264.62	4.9	0.0171	393.5	272.89	4.5	0.0278	926.1	263.30
120	4.7	0.2676	474.5	267.62	4.7	0.0176	392.8	279.73	4	0.0269	923.6	255.09
140	4.1	0.2464	471.8	246.38	4.2	0.0168	392.1	267.64	3.8	0.0278	921.0	263.42
160	4.2	0.2656	469.9	265.58	4.1	0.0175	391.7	279.10	3.6	0.0287	919.7	272.50
180	3.7	0.2473	468.0	247.33	3.8	0.0174	391.3	277.18	2.9	0.0254	918.4	240.51
200	3.8	0.2675	466.1	267.46	3.5	0.0172	390.9	273.44	2.9	0.0275	917.0	260.57
220	3.3	0.2458	464.2	245.76	3.2	0.0168	390.4	267.53	2.6	0.0269	915.7	254.93
240	3.2	0.2509	462.2	250.95	3.1	0.0174	390.0	276.93	2.4	0.0270	914.4	256.32
260	3	0.2481	460.3	248.09	2.8	0.0168	389.6	267.95	2	0.0246	913.1	232.81
280	2.8	0.2441	458.4	244.06	2.5	0.0161	389.2	255.71	2	0.0265	911.7	251.66
300	2.7	0.2482	457.1	248.23	2.6	0.0178	388.9	283.46	1.7	0.0246	911.1	232.98
320	2.5	0.2427	455.9	242.71	2.2	0.0162	388.7	257.54	1.6	0.0250	910.4	237.26
340	2.4	0.2458	454.6	245.76	2	0.0157	388.4	249.70	1.4	0.0237	909.7	224.98
360	2.3	0.2486	453.3	248.63	1.9	0.0159	388.2	252.48	1.3	0.0238	909.0	225.43
380	2.2	0.2513	452.1	251.27	1.9	0.0169	387.9	268.94	1.2	0.0237	908.4	224.59
400	1.8	0.2174	450.8	217.39	1.7	0.0162	387.7	257.44	1.1	0.0234	907.7	222.15
420	2	0.2534	449.5	253.38	1.6	0.0162	387.4	258.45	1.1	0.0253	907.0	239.51
440	1.7	0.2281	448.6	228.10	1.4	0.0152	387.2	241.35	0.8	0.0199	906.7	189.05
460	1.7	0.2401	447.7	240.14	1.3	0.0150	387.1	238.12	0.8	0.0213	906.3	201.54
480	1.5	0.2237	446.7	223.75	1.3	0.0159	386.9	252.80	0.7	0.0199	905.9	188.83
500	1.5	0.2354	445.8	235.36	1.1	0.0143	386.7	227.97	0.6	0.0182	905.5	172.54
520	1.4	0.2318	444.9	231.75	1.1	0.0152	386.5	241.40	0.6	0.0193	905.2	182.89
540	1.3	0.2269	443.9	226.86	1	0.0146	386.4	233.20	0.6	0.0205	904.8	194.58
560	1.2	0.2205	443.0	220.51	0.9	0.0140	386.2	222.55	0.4	0.0146	904.4	138.58
			h_avg	247.57			**h_avg**	262.49			**h_avg**	233.94
			st. dev.	15.23			**st. dev.**	18.31			**st. dev.**	35.75

Table 5 shows that the calculated convection coefficients increase even further with a greater air flow speed. This result confirms expected behavior, as the convection coefficient must increase with a greater level of forced convection. The stainless steel Biot numbers for this air flow speed, however, are also greater than 0.1 so we cannot trust these calculated coefficients to be fully accurate. The Biot numbers of copper and aluminum remain below 0.1.

Convection Coefficient Results Comparison:

Table 6: Calculated Convection Coefficients of Each Scenario

Material	**h [W/(m^2*K)]**			**% Increase from Free Convection**	
	Air flow speed V (m/s)				
	0	2	3.5	2 m/s	3.5 m/s
Stainless Steel	60.27	160.66	247.57	166.57	310.77
Copper	68.73	178.06	262.49	159.07	281.91
Aluminum	59.02	161.63	233.94	173.86	296.37

Free convection results from this table summary show that the three tested materials have similar nominal convection coefficients. Given that the air conditions were the same despite different materials, this can be expected.

The difference in how each of these materials respond to forced convection is also evaluated using these coefficients and those calculated for forced convection. The case of free convection is a baseline that can be used to evaluate how much forced convection changes the convection coefficient of a material. As seen in the final two columns, the percent increase of the convection coefficient from free convection is calculated for V = 2 m/s and 3.5 m/s. There is no significant variation in this value between materials for V = 2 m/s, although this variation is slightly higher for V = 3.5 m/s because it is a more significant change from free convection. These results suggest that materials have slight differences in how their rate of convection changes with an added forced convection air flow.

<u>Uncertainty Analysis</u>:

Although we see some variation in the calculated convection coefficient at each time step, it should theoretically not change throughout the heat dissipation process since it is a constant given steady-state conditions. We do see some variation quantified by a calculated standard deviation, however, which indicates the presence of non-ideal conditions and possible precision error. This standard deviation is of the calculated convection coefficient at each time step, but it also represents precision error of the collected temperature change data because the collected data dT/dt is proportional to the calculated h as shown by Equation 5. Any errors in measuring temperature at a time step creates differing h values at these steps. Environmental factors may also have an impact on temperature measurements, however, and be a factor in these differing h calculations. These include a changing room temperature and slight changes in the wind tunnel speed. The standard deviation calculations shown in Table 7 quantify the error of each scenario, of which all of these factors may have contributed.

Table 7: Standard deviation of the Calculated h in Each Scenario

Nominal h [W/(m^2*K)]				**Standard Deviation**		
Material	Air flow speed V (m/s)					
	0	2	3.5	0	2	3.5
Stainless Steel	60.27	160.66	247.57	16.63	6.40	15.23
Copper	68.73	178.06	262.49	5.63	5.95	18.31
Aluminum	59.02	161.63	233.94	9.59	11.24	35.75

The standard deviation values indicate that there seems to be measurable precision error within this experiment. The greatest error appears to be at the largest air speed V = 3.5 m/s, which is expected because this had the quickest temperature change and introduces the greatest human error to the manual temperature time interval recordings. The Biot number is also larger at this greatest air flow speed due to a higher calculated h. Although most scenarios fell under lumped capacitance, it may have still affected the accuracy of the higher air flow h calculations.

Conclusion

This experiment demonstrates the quantity of change that the convection coefficient of a material experiences when placed under a forced convection condition. Using two different air flow speeds in comparison to the free convection condition, this experiment generated results of the calculated convection coefficients themselves and a percentage representation of the convection coefficient increase from the nominal free convection value. These results help us understand the impact air flow has on the convection heat transfer of an object and how this impact differs between materials.

<u>Recommendations for Improvement</u>:
To improve this experiment, it would be valuable to address some of the sources of error, particularly precision error. The experiment required manual recording of a thermocouple temperature measurement every 20 seconds. This introduces human error, but implementation of a digitally-compatible thermocouple would allow for automatic temperature logging and eliminate the human error. Digital data collection can also introduce far shorter time intervals for more accurate dT/dt data and therefore h calculations. This experiment involved only one trial per scenario, so to ensure the dT/dt data collection is accurate and consistent, it should involve at least 3 trials per scenario. Ensuring consistency of data collection under the same conditions can quantify precision error and is a factor in determining how accurate the final convection coefficient calculations are.

<u>Further Investigation</u>:
In this experiment, the primary factors under investigation are the impact of forced convection on the calculated convection coefficient of a material specimen and the differences of materials in how much forced convection changes the calculated coefficient. To expand on this experiment, more wind speeds can be tested and a convection coefficient calculated for each. This would create enough calculated coefficients over a variety of air flow speeds to plot convection coefficient vs air speed. The plot would provide a better understanding of how convection coefficient changes with air speed and create a predictive trendline for each material.

Appendices

<u>Appendix A</u>: Additional plots comparing temperature change over time (dT/dt) to air velocity

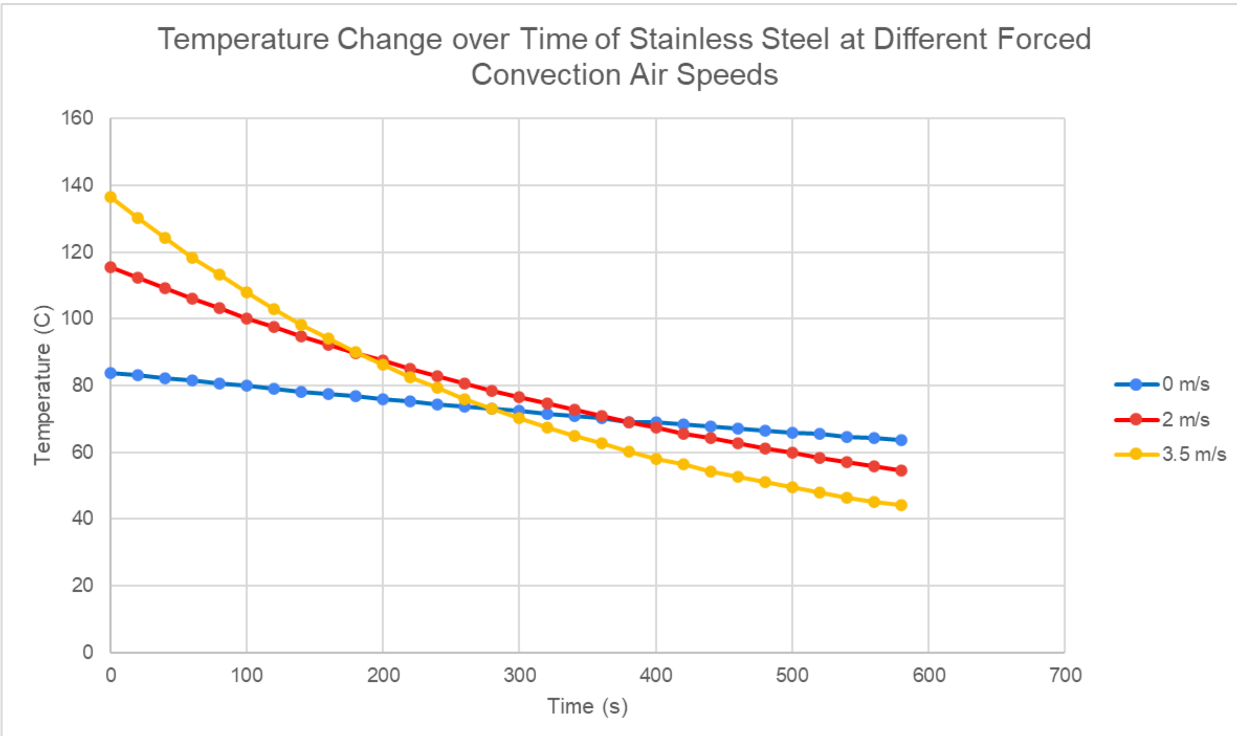

Figure 5

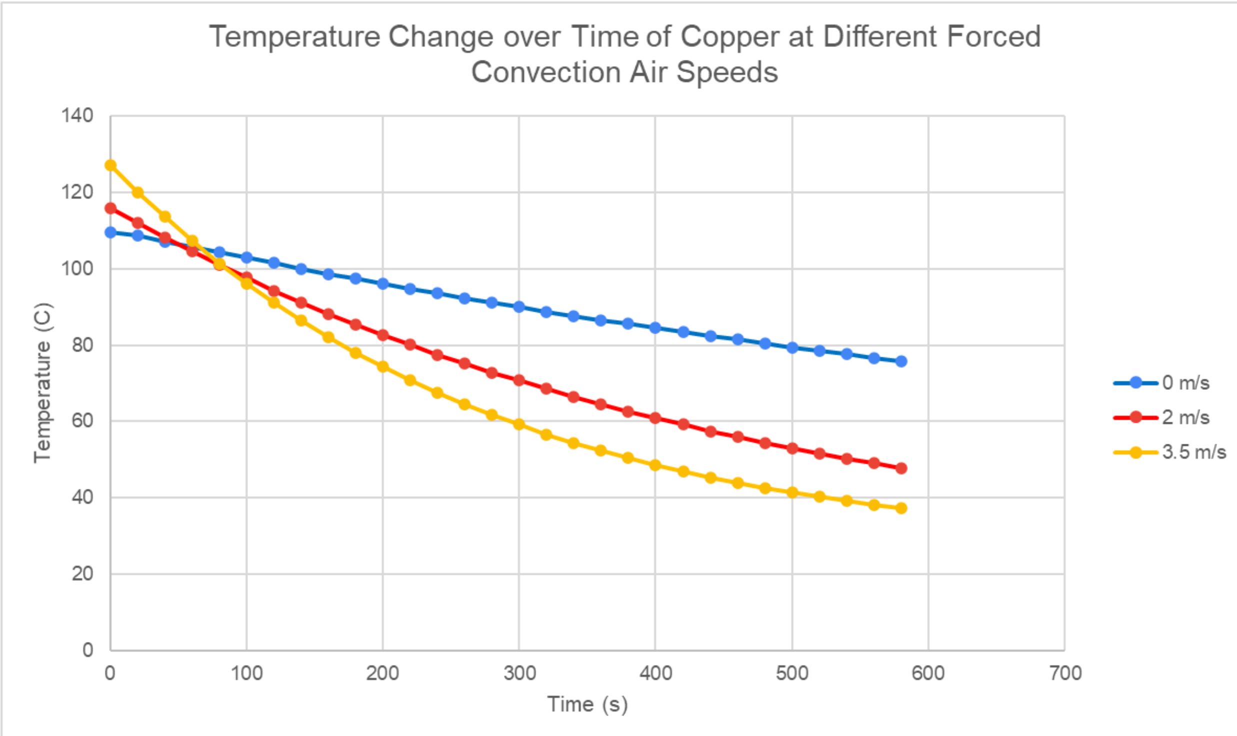

Figure 6

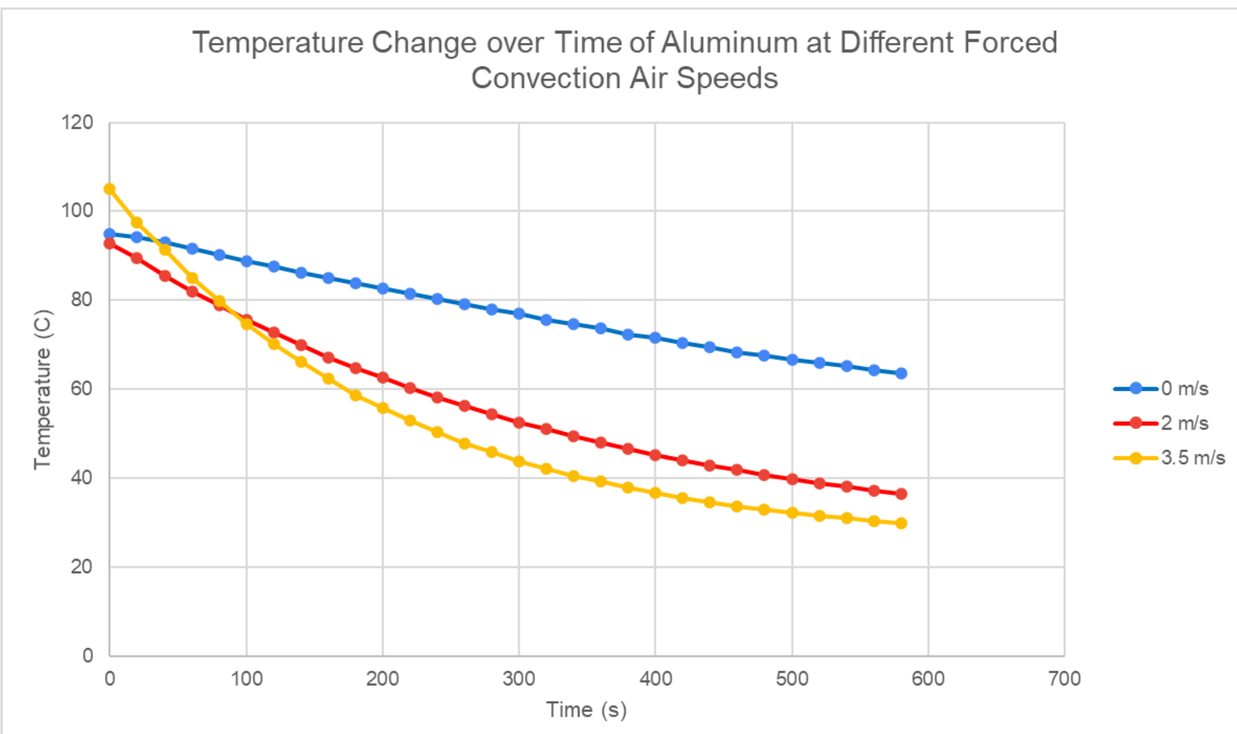

Figure 7

Appendix B: Time Spent on Experimental Process

Table 8

Activity	**Date and Time**
Designed experiment: Free vs forced convection	9/30
Determined research question	9/30
Found calculation methods of h	10/7
Created experimental procedure / setup	10/7 - 10/13
Gathered materials	10/14 11:00 am - 11:15 am
Took experimental data (Table 1)	10/14, 10/21 11:00 am - 12:30 pm
Performed data analysis	10/21 - 10/28
Wrote report	10/26 - 10/28