Convective Heat Transfer Over a Flat Plate

By

Caleb Capps,

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Lab Section: 904

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Instructor: Tikran (Ted) Kocharian

Objective

The objective of this laboratory exercise is to experimentally determine the convective heat transfer coefficient, h, for a flat plate in external flow.

Background

Convective heat transfer occurs when a solid and a fluid exchange energy across a boundary. This energy exchange is governed by the coefficient of convective heat transfer, h, which depends on fluid flow conditions (turbulent vs. laminar), geometry of the convecting body, fluid type (Newtonian vs. non-Newtonian), and surface condition (isothermal or constant heat flux). The fluid flow condition can be quantified using unitless Reynold's number using eq. 1 for the case of crossflow of a cylinder.

$$Re_x = \frac{ux}{\nu} \tag{1}$$

Where:

- u is the velocity of the fluid ($\mathrm{ft/s}$)
- x is the distance from the leading edge of the sample (ft)
- ν is the kinematic viscosity of the fluid ($\mathrm{ft^2/s}$)

Additionally, the ratio for the growth of the velocity boundary layer versus the thermal boundary layer is quantified using Pr, the Prandtl Number.

$$Pr = \frac{\nu}{\alpha} \tag{2}$$

Where:

- α is the thermal diffusivity of the material ($\mathrm{m^2/s}$)

Using these, for a flat plate if Re is less than $5 * 10^5$, then the flow regime is considered to be laminar, and the convective heat transfer coefficient is calculated as

$$h_x = \frac{k}{x} * 0.453 * Re_x^{1/2} * Pr^{1/3} = \frac{k}{x} * Nu_x \tag{3}$$

Where:

- k is the coefficient conductive heat transfer ($\mathrm{W/m^2 \cdot k}$)
- Nu_x is the Nusselt Number

If the Reynold's Number is more than $5 * 10^5$, then the flow regime is considered to be turbulent, and the convective heat transfer coefficient is calculated as

$$h_x = \frac{k}{x} * 0.0308 * Re_x^{\frac{4}{5}} * Pr^{1/3} \tag{4}$$

In this laboratory exercise, a flat plate was placed in a wind tunnel, with nine thermocouples attached as shows in figure X as shown below,

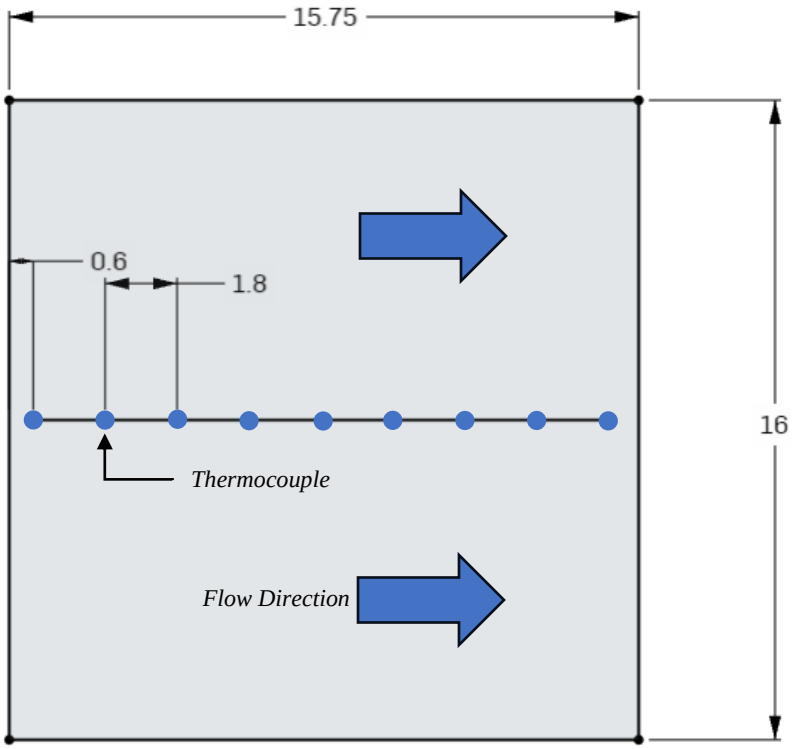

Figure 1. Experimental Setup

It is important to note that fluid properties are determined at the film temperature, which is given by:

$$T_f = \frac{T(x)+T_\infty}{2} \tag{5}$$

Additionally, the nominal wind velocity was given, but due to the introduction of the plate, a blockage is created, which increases the velocity according to the relationship:

$$PAu = PA'u' \tag{6}$$

Where:

- P is the pressure (Pa)
- A is the inlet area (m^2)
- u is the inlet fluid velocity (m/s)
- A' is the adjusted area (m^2)
- u' is the adjusted fluid velocity (m/s)

Finally, using the fluid properties, for a system at steady state, the surface temperature is given by:

$$T_s = \frac{q''}{h} + T_\infty \tag{7}$$

Where:

- T_s is the surface temperature (K)

- q'' is the heat flux ($W/m^2 * K$)
- T_∞ is the ambient temperature of the surrounding environment (K)

Results & Discussion

To begin, a flat plate was installed into a wind tunnel with a heating pad attached to the bottom to provide a constant source of heat flux. Next, the plate was heated until it reached a steady temperature, and then the wind tunnel was turned on. The tunnel was run until the plate temperature reached a steady state. This process was completed for 15 m/s, 35 m/s, and 60 m/s to make a total of 3 trials. Appendix A gives the raw data for all trials. Table 1 shows the corrected velocity after accounting for the blockage factor where $A = 0.163m^2$ and $A' = 0.145m^2$.

Table 1. Velocity and Corrected Velocity

Speed (m/s)	adj. speed (m/s)
15	16.8
35	39.20001
60	67.20002

The plate was then measured and the value were recorded (table 2),

Table 2. Measurements of the flat plate specimen

material	Al 6061 T6
mass (kg)	2.68
surface area (m^2)	0.16258
thickness (m)	6.48E-03
Heat Flux (W/m^2)	1163.00
Heat (W)	189.08

Additionally, the locations of each of the nine thermocouples were recorded (table 3).

Table 3. Thermocouple distances from the leading edge

Index	Distance	
	(in)	(m)
TC1	0.6	0.01524
TC2	2.4	0.06096
TC3	4.2	0.10668
TC4	6	0.1524
TC5	7.8	0.19812
TC6	9.6	0.24384
TC7	11.4	0.28956
TC8	13.2	0.33528
TC9	15	0.381

Once the data had been collected, the coefficient of thermal conductivity (k, W/m^2*K), Prandtl Number (Pr), kinematic viscosity (ν, m^2/s), Reynold's Number (Re), and corresponding theoretical surface temperature using equation 7 and Table B1 from the appendix for the air properties and table B2 for the aluminum properties. Table 3 below shows the properties at time zero for the 15 m/s trial.

Table 4. Fluid Properties at t=0 for u=15m/s

	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9
Pr	0.7026	0.7014	0.7008	0.7011	0.7003	0.7007	0.7000	0.7002	0.7003
$Re * 10^3$	13.43	51.34	88.00	127.2	160.9	201.0	232.6	271.5	308.7
Nu_x	46.67	91.19	119.36	143.54	161.34	180.39	194.00	209.59	223.50
$h_x\ W/m^2K)$	87.69	43.81	33.11	27.71	24.29	21.90	20.10	18.68	17.52
$T_x\ (K)$	311.54	324.82	333.40	340.26	346.15	351.38	356.15	360.55	364.66

Figure 2 shows the experimental surface temperature and figure 3 shows the actual surface temperature. Note that theoretical values were only determined after 200 seconds, as that was when the plate reached steady state.

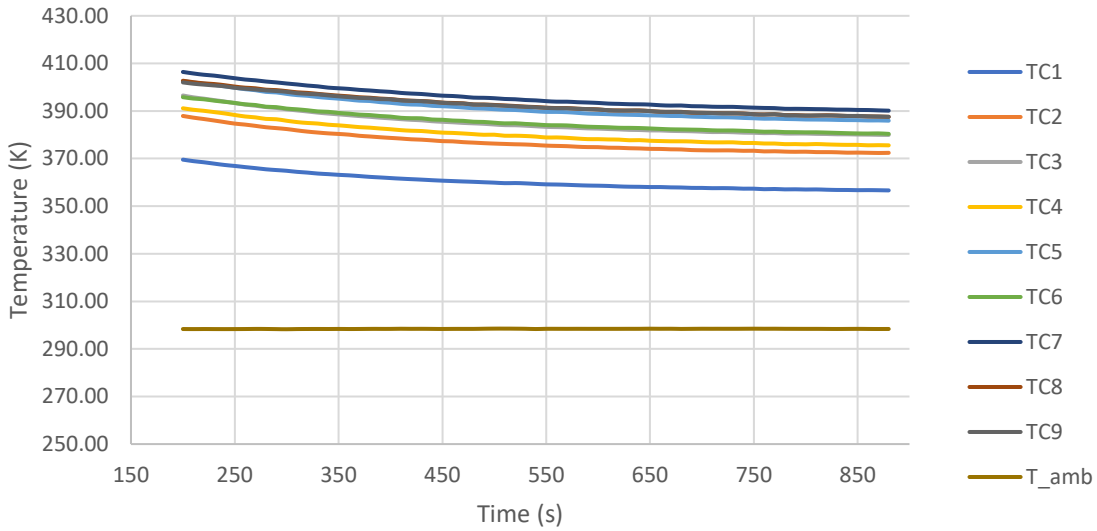

Figure 2. Experimental Thermocouple Temperatures at u=15 m/s

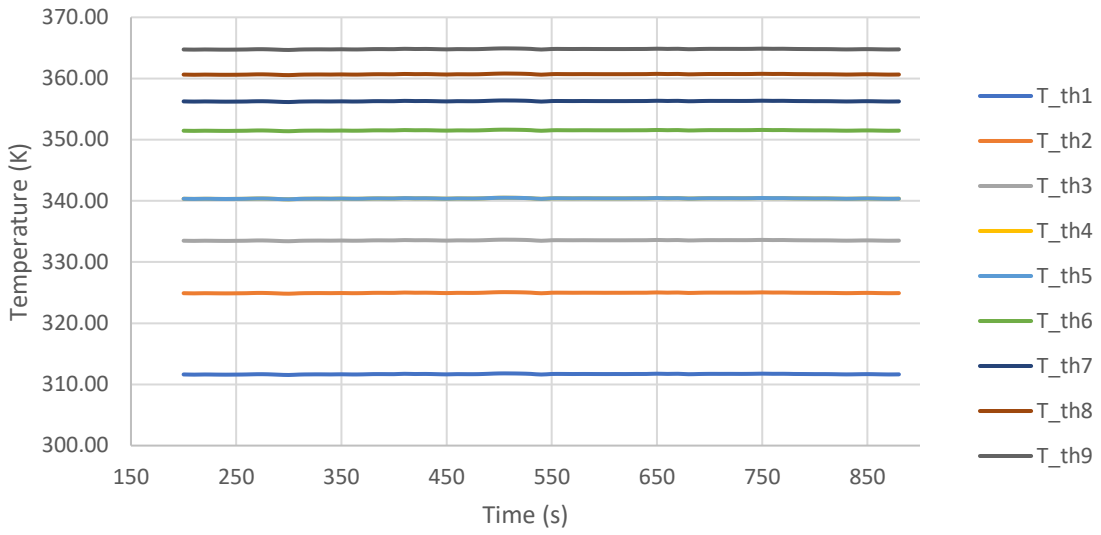

Figure 3. Theoretical Thermocouple Temperature at u=15 m/s

Next, the percentage error was calculated between the experimental and theoretical was calculated.

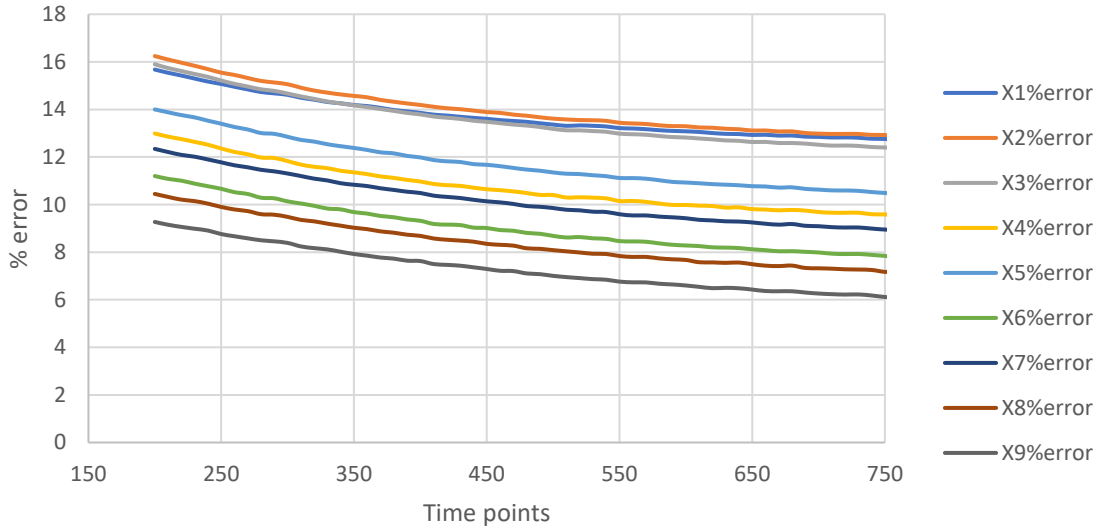

Figure 4. Percent error at u=15 m/s

This process was repeated for 35 and 60 m/s to make a total of three trials.

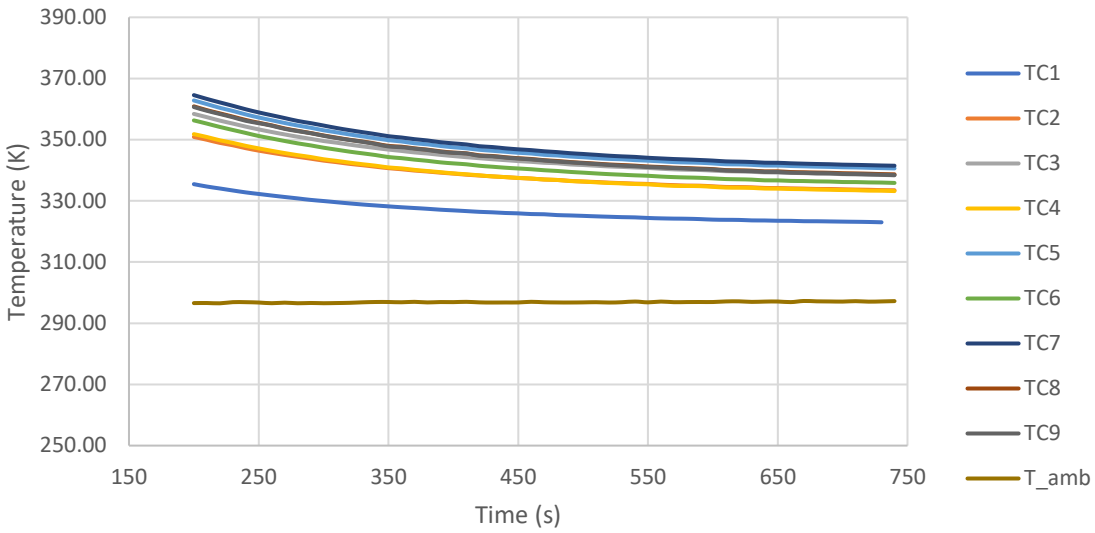

Figure 5. Experimental Thermocouple Temperatures at u=35 m/

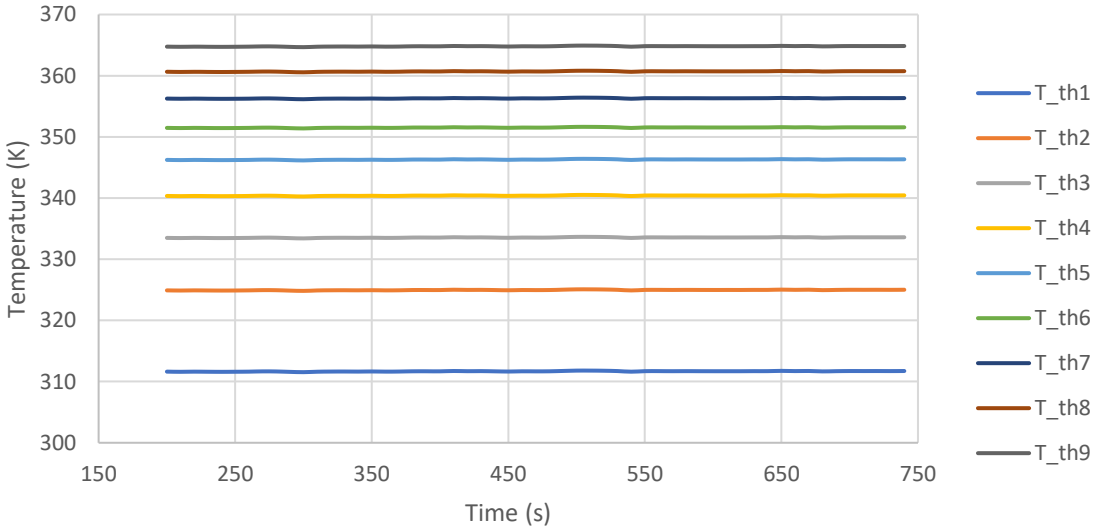

Figure 6. Theoretical Thermocouple Temperature at u=35 m/s

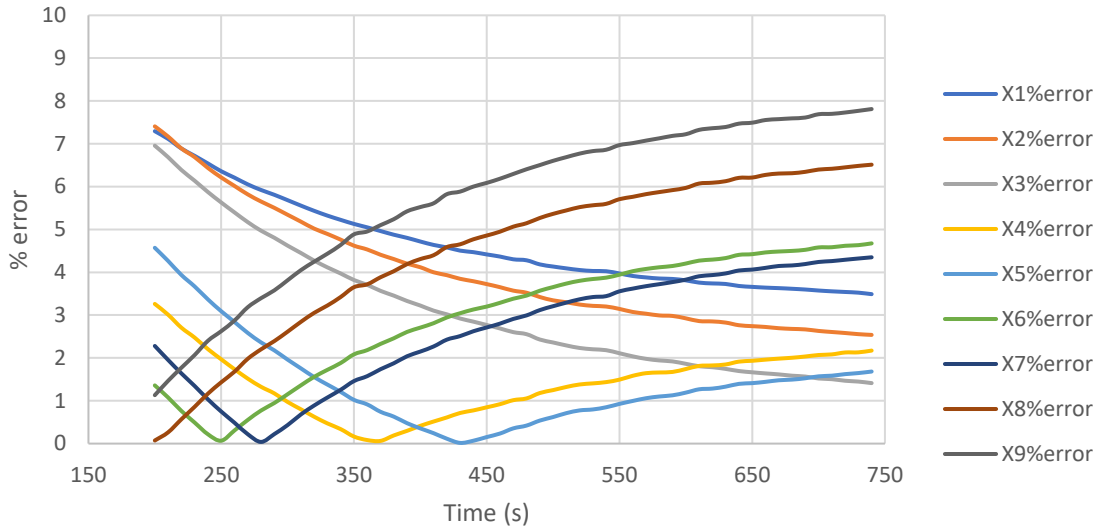

Figure 7. Percent error at u=35 m/s

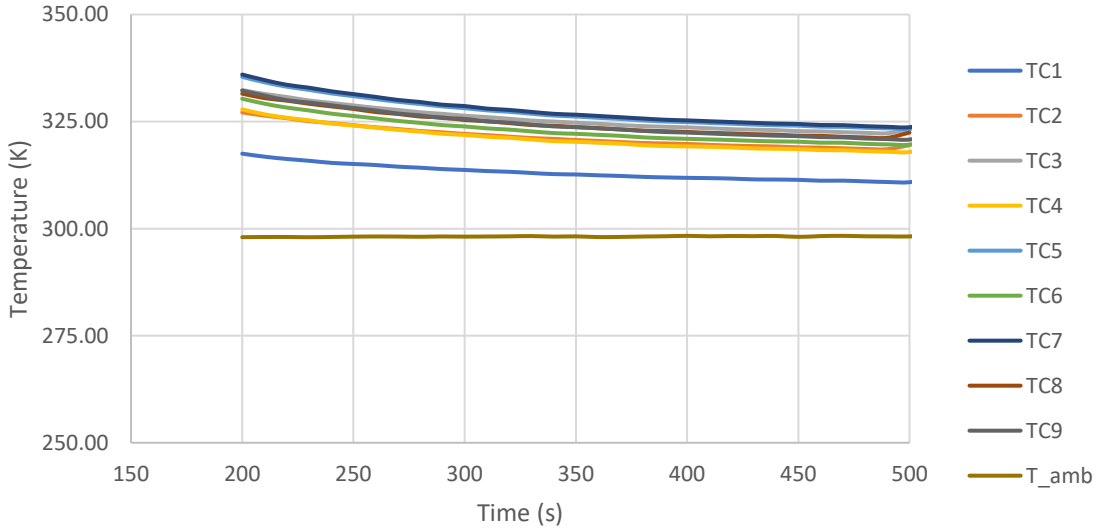

Figure 8. Experimental Thermocouple Temperatures at u=60 m/

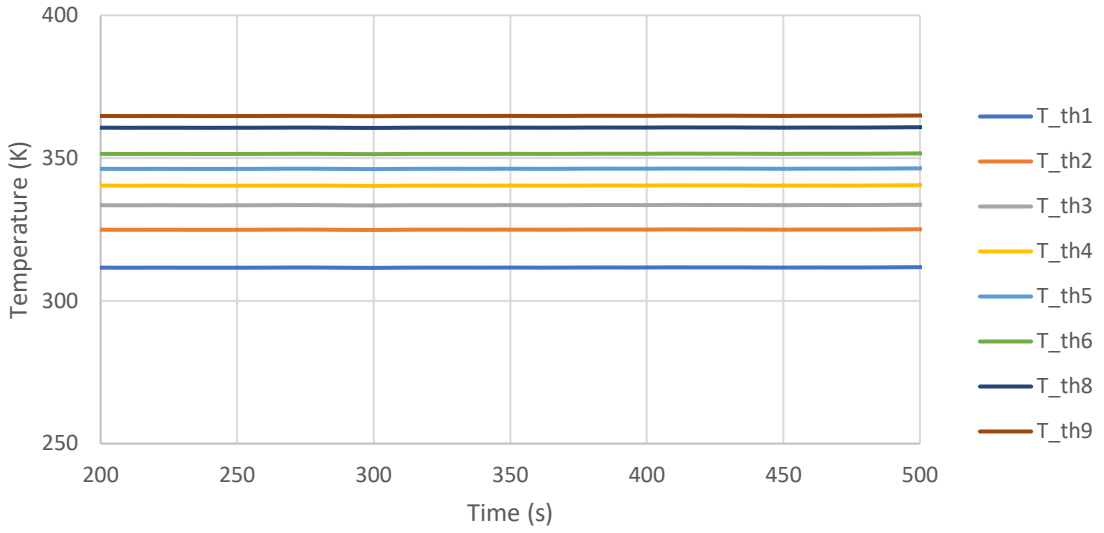

Figure 9. Theoretical Thermocouple Temperature at u=60 m/s

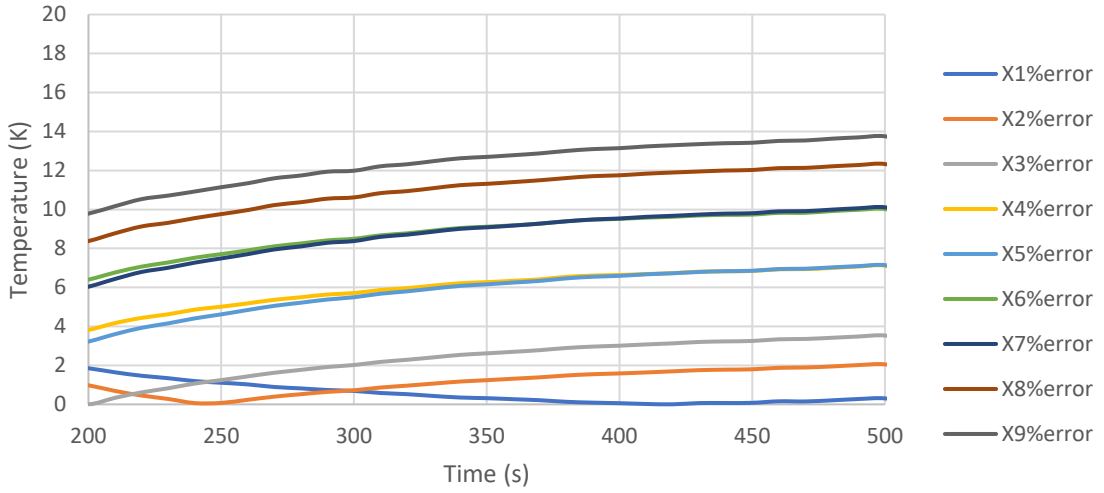

Figure 10. Percent error at u=60 m/s

Note that for all trials, the percentage error was roughly less than 15%, which matches the expected accuracy for the relationships used. Additionally, it is worth noting that as time increased, the percent error generally settled to a value, which is likely due to the decreasing uncertainty in the time measurement as time increases as shown below.

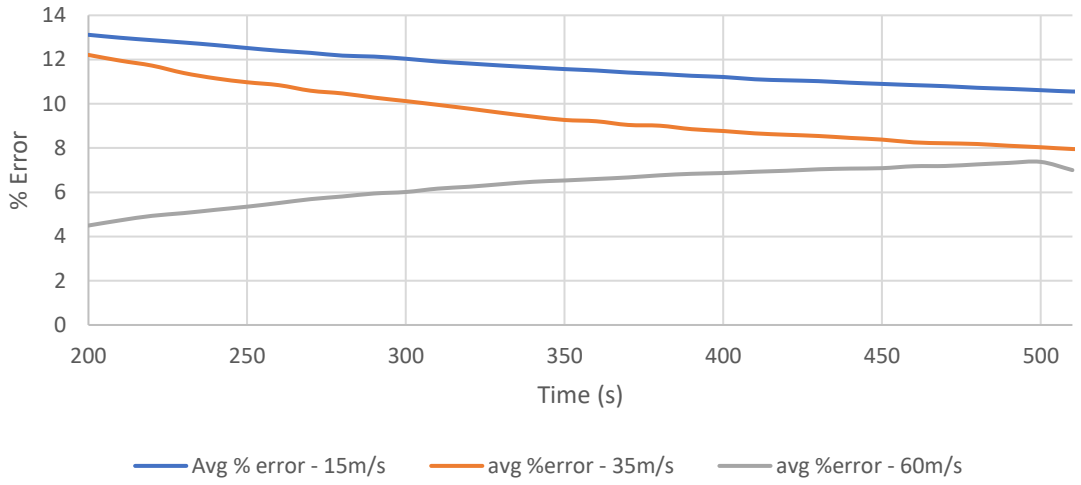

Figure 11. Average %error vs. time

Conclusion

Comparison of actual versus theoretical temperature for a flat plate experiencing isothermal flux was performed for 15 m/s, 35 m/s, and 60 m/s using laminar and turbulent constant property boundary layer equations. Results of the analysis showed that the actual and theoretical temperatures matched well for the relationship used, with all percent errors in the surface temperatures settling to less than 15% difference as compared to the measures value, which is the accepted accuracy of the relationship. It was also found that percentage error decreased over time, which is attributed to the decreasing uncertainty in the time as time increases.

Appendix A – Raw Data

Table 5. Plate Temperature at 15 MPH

Time (s)	***Temperature (K), $u = 15$ MPH***									
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8	TC_9	T_{amb}
0	430.08	436.59	439.15	437.22	439.11	437.21	439.55	436.80	434.74	301.30
10	417.81	429.13	433.33	428.23	434.21	428.39	435.02	430.81	428.87	299.84
20	397.60	417.42	423.80	413.47	424.71	414.65	425.12	419.33	418.03	298.50
30	395.11	415.17	421.89	412.66	423.43	414.16	424.06	418.70	417.34	298.40
40	391.29	411.25	418.60	409.92	420.64	411.58	421.49	416.32	415.11	298.46
50	388.46	408.64	416.21	407.97	418.70	409.89	419.97	414.88	413.56	298.47
60	386.10	406.20	414.01	406.15	417.07	408.53	418.51	413.71	412.45	298.62
70	384.18	404.05	412.17	404.70	415.54	407.22	417.34	412.53	411.28	298.45
80	381.86	401.66	409.92	402.85	413.85	405.57	415.54	410.72	409.64	298.41
90	380.08	399.72	408.01	401.17	412.25	404.19	414.27	409.78	408.76	298.41
100	378.51	397.97	406.52	399.94	410.98	403.18	413.31	408.83	407.97	298.43
110	377.29	396.73	405.11	398.70	410.03	402.31	412.41	408.15	407.16	298.45

120	376.16	395.41	403.98	397.76	408.91	401.57	411.78	407.47	406.63	298.34
130	375.12	394.30	402.91	396.84	408.02	400.65	410.92	406.78	405.88	298.42
140	374.10	393.16	401.80	395.77	407.20	399.86	410.25	406.18	405.24	298.30
150	373.25	392.08	400.79	394.91	406.40	399.13	409.52	405.68	404.75	298.36
160	372.39	391.21	399.99	394.19	405.50	398.56	408.84	404.97	404.07	298.30
170	371.61	390.33	399.01	393.39	404.84	397.84	408.24	404.23	403.54	298.34
180	370.91	389.46	398.09	392.59	404.08	397.10	407.51	403.70	403.07	298.37
190	370.18	388.64	397.36	391.82	403.26	396.55	407.01	403.29	402.62	298.33
200	369.55	387.92	396.52	391.15	402.60	395.80	406.42	402.72	402.02	298.36
210	368.93	387.21	395.75	390.52	402.00	395.24	405.78	402.12	401.47	298.33
220	368.46	386.63	395.19	390.09	401.48	394.93	405.24	401.64	401.10	298.36
230	367.88	386.01	394.59	389.55	401.01	394.35	404.87	401.34	400.74	298.34
240	367.32	385.35	394.01	388.99	400.35	393.87	404.32	400.85	400.39	298.33
250	366.90	384.70	393.30	388.32	399.78	393.40	403.78	400.25	399.75	298.34
260	366.42	384.28	392.69	387.69	399.17	392.80	403.23	399.80	399.37	298.36
270	365.98	383.74	392.21	387.31	398.73	392.51	402.89	399.54	399.03	298.40
280	365.50	383.17	391.65	386.69	398.03	391.81	402.39	398.95	398.66	298.39
290	365.18	382.80	391.28	386.53	397.81	391.63	402.02	398.78	398.40	298.33
300	364.87	382.41	390.71	385.90	397.19	391.01	401.55	398.33	398.06	298.28
310	364.42	381.84	390.25	385.34	396.68	390.70	401.16	397.86	397.50	298.35
320	364.11	381.34	389.80	384.97	396.39	390.32	400.69	397.61	397.21	298.38
330	363.70	380.95	389.31	384.72	395.88	389.82	400.36	397.19	396.99	298.38
340	363.46	380.60	388.93	384.24	395.50	389.66	399.82	396.81	396.56	298.37
350	363.17	380.35	388.59	383.97	395.19	389.18	399.55	396.45	396.17	298.39
360	362.95	380.05	388.22	383.61	394.78	388.89	399.28	396.17	395.84	298.37
370	362.65	379.58	387.87	383.22	394.34	388.47	398.88	395.78	395.51	298.38
380	362.31	379.30	387.56	383.00	394.20	388.29	398.62	395.58	395.37	298.42
390	362.07	378.97	387.18	382.63	393.72	387.90	398.28	395.22	394.99	298.42
400	361.81	378.69	386.90	382.34	393.43	387.65	398.04	395.00	394.92	298.42
410	361.56	378.42	386.57	381.95	393.00	387.14	397.60	394.58	394.44	298.47
420	361.35	378.11	386.29	381.70	392.73	386.98	397.33	394.33	394.26	298.44
430	361.16	377.94	386.09	381.58	392.61	386.92	397.14	394.18	394.12	298.45
440	360.92	377.65	385.70	381.23	392.18	386.43	396.77	393.95	393.80	298.42
450	360.71	377.33	385.46	380.91	392.01	386.31	396.45	393.51	393.47	298.38
460	360.54	377.23	385.25	380.78	391.80	385.99	396.29	393.38	393.19	298.42
470	360.38	376.90	384.99	380.55	391.46	385.86	396.00	393.23	393.12	298.41
480	360.24	376.71	384.81	380.28	391.16	385.48	395.62	392.76	392.72	298.42
490	360.05	376.48	384.61	380.00	391.02	385.39	395.55	392.72	392.65	298.48
500	359.89	376.30	384.32	380.04	390.76	385.07	395.37	392.54	392.40	298.53
510	359.67	376.15	384.05	379.60	390.52	384.79	395.06	392.34	392.19	298.53
520	359.72	376.02	384.02	379.61	390.43	384.84	394.93	392.10	391.98	298.51

530	359.58	375.91	383.82	379.48	390.15	384.56	394.62	391.82	391.74	298.46
540	359.35	375.69	383.58	379.25	389.87	384.35	394.45	391.67	391.53	298.36
550	359.17	375.45	383.33	378.86	389.63	384.05	394.14	391.40	391.29	298.45
560	359.10	375.33	383.23	378.89	389.62	384.01	393.92	391.24	391.17	298.45
570	358.97	375.22	383.12	378.71	389.50	383.93	393.91	391.24	391.14	298.44
580	358.80	374.98	382.89	378.42	389.22	383.66	393.70	390.97	390.92	298.45
590	358.68	374.83	382.69	378.18	388.91	383.40	393.56	390.80	390.78	298.44
600	358.60	374.80	382.60	378.16	388.79	383.27	393.39	390.69	390.60	298.44
610	358.49	374.58	382.43	378.04	388.65	383.17	393.11	390.28	390.36	298.44
620	358.30	374.53	382.27	377.98	388.50	382.95	392.99	390.25	390.13	298.44
630	358.17	374.35	382.08	377.71	388.40	382.91	392.84	390.18	390.19	298.45
640	358.14	374.26	382.01	377.75	388.30	382.83	392.80	390.24	390.12	298.45
650	358.03	374.08	381.84	377.49	388.18	382.66	392.69	389.99	389.94	298.49
660	358.03	374.06	381.82	377.37	388.08	382.47	392.41	389.69	389.65	298.46
670	357.90	373.90	381.64	377.27	387.90	382.30	392.27	389.64	389.63	298.48
680	357.85	373.84	381.57	377.26	387.88	382.25	392.31	389.66	389.56	298.41
690	357.69	373.58	381.48	377.18	387.63	382.17	392.02	389.27	389.37	298.44
700	357.67	373.50	381.31	376.95	387.53	382.08	391.98	389.24	389.22	298.47
710	357.56	373.43	381.15	376.83	387.38	381.87	391.80	389.17	389.10	298.46
720	357.58	373.45	381.17	376.82	387.36	381.80	391.74	389.06	389.04	298.47
730	357.52	373.42	381.08	376.82	387.29	381.81	391.73	389.01	389.06	298.46
740	357.35	373.26	380.89	376.56	387.09	381.66	391.55	388.95	388.88	298.47
750	357.35	373.29	380.85	376.57	386.95	381.52	391.40	388.64	388.65	298.50
760	357.13	373.02	380.69	376.33	386.76	381.27	391.27	388.56	388.47	298.48
770	357.22	373.08	380.73	376.32	386.78	381.32	391.21	388.62	388.65	298.48
780	357.06	372.92	380.52	376.07	386.65	381.13	390.92	388.28	388.22	298.45
790	357.10	372.86	380.51	376.09	386.57	381.10	390.92	388.26	388.16	298.44
800	357.00	372.89	380.51	375.99	386.44	381.03	390.86	388.11	388.06	298.43
810	357.04	372.73	380.38	376.12	386.40	381.04	390.78	388.08	388.15	298.43
820	356.92	372.72	380.34	375.97	386.35	380.93	390.73	388.22	388.10	298.41
830	356.81	372.65	380.22	375.85	386.26	380.80	390.58	388.08	388.07	298.38
840	356.80	372.48	380.21	375.77	386.17	380.68	390.56	387.93	387.90	298.40
850	356.73	372.51	380.10	375.76	386.16	380.57	390.44	387.87	387.93	298.43
860	356.75	372.44	380.07	375.59	386.03	380.53	390.41	387.73	387.77	298.40
870	356.70	372.36	379.98	375.64	386.04	380.59	390.26	387.67	387.68	298.37
880	356.62	372.41	379.95	375.56	385.93	380.39	390.13	387.56	387.54	298.39

Table 6. Plate Temperature at 35 MPH

Time (s)	***Temperature (K), $u = 35$ MPH***									
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8	TC_9	T_{amb}

0	416.44	424.61	429.27	430.43	434.21	433.10	434.75	432.83	432.70	297.02
10	406.32	418.47	424.21	421.40	428.56	423.75	431.59	427.97	426.33	296.94
20	373.44	395.52	403.79	391.24	406.84	396.86	408.57	402.54	401.95	296.74
30	367.62	389.95	398.68	387.00	402.10	392.34	403.64	397.78	396.97	296.77
40	363.45	385.18	394.34	383.43	398.12	388.79	399.70	394.07	393.08	296.53
50	359.90	381.17	390.46	380.14	394.46	385.43	396.13	390.67	389.76	296.42
60	356.83	377.46	386.84	377.13	391.27	382.50	392.98	387.73	386.88	296.49
70	354.32	374.31	383.65	374.33	388.18	379.70	390.01	384.90	384.20	296.75
80	352.09	371.48	380.80	371.91	385.50	377.24	387.29	382.32	381.59	296.68
90	350.02	368.90	378.03	369.39	382.85	374.75	384.69	379.95	379.30	296.56
100	348.24	366.57	375.59	367.26	380.39	372.49	382.21	377.47	376.90	296.80
110	346.51	364.45	373.30	365.25	378.27	370.56	380.09	375.55	374.96	296.75
120	344.88	362.30	371.06	363.32	375.98	368.50	377.89	373.44	372.89	296.71
130	343.54	360.59	369.15	361.54	374.06	366.74	375.91	371.57	371.17	296.63
140	342.24	358.86	367.33	359.97	372.17	364.96	374.06	369.85	369.46	296.72
150	341.01	357.25	365.52	358.31	370.28	363.24	372.13	368.03	367.61	296.59
160	339.95	355.86	363.98	356.96	368.80	361.83	370.63	366.58	366.19	296.59
170	338.85	354.48	362.36	355.42	366.98	360.18	368.81	364.86	364.52	296.77
180	337.95	353.27	361.08	354.30	365.67	358.99	367.45	363.59	363.27	296.67
190	337.05	352.08	359.75	353.05	364.24	357.67	366.08	362.34	362.07	296.45
200	336.15	350.91	358.42	351.82	362.82	356.31	364.57	360.90	360.67	296.59
210	335.47	349.97	357.36	350.88	361.63	355.26	363.33	359.67	359.45	296.61
220	334.69	348.96	356.25	349.81	360.42	354.17	362.19	358.60	358.40	296.51
230	334.05	348.18	355.27	348.96	359.40	353.18	361.09	357.54	357.34	296.89
240	333.40	347.22	354.26	347.98	358.26	352.20	359.94	356.45	356.17	296.88
250	332.77	346.42	353.36	347.15	357.25	351.21	358.91	355.53	355.40	296.76
260	332.26	345.71	352.52	346.36	356.36	350.39	357.99	354.68	354.56	296.55
270	331.75	345.03	351.72	345.63	355.46	349.58	357.07	353.68	353.53	296.72
280	331.27	344.40	350.96	344.94	354.64	348.80	356.13	352.90	352.80	296.53
290	330.81	343.80	350.29	344.34	353.90	348.13	355.42	352.17	352.11	296.62
300	330.32	343.16	349.56	343.60	353.07	347.38	354.62	351.37	351.27	296.54
310	329.95	342.66	349.01	343.08	352.41	346.74	353.82	350.66	350.54	296.60
320	329.55	342.09	348.38	342.50	351.71	346.09	353.11	349.97	349.90	296.67
330	329.17	341.65	347.82	341.97	351.09	345.54	352.47	349.39	349.28	296.84
340	328.81	341.16	347.29	341.50	350.47	344.98	351.83	348.71	348.59	296.94
350	328.50	340.68	346.76	340.93	349.84	344.32	351.14	347.96	347.79	296.94
360	328.20	340.34	346.33	340.62	349.43	343.96	350.72	347.71	347.54	296.85
370	327.92	339.91	345.84	340.14	348.84	343.49	350.17	347.17	347.06	296.99
380	327.66	339.60	345.48	339.75	348.49	343.09	349.74	346.74	346.64	296.80
390	327.41	339.22	345.03	339.39	347.95	342.59	349.18	346.19	346.04	296.93
400	327.11	338.92	344.65	338.99	347.52	342.25	348.80	345.79	345.71	296.90

410	326.90	338.55	344.28	338.70	347.18	341.96	348.44	345.54	345.47	297.00
420	326.66	338.28	343.94	338.35	346.70	341.48	347.87	344.89	344.75	296.82
430	326.42	338.00	343.61	338.00	346.37	341.16	347.60	344.68	344.56	296.76
440	326.26	337.76	343.31	337.77	346.05	340.84	347.18	344.27	344.15	296.79
450	326.04	337.49	343.00	337.50	345.72	340.59	346.85	343.95	343.84	296.79
460	325.92	337.28	342.76	337.29	345.48	340.33	346.59	343.69	343.56	297.00
470	325.69	336.99	342.45	336.97	345.06	340.01	346.21	343.30	343.19	296.85
480	325.62	336.83	342.29	336.84	344.84	339.78	345.94	343.04	342.84	296.79
490	325.35	336.54	341.91	336.48	344.50	339.46	345.58	342.70	342.58	296.77
500	325.24	336.32	341.72	336.30	344.27	339.23	345.33	342.44	342.31	296.81
510	325.09	336.17	341.48	336.06	343.96	338.97	345.05	342.18	342.04	296.87
520	324.94	335.96	341.25	335.85	343.72	338.73	344.77	341.91	341.75	296.77
530	324.81	335.80	341.09	335.71	343.59	338.55	344.54	341.72	341.52	296.87
540	324.68	335.64	340.91	335.51	343.31	338.35	344.37	341.51	341.32	297.09
550	324.60	335.54	340.75	335.41	343.13	338.20	344.09	341.24	341.06	296.83
560	324.41	335.30	340.51	335.12	342.91	337.94	343.88	341.07	340.91	297.08
570	324.28	335.15	340.29	334.90	342.68	337.76	343.68	340.86	340.72	296.88
580	324.20	335.01	340.17	334.86	342.55	337.64	343.53	340.71	340.55	296.92
590	324.16	334.97	340.09	334.81	342.45	337.54	343.36	340.56	340.37	296.94
600	324.04	334.77	339.89	334.58	342.23	337.35	343.17	340.38	340.24	296.94
610	323.87	334.55	339.69	334.34	341.97	337.13	342.91	340.06	339.92	297.12
620	323.80	334.52	339.61	334.30	341.91	337.05	342.82	340.00	339.79	297.15
630	323.77	334.44	339.49	334.24	341.77	336.95	342.70	339.89	339.71	296.98
640	323.62	334.23	339.32	334.02	341.55	336.71	342.48	339.65	339.47	297.07
650	323.59	334.19	339.26	334.00	341.54	336.70	342.45	339.66	339.44	297.10
660	323.50	334.09	339.13	333.88	341.40	336.53	342.28	339.43	339.21	296.91
670	323.48	334.02	339.07	333.82	341.30	336.48	342.16	339.35	339.16	297.27
680	323.36	333.89	338.90	333.69	341.18	336.37	342.05	339.26	339.04	297.16
690	323.33	333.88	338.87	333.63	341.11	336.32	341.98	339.19	339.01	297.11
700	323.28	333.79	338.74	333.53	340.98	336.16	341.84	339.04	338.79	297.08
710	323.21	333.70	338.68	333.48	340.92	336.14	341.77	338.98	338.76	297.21
720	323.17	333.62	338.55	333.34	340.81	336.04	341.67	338.88	338.66	297.05
730	323.10	333.52	338.48	333.32	340.71	335.98	341.57	338.76	338.54	297.13
740	323.00	333.47	338.37	333.20	340.60	335.86	341.49	338.68	338.41	297.23

Table 7. Plate Temperature at 60 MPH

Time (s)	***Temperature (K), $u = 60$ MPH***									
	TC_1	TC_2	TC_3	TC_4	TC_5	TC_6	TC_7	TC_8	TC_9	T_{amb}
0	358.36	383.79	392.92	377.62	393.22	382.13	393.64	387.20	385.75	297.45
10	352.04	376.25	385.75	371.83	386.73	376.19	387.35	381.16	379.53	297.49
20	347.39	370.12	379.75	367.15	381.41	371.57	382.05	376.08	374.40	297.57

30	343.38	364.83	374.29	362.71	376.41	366.98	376.97	371.15	369.42	297.62
40	339.96	360.20	369.44	358.64	371.81	362.79	372.32	366.58	364.87	297.72
50	337.10	356.19	365.23	355.18	367.80	359.19	368.23	362.75	361.16	297.84
60	334.35	352.49	361.28	351.74	363.96	355.73	364.54	359.21	357.73	297.78
70	332.29	349.47	357.98	349.09	360.84	352.90	361.40	356.34	354.87	297.77
80	330.27	346.74	354.88	346.38	357.67	350.07	358.19	353.30	351.97	297.87
90	328.64	344.25	352.16	344.19	355.05	347.77	355.59	350.90	349.63	297.87
100	326.72	341.66	349.28	341.47	352.04	345.04	352.56	348.04	346.95	298.00
110	325.60	339.83	347.14	339.79	349.94	343.25	350.53	346.19	345.20	297.95
120	324.14	337.85	344.92	337.75	347.56	341.05	348.06	343.86	342.92	297.94
130	322.81	336.07	342.86	335.89	345.38	339.03	345.90	341.87	341.04	297.93
140	322.04	334.73	341.24	334.67	343.78	337.78	344.37	340.48	339.70	297.93
150	321.14	333.34	339.64	333.24	342.03	336.24	342.63	338.90	338.16	297.87
160	320.11	331.91	338.01	331.75	340.33	334.77	340.87	337.29	336.65	297.92
170	319.25	330.79	336.69	330.50	338.89	333.36	339.49	336.01	335.44	298.05
180	318.48	329.73	335.45	329.40	337.50	332.09	338.06	334.70	334.16	298.01
190	317.89	328.79	334.32	328.44	336.30	331.05	336.81	333.47	332.97	297.84
200	317.51	328.12	333.51	327.83	335.43	330.33	335.98	332.77	332.24	298.01
210	316.81	327.14	332.35	326.69	334.17	329.18	334.70	331.52	331.06	298.04
220	316.27	326.39	331.45	325.89	333.15	328.27	333.59	330.47	330.00	298.05
230	315.85	325.79	330.74	325.29	332.40	327.60	332.91	329.90	329.44	297.99
240	315.36	325.09	329.93	324.54	331.58	326.85	332.08	329.16	328.81	298.06
250	315.10	324.65	329.37	324.09	330.93	326.30	331.42	328.55	328.17	298.12
260	314.85	324.15	328.77	323.57	330.25	325.73	330.76	327.95	327.59	298.17
270	314.47	323.67	328.21	323.05	329.62	325.15	330.05	327.23	326.88	298.15
280	314.23	323.25	327.72	322.64	329.10	324.69	329.57	326.78	326.45	298.10
290	313.90	322.80	327.18	322.15	328.53	324.16	328.93	326.18	325.82	298.17
300	313.70	322.49	326.80	321.88	328.12	323.87	328.62	325.95	325.63	298.13
310	313.44	322.12	326.37	321.47	327.62	323.41	328.04	325.37	325.03	298.16
320	313.28	321.83	326.04	321.21	327.27	323.13	327.72	325.09	324.76	298.20
330	313.00	321.50	325.65	320.82	326.83	322.71	327.26	324.65	324.31	298.27
340	312.73	321.16	325.24	320.44	326.40	322.31	326.82	324.19	323.87	298.14
350	312.65	320.96	325.01	320.29	326.18	322.14	326.60	324.01	323.69	298.19
360	312.46	320.69	324.73	320.06	325.87	321.90	326.31	323.73	323.41	298.03
370	312.30	320.48	324.48	319.84	325.62	321.67	326.02	323.47	323.15	298.06
380	312.09	320.22	324.17	319.50	325.27	321.32	325.71	323.17	322.83	298.16
390	311.96	320.01	323.94	319.30	325.02	321.11	325.43	322.90	322.56	298.22
400	311.86	319.89	323.79	319.20	324.87	320.97	325.28	322.76	322.43	298.31
410	311.79	319.78	323.64	319.11	324.68	320.84	325.07	322.57	322.22	298.21
420	311.69	319.57	323.44	318.94	324.49	320.68	324.89	322.37	322.02	298.28
430	311.50	319.39	323.23	318.73	324.29	320.50	324.70	322.23	321.86	298.25

440	311.46	319.27	323.10	318.64	324.14	320.37	324.53	322.05	321.70	298.29
450	311.40	319.19	323.00	318.56	324.04	320.30	324.44	321.95	321.60	298.08
460	311.19	318.99	322.77	318.34	323.81	320.08	324.20	321.71	321.37	298.26
470	311.21	318.92	322.70	318.30	323.75	320.06	324.16	321.66	321.30	298.32
480	311.04	318.76	322.53	318.12	323.55	319.81	323.93	321.44	321.05	298.22
490	310.88	318.60	322.38	317.96	323.41	319.67	323.78	321.30	320.91	298.20
500	310.84	318.54	322.27	317.88	323.31	319.61	323.68	321.20	320.80	298.17
510	311.89	319.49	323.22	319.23	324.43	320.88	324.79	322.43	321.98	298.50
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15

	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15
	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15	273.15

Appendix B – Properties of Air at 1 ATM

Table 1. Properties of Air at 1 ATM[1]

Temperature (K)	ρ (kg/m^3)	cp (kJ/kg · K)	$\mu \cdot 10^7$ (N · s/m^2)	$\nu \cdot 10^6$ (m^2/s)	k (W/m · K)	$\alpha \cdot 10^6$ (m^2/s)	Pr
100	3.5562	1.032	71.10	2.00	9.3E-3	2.54	0.786
150	2.3364	1.012	103.40	4.43	13.8E-3	5.84	0.758
200	1.7458	1.007	132.5	7.59	18.1E-3	10.30	0.737
250	1.3947	1.006	159.6	11.44	22.3E-3	15.90	0.72
300	1.1614	1.01	184.6	15.89	26.3E-3	22.50	0.707
350	0.9950	1.01	208.2	20.92	30.0E-3	29.90	0.7
400	0.8711	1.01	230.1	26.41	33.8E-3	38.30	0.69
450	0.7740	1.02	250.7	32.39	37.3E-3	47.20	0.686
500	0.6964	1.03	270.1	38.79	40.7E-3	56.70	0.684
550	0.6329	1.04	288.4	45.57	43.9E-3	66.70	0.683
600	0.5804	1.05	305.8	52.69	46.9E-3	76.90	0.685
650	0.5356	1.06	322.5	60.21	49.7E-3	87.30	0.69
700	0.4975	1.08	338.8	68.10	52.4E-3	98.00	0.695
750	0.4643	1.09	354.6	76.37	54.9E-3	109.00	0.702
800	0.4354	1.10	369.8	84.93	57.3E-3	120.00	0.709
850	0.4097	1.11	384.3	93.80	59.6E-3	131.00	0.716
900	0.3868	1.12	398.1	102.90	62.0E-3	143.00	0.72
950	0.3666	1.13	411.3	112.20	64.3E-3	155.00	0.723
1000	0.3482	1.14	424.4	121.90	66.7E-3	168.00	0.726
1100	0.3166	1.16	449	141.80	71.5E-3	195.00	0.728
1200	0.2902	1.18	473	162.90	76.3E-3	224.00	0.728
1300	0.2679	1.19	496	185.10	82.0E-3	257.00	0.719
1400	0.2488	1.21	530	213.00	91.0E-3	303.00	0.703
1500	0.2322	1.23	557	240.00	100.0E-3	350.00	0.685
1600	0.2177	1.25	584	268.00	106.0E-3	390.00	0.688
1700	0.2049	1.27	611	298.00	113.0E-3	435.00	0.685
1800	0.1935	1.29	637	329.00	120.0E-3	482.00	0.683
1900	0.1833	1.31	663	362.00	128.0E-3	534.00	0.677
2000	0.1741	1.34	689	396.00	137.0E-3	589.00	0.672
2100	0.1658	1.37	715	431.00	147.0E-3	646.00	0.667
2200	0.1582	1.42	740	468.00	160.0E-3	714.00	0.655
2300	0.1513	1.48	766	506.00	175.0E-3	783.00	0.647
2400	0.1448	1.56	792	547.00	196.0E-3	869.00	0.63

[1] Taken from Bergman, T, Lavine, A (2019), "Fundamentals of Heat and Mass Transfer, 8th Edition", Wiley Press, ISBN 978-1-119-53734-2

2500	0.1389	1.67	818	589.00	222.0E-3	960.00	0.613
3000	0.1135	2.73	955	841.00	486.0E-3	1570	0.536

Table 2. Specific Heat of Al at selected temperatures[2]

Temperature (K)	Cp ($J/mol * K$)
298	24.20
300	24.25
400	25.78
500	26.84
600	27.89
700	29.10
800	30.56
900	32.31

[2] https://webbook.nist.gov/cgi/cbook.cgi?ID=C7429905&Mask=2&Type=JANAFS&Table=on

Appendix C – Hand Calculations