Lab Experiment 5: Compare Convection and Radiant Heat Transfer

Section 23L

Jonathan Smith: Team Leader, Graphs/Tables, Data Recorder
Adam VanBuskirk: Theoretical, Procedure, Design Objective Analysis
Brandon Golino: Discussion, Conclusion, Design Objective Analysis
Jacob Klofta: Graphs/Tables, Uncertainty Analysis
Kyle Rodriguez: Equipment Diagram, Uncertainty Analysis, Summary Letter

Experiment Performed: April 24, 2019
Report Submitted: May 8, 2019

Objectives:

- Measure and compare heat transfer rates from a heated surface through free convection, forced external convection, and radiant transfer
- Apply methods of heat transfer to a practical application

Summary:

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After reviewing the given conditions, we have determined that the electrical resistance heater required to operate within the required temperature range at altitude to be 632W. In addition, the convective heat loss of the package on the ground prior to launch was determined to be 172W. As the heat loss on the ground is significantly lower than while at altitude, the heater must provide a minimum of 632W to maintain package temperature.

Attached are our test results and methodology. Thank you for requesting our consultation, and please reach out with any questions or further inquiries.

Sincerely,
Team 23L-A1
Mechanical Engineering Dept
University of Delaware

Theoretical Background:

This lab uses an apparatus in which all three modes of heat transfer are present: natural convection, forced convection, and radiant.The basic equations are given respectively.

$$q_{nc} = h_{nc}A_s(T_s - T_\infty) \qquad q_{fc} = h_{fc}A_s(T_s - T_\infty) \qquad Q_{rad} = A_s\varepsilon\sigma F(T_s^4 - T_{sur}^4)$$

Natural convection is defined as the movement of fluid as a result of being heated by a surface. Forced convection is when a fluid is forced, usually by a pump or a fan, over a surface to exchange heat. Radiant heat transfer occurs from one surface to another through radiation. This has entirely different physics from conduction and convection, however for this lab the fundamental relationship will be used. This apparatus works the same as equipment found in industrial applications, just on a smaller scale.

In order to find the emissivity, ε, the equations governing added heat and mass flow rate as needed.

$$Q = mc_p(T_{out} - T_{in}) \qquad m = \rho A_c V$$

With these equations for the three modes of heat transfer, this experiment can be analyzed.

Equipment:

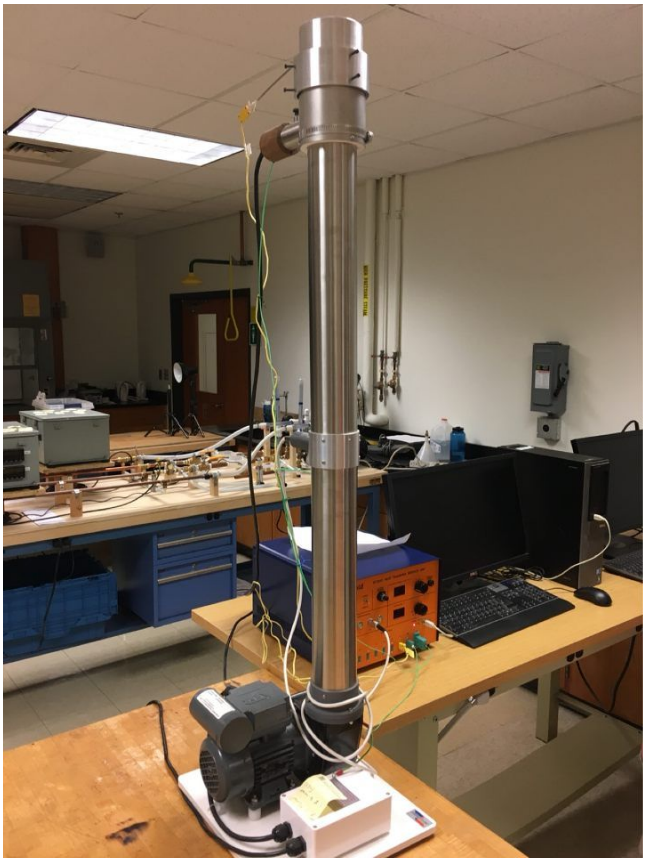


Figure 1. System with tube and heater to measure convection

The apparatus in figure 1 is a tall tube with a heater element at the top end of the tube. At the bottom there is a fan motor that gradually heats the system, along with temperature probes and an anemometer.

Procedure:

Part 1 – Measurement of Natural Convection:

Open the air flow throttle plate, and make sure the blower motor is turned off. Set the heater voltage to 12V with the voltage control potentiometer. Allow the heater temperature to stabilize. Record T9, T10, V and I. Repeat these measurements for Heater Voltages of 16V and 20V.

Part 2 – Measurement of Forced Convection:

Start the blower first. Adjust the throttle plate on the fan to get a velocity reading of 1.6 meter/sec. Set the heater voltage to 20V but make sure the temperature do not exceed 500C. When temperatures are stable, record the flow, voltage, amperage, inlet temperature, outlet temperature, and the surface temperature. Repeat these measurements for air velocities of 2.1 m/sec.

Results:

Part I

Voltage (V)	**Amperage (A)**	**T9: Inlet (C)**	**T10: Heater (C)**	**T8: Outlet (C)**
12	2.5	23.5	312	49.2
16	2.96	24.0	421.5	61.5
18	3.29	24.5	489	69

Table 1: Raw data for Part I, natural convection and radiant heat transfer

	1	2	3
Power to Heater (W)	30	47.36	59.22
Heat Transfer Area (m^2)	0.0022	0.0022	0.0022
Heat Transfer Coefficient (W/m^2)	2.046	2.115	2.152
Natural Convection Heat Transfer (W)	1.240	1.762	2.093
Radiant Heat Transfer (W)	8.08	16.67	24.46
Total Heat Transfer (W)	9.32	18.44	26.55
Emissivity	0.60	0.60	0.60
Heat Power Adjustment	0.69	0.61	0.55

Table 2: Free convection heat transfer analysis

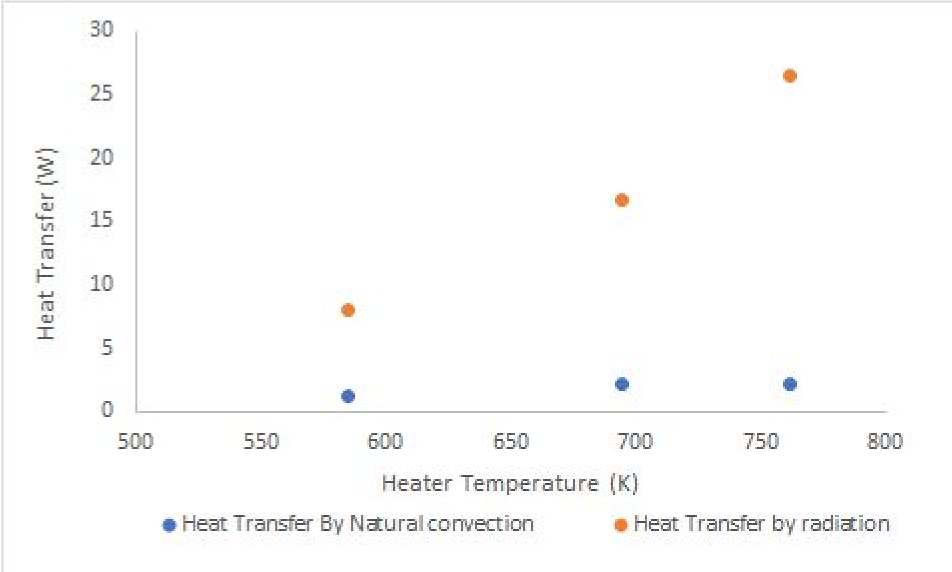


Figure 2. Natural convective heat transfer and radiative heat transfer versus heater temperature. Both natural convective and radiative heat transfers increase as the heater temperature increases, but natural convection transfers less heat than radiation.

Part II

Flow (m/s)	**Amperage (A)**	**T9: Inlet (C)**	**T10: Heater (C)**	**T8: Outlet (C)**
1.6	3.28	26.4	342	34.5
2.1	3.31	27.5	313	34.0

Table 3: Raw data for Part II, forced convection. All values measured with 18V voltage.

	1	2
Power to Heater (W)	59.04	59.58
Heat Transfer Area (m^2)	0.0022	0.0022
Ambient Temperature (K)	300	300
Air Velocity (m/s)	1.6	2.1
Air Mass Flow Rate (kg/s)	0.00191	0.00251
Reynolds Number	7110	9330
Heat Transfer Coefficient (W/m^2)	21.98	25.51
Surface Temperature (K)	615.16	586.15

Air Outlet Temperature (K)	307.65	307.15
Forced Convection Heat Transfer (W)	15.06	15.83
Radiant Heat Transfer (W)	10.08	8.19
Total Heat Transfer (W)	25.14	24.03
Eqn 1 Heat Transfer (W)	48.98	51.59

Table 4: Forced convection heat transfer analysis

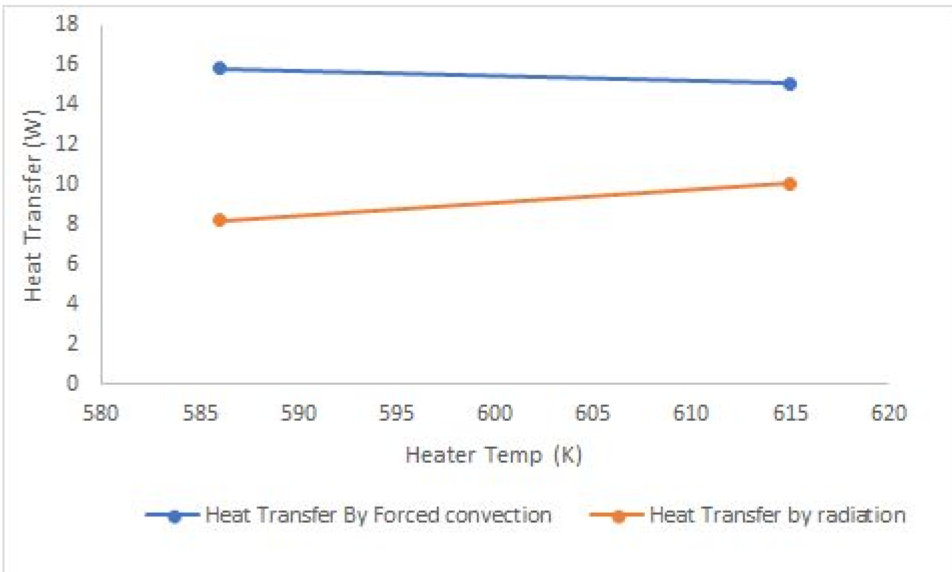


Figure 3. Forced convective heat transfer and radiative heat transfer versus heater temperature. The radiative heat transfer was comparable to that during natural convection. The forced convective heat transfer decreases as the heater temperature increase as the fluid velocity increases.

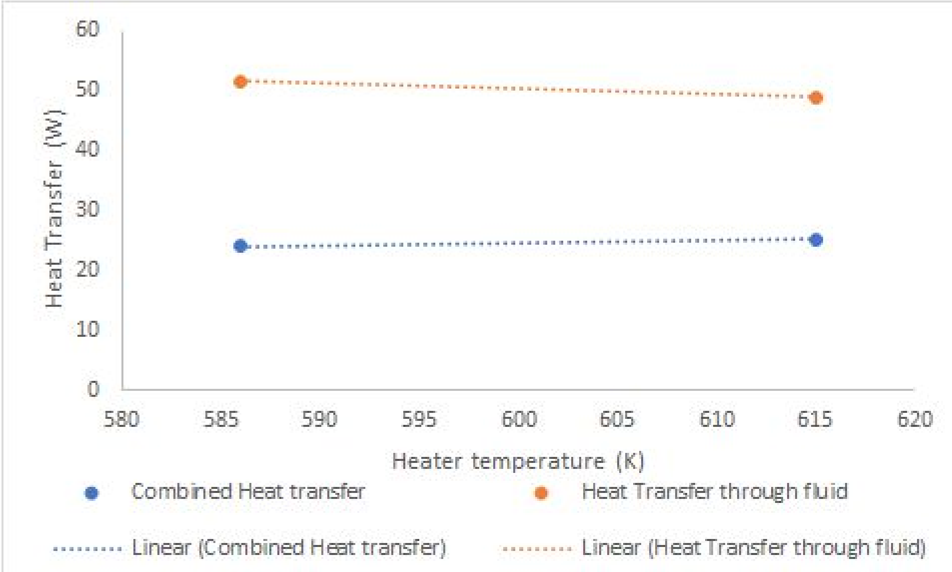


Figure 4. Combined heat transfer and heat transfer through a fluid versus heater temperature. The heat transfer determined from forced convection and radiation had a comparable trend to the heat transfer to the fluid through the flow, but was much lower.

Uncertainty Analysis:

	Natural Convection			**Free Convection**	
Trial #	1	2	3	1	2
Surface Area (m^2)	0.0022	0.0022	0.0022	0.0022	0.0022
ΔArea	0.0001	0.0001	0.0001	0.0001	0.0001
Emissivity	0.60	0.60	0.60	0.60	0.60
ΔEmissivity	0.01	0.01	0.01	0.01	0.01
Shape Factor F	1	1	1	1	1
ΔF	0.1	0.1	0.1	0.1	0.1
T_sur (K)	310	316	315	304	304
ΔT_sur	3	3	3	3	3
T_s (K)	585	695	762	615	586
ΔT_s	3	3	3	3	3

σ	5.67E-8	5.67E-8	5.67E-8	5.67E-8	5.67E-8
Δσ	0	0	0	0	0
Uncertainty of Radiant Heat Transfer (W)	0.916	1.877	2.752	1.139	0.928

Table 5: Using the Propagation of Statistical Analysis method, the uncertainty for each trial was obtained. Each value for uncertainty was either provided in the lab instructions or reasonably deduced from the data recorded. Note that the Stefan-Boltzmann constant has no uncertainty. All data and calculations can be found in Appendix C.

Discussion and Conclusion:

1) In both cases, radiant heat transfer was significantly less than the natural or forced convection methods. However, in comparing the natural and forced methods, we can easily see that forced convection is significantly more powerful.
2) Radiant heat transfer becomes important when the temperature of the heater surface becomes very high. Despite the fact that it is significantly smaller than the other forms of heat transfer, radiant becomes increasingly important as the surface temperature rises allowing the generation of more radiant transmitted waves
3) No, free convection is not truly insignificant in a forced convection circumstance. Forced convection is partly made up of free convection. Any values of forced convection obtained through the experiment also inherently include the free convection.
4) Yes, radiant heat transfer does contribute to heating the air. As the radiant waves move in the air they give energy to the particles around them. This becomes a disorganized thermal energy that generates some heat, thus increasing the temperature of the air as a result of the waves.

The most reliable results are those derived from the complete heat transfer. In the case of using handbook correlations and coefficient values, there is much energy that is not accounted for. The textbook cannot accurately account for all sources of energy transfer in the real world. Therefore, the overall energy transfer from equation (1) (Flow*Delta_T) is the most reliable source of heat transfer analysis.

Design Objective:

In altitude:

Assuming no heater: $\alpha A F_s q_s = \varepsilon A \sigma (T_s{}^4 - T_{sp}{}^4) + \dot{G}$

$(0.2)(\pi)(1)(1.1)(0.32)(1385) = \varepsilon(\pi)(1)(1.1)(5.67(10^{-8}))(T_s{}^4 - 0) + 50$

If $\varepsilon = 0.65 \longrightarrow T_s = 179.9K$

Need $T_s = 293K \longrightarrow$ solar energy absorbed $\approx$ 307W

$E_{out} = \varepsilon A \sigma (T_s{}^4 - T_{sp}{}^4) = (0.65)(\pi)(1)(1.1)(5.67(10^{-8}))(293^4) \approx 939W$

$$Q_{heater} = E_{out} - E_{abs} = 939 - 307 \Rightarrow E_{in}(20^{\circ}\text{C}) = 632W$$

On ground:

$$E_{in} = Q + Q_{heater} = 50 + 632 = 682W$$

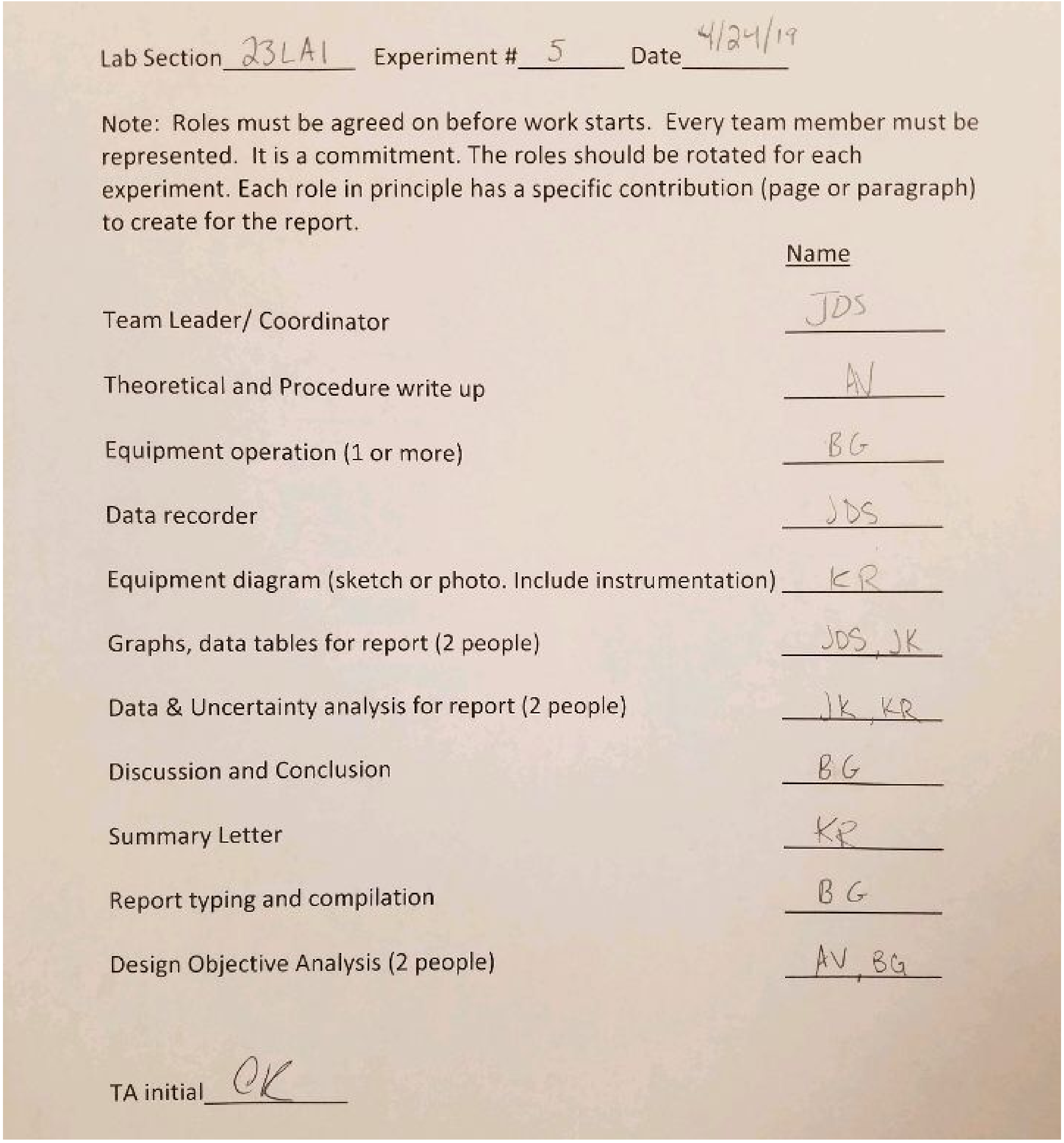
$$Ra_L = \frac{g\beta(T_s - T_\infty)L^3}{\nu\alpha} = \frac{(9.81)(\frac{1}{300})(20-7)(1.1)^3}{(15.89(10^{-6}))(22.5(10^{-6}))} = 1.6(10^9) \longrightarrow$$

$$Nu = CRa_L{}^n = (0.125)(1.6(10^9))^{\frac{1}{3}} = 146$$

$$h = \frac{Nuk}{D} = \frac{(146)(26.3(10^{-3}))}{1} = 3.84\frac{W}{m^2K}$$

$$E_{out} = hA(T_s - T_\infty) = (3.84)(\pi)(1)(1.1)(20-7) \approx 172W$$

Appendix A: Lab Roles



Lab Section 23LA1 Experiment # 5 Date 4/24/19

Note: Roles must be agreed on before work starts. Every team member must be represented. It is a commitment. The roles should be rotated for each experiment. Each role in principle has a specific contribution (page or paragraph) to create for the report.

	Name
Team Leader/ Coordinator	JDS
Theoretical and Procedure write up	AV
Equipment operation (1 or more)	BG
Data recorder	JDS
Equipment diagram (sketch or photo. Include instrumentation)	KR
Graphs, data tables for report (2 people)	JDS, JK
Data & Uncertainty analysis for report (2 people)	JK, KR
Discussion and Conclusion	BG
Summary Letter	KR
Report typing and compilation	BG
Design Objective Analysis (2 people)	AV, BG

TA initial CK

Appendix B: Data Sheets

LaB #[redacted]5

$\mathcal{E} = 0.6$

Voltage	Amps	T(9) inlet	T(10) heater	T(8) outlet
12	2.5 A	23.5 °C	312 °C	49.2 °C
16	2.96 A	24.0 °C	421.5 °C	61.5 °C
18	3.29 A	24.5 °C	489 °C	69 °C

Flow	Voltage	Amps	T(9) inlet	T(10) heater	T(8) outlet
1.6 %	18	3.78 A	26.4 °C	342 °C	34.5 °C
2.1 %	18	3.31 A	27.5 °C	313 °C	34.0 °C

CK

Appendix C: Sample Calculations

		Free Convection			Forced Convection
run	1	2	3	1	2
Surface Area (m2)	0.0022	0.0022	0.0022	0.0022	0.0022
Del(Area) (m2)	0.0001	0.0001	0.0001	0.0001	0.0001
emissivity	0.6000	0.6000	0.6000	0.6000	0.6000
del(emissivity)	0.01	0.01	0.01	0.01	0.01
Shape factor	1	1	1	1	1
Del(F)	0.1	0.1	0.1	0.1	0.1
T_sur (K)	310	316	315	304	304
Del(T_sur) (K)	3	3	3	3	3
T_s (K)	585	695	762	615	586
Del(T_s) (K)	3	3	3	3	3
Stefan-Boltzmann (W/m2-K)	5.67E-08	5.67E-08	5.67E-08	5.67E-08	5.67E-08
Uncertainty of radiant heat transfer (W)	0.916	1.877	2.752	1.139	0.928