Lab Experiment 1: Heat Transfer From an Extended Surface
Heat Transfer From a Steam Pipe

Section 23L: Team A1 & AA1

Jonathan Smith: Data Recorder, Results, Design Objective
Adam VanBuskirk: Equipment Diagram, Procedure
Brandon Golino: Uncertainty Analysis
Jacob Klofta: Theoretical Background, Results
Kyle Rodriguez: Summary, Discussion, Equipment Diagram

Experiment Performed: February 25, 2019
Report Submitted: March 6, 2019

Objectives:
A1:

- Observe two fundamental modes of heat transfer
- Compare measurements to an equation for the temperature distribution developed form basic principles
- Determine the surface heat transfer

AA1:

- Observe two fundamental modes of heat transfer
- Measure temperature distribution along a non insulated, exposed air line
- Determine the overall heat coefficient

Summary:
A1:

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Wilmington, DE

Based on our experimental analysis the rod may get hot enough at the end near the heater to damage the cable .One recommendation for practical changes to prevent damage to the cable would be moving the cable further down the road as temperature drops further down the rod. Another idea is to add standoff clamps along the rod so that cable does not sit directly on the rod, or insulate the entire rod.

Thank you for

AA1:

Dear Ship Owner,

After completing this experiment, we determined that when heat is moving through a narrow pipe the heat quickly drops as the length increases. Thus, adding insulation along the 4 additional meters of pipe will consequently reduce the heat loss in the pipe going from the engine room to the crew's cabin. This will ensure an adequate amount of warm air reaches the crew's quarter.

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Theoretical Background:

A1:

The extended brass rod used in this experiment is used as an example of a fin. While effective fins can take many shapes, a circular rod is one of the simplest examples. When a fin is used to dissipate heat, the thermal energy from the source is conducted through the rod material before being transferred to the surrounding air through convection. It is important to note that in this experiment, free convection occurs, with no forced heat flow. Using this fin geometry, the conductivity of brass, and the heat transfer coefficient, the temperature distribution T(x) along the rod can be determined in relation to the temperature of the wall and the ambient temperature. To find the total heat transferred to the air, we can consider that the total heat convected must be equal to the amount of heat conducted through the rod at x=0, where the rod meets the wall before any heat can be lost by convection. To find this total heat Q, the following equation is used, which is derived from the Fourier equation as shown in the lab notes:

$$Q = \sqrt{hPkA_c} * (T_{x=0} - T_{air}) * tanh(mL) \text{ ,}$$

Where the variables are defined as:

h = heat transfer coefficient

P = perimeter of the cross-sectional area of the rod

k = thermal conductivity

A = cross-sectional area

L = length of the rod

AA1:

To model an overhead steam pipe in a passageway, we must consider heat loss through both conduction through the pipe wall as well as convection into the surrounding air. Due to this total heat loss, the temperature of the fluid within the pipe decreases as the length increases. The overall heat transfer coefficient, U, is used to evaluate this heat loss. While this value can be estimated theoretically, there is often a high uncertainty, which can be determined by comparing an experimental value to the theoretical. The provided test pipe, constructed of aluminum with thermal sensors at intervals along it, will provide the temperature distribution T(x) that can be used to determine the heat transfer coefficient. Using the equations for both convection and conduction heat transfer, a governing equation can be derived that uses U, which combines all the transfer coefficients, h and k:

$$\frac{T_{amb} - T(x)}{T_{amb} - T_{in}} = e^{\left(\frac{-U*A}{m*cp}\right)}$$

Where the variables are defined as:
T_{amb} = ambient temperature
A_s = pipe surface area πDL, where L=x
m = fluid mass flow rate
C_p = fluid specific heat
U = combined heat transfer coefficient

Equipment:
A1:

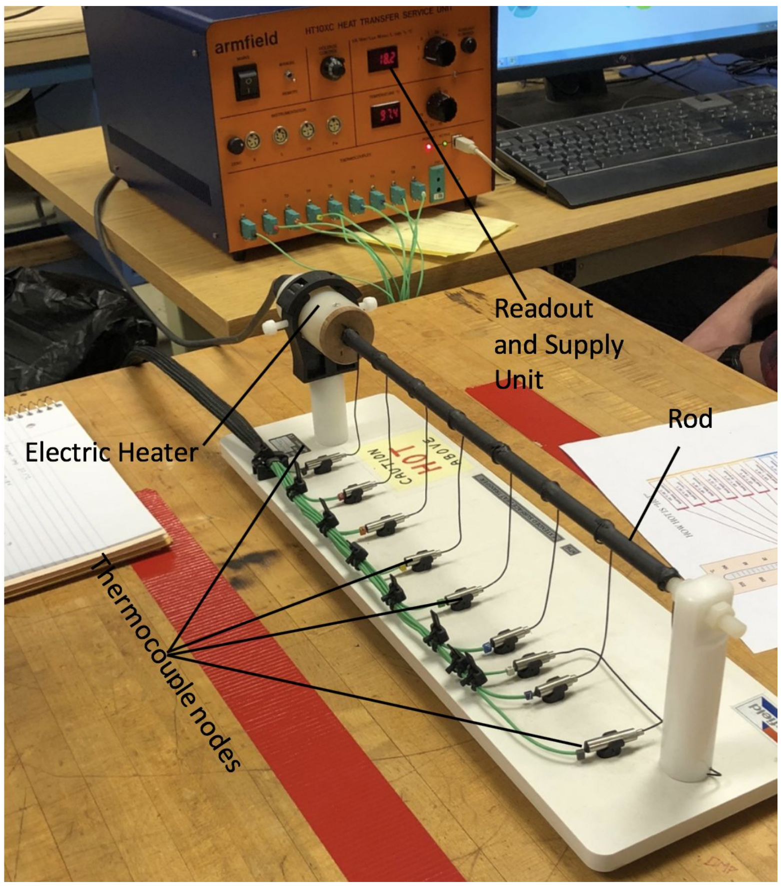


Figure 1: Support Rod heated from one end on which the temperature measurements were taken

AA1:

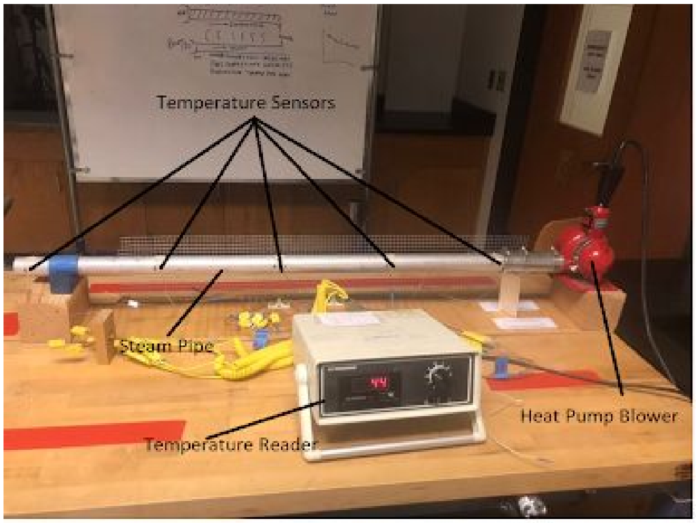


Figure 2: Steam Pipe in cable passage used to measure the temperature distribution.

Procedure:

A1:

Record the initial ambient temperatures on the rod when no power is applied. Then, turn on the power and waiting for the temperatures in the rod to reach steady state. The time required can be minimized by initially heating the rod at high voltage to about 80°C at x=0, then adjusting voltage downward to the levels required. This is done using the software to set the heater voltage to 20V. Monitor the first temperature, T_1, until 80°C, then reduce the heater voltage 18V and allow the temperatures to stabilize. Monitor the temperatures using either the software or the lower selector switch meter.

AA1:

Record the initial ambient temperatures on the rod when no power is applied. Then, turn on the air flow without heating using the toggle switch on the air heater and wait for it to reach steady state. Turn on the heater. Calculate the air mass flow rate, making sure the heater is control is set to 4. Monitor the tube outlet air temperature until it reaches steady state. Turn the dial and record the five temperatures along the pipe.

Results:

A1:
Starting ambient temperature: 22.1 C
Voltage: 18V
D = 10mm
L = 350mm

Table 1: Steady-state temperatures along the conduction rod

Thermocouple	Distance from Heat Source (mm)	Temperature (C)
1	0	103.7
2	50	78.2
3	100	61.6
4	150	48.4
5	200	41.3
6	250	36.2
7	300	34.6
8	350	32.5
9 (ambient)	N/A	23.1

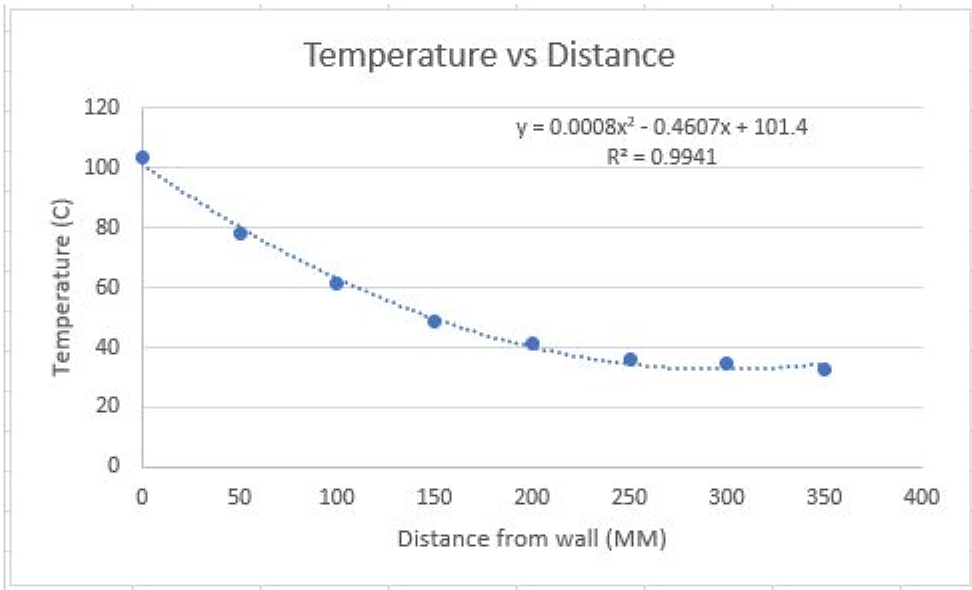


Figure 3: Temperature as a function of distance in the conduction rod, approximated by the trendline T(x).

Using the equation $\frac{T(x)-T_{air}}{T_{wall}-T_{air}} = \frac{cosh(m(L-x))}{cosh(mL)}$, the value for m is adjusted to minimize error using a value of m = 7.75.

Using known parameters and the calculated value of m, the value of h can be determined.

$$h = \left(\frac{Q}{(T_{x=0}-T_{air})(tanh(mL))}\right)^2 \frac{1}{PkA_c} = \left(\frac{Q}{(103.7C-23.1C)(tanh(7.75*.3))}\right)^2 \frac{1}{111\frac{W}{m*K}*.01\pi^2*(\frac{.01m}{2})^2} = 10.5\ \frac{W}{m^2*K}$$

The cable's maximum temperature as specified by the manufacturer is 115C. During testing, the wall reached a temperature of about 104C. The ship's temperature range of 60C to 160C will therefore damage the cable if it is laid directly on the rod. In addition, a higher ambient temperature will raise the temperature of the rod as well, as less heat will dissipate through convection before reaching steady state.

AA1:
<u>Givens:</u>

$$q = I \cdot V$$

Where q : heat generated (Watts), I : Current (Amps), V : voltage (volts)
T(ambient) = 22°C
T(steady state) = 187°C
Material = 6061-T6 Aluminum
Inner Diameter (ID) = 33.78 mm
Outer Diameter (OD) = 28.08 mm

Voltage = 120.8 volts
Current (Amps) of fan blower only = 0.47 A
Current (Amps) of fan blower (w/heater) = 10.12 A

Table 2: Steady state temperatures along the hollow tube at discrete distances from the heated fan.

Thermocouple	Distance from Fan	Temperature
1	0 m	256 ℃
2	0.235 m	227 ℃
3	0.47 m	219 ℃
4	0.705 m	210 ℃
5	1.0 m	187 ℃

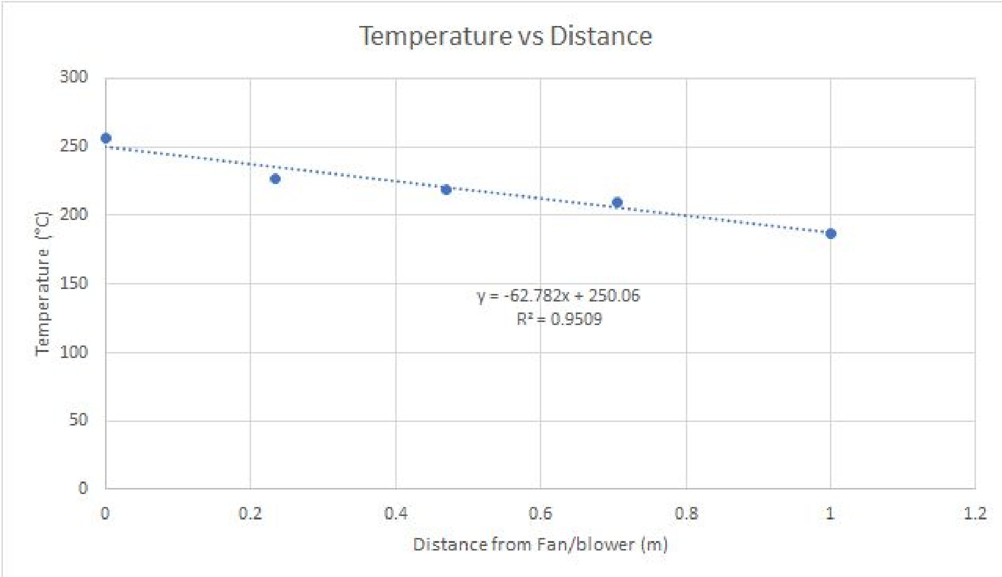


Figure 4: A plot of the measured thermocouple temperature at steady state along the tube at increasing distance from the heat source (fan blower). The trendline approximates the temperature as a function of distance, T(x).

Uncertainty Analysis:

A1:

Table 3: Root Mean Squared Analysis of Experiment A1

Thermocouple	Temp Measured (°C)	Temp Theoretical (°C)	Difference	Difference Squared
1	103.2	103.5	-0.3	0.09
2	78.2	78.31	-0.11	0.0121
3	61.6	61.27	0.33	0.1089
4	48.4	49.92	1.52	2.3104
5	41.3	42.53	-1.23	1.5129
6	36.2	37.94	-1.74	3.0276
7	34.6	35.44	-0.84	0.7056
8	32.5	34.64	-2.14	4.5796
			Sum	**12.3471**
			RMS	3.514

Our RMS analysis shows that the worst case error is within four degrees celsius of the actual value. Therefore we consider this to be an accurate model. The measurement uncertainties were around the RMS value because the accuracy of the thermocouples should be about 1.1 degrees celsius at 25K.

AA1:

Table 4: Root Mean Squared Analysis of Experiment AA1

Thermocouple	Temp Measured (°C)	Temp Theoretical (°C)	Difference	Difference Squared
1	256	212	44	1936
2	227	199.14	27.86	776.18
3	219	187.15	31.85	1014.42
4	210	175.97	34.03	1158.04
5	187	163	24	576
			Sum	**5460.643**
			RMS	73.90

The worst case error derived from RMS analysis was definitely much higher than most of the measured uncertainties were. This error may have resulted from a mistake in the setup of the experiment, as we were not the ones to set up the apparatus. The U-value would be nearly correct for any piece of equipment that was nominally similar, as long as the thermocouples were set up correctly.

Discussion and Conclusions:

1. The temperature and theoretical profiles were nearly identical matches. The thermocouples on the solid bar were accurate and yielded low errors. The steady-state temperatures were very accurate to their theoretical values, because they were allowed a lot of time to settle on a steady temperature.

2. Because the theoretical temperature profile matches the actual temperature profile under the assumption of a constant h value so well, it implies it's a reasonable assumption. This assumption holds true for the situation specified in the lab, of comparable length and constant cross sectional area.

3. Although the majority of the heat transfer is lost through convection off the rod's surface, not all heat may be lost this way. Smaller amounts of heat are directly conducted out of the rod through the thermocouples. If the thermal conductivity of the thermocouples are very high, a large amount of heat could be lost through that conduit.

4. If the rod was near the ceiling, our results may or may not be as accurate depending on the specific air temperature in the area around the rod. If the rod is near the ceiling, continuous heat transfer by convection off the rod could result in the air trapped above the rod heating up hotter than the other air in the passageway to a degree which could result in heat transfer from the air to the cable in significant amounts to contribute to the cable degradation.

5. Option 1: coat the pipe in an insulating material which would create enough thermal resistance to keep the outer pipe surface temperature below the cable's limit of 115 C under all operational situations.
Option 2: Design a new pipe made from a better insulation material which has higher thermal resistance that will result in slower heat transfer and a maximum steady state temperature of the outer surface of the pipe below 115 C. A plastic such as PVC with thicker walls thicker walls or a composite construction would suffice.
Option 3: Use standoff clamps at regular intervals along the pipe to attach the cable to using wire ties or similar. This will keep the cable from being in contact with the pipe. The standoffs should be made of plastic or other material with high thermal resistance.

6. By increasing h by 50%, it increases the value of m by 21%. The allows more heat to be dissipated by convective heat loss per length of the rod. As heat is more quickly lost, the temperature of the rod of reaches usable temperatures very close to the wall. Depending on how close the ribbon cable may be to the heated wall, this may not mean much; if the cable is too close to the wall, the temperature would not be able to lose heat fast enough to reduce it to safe conditions.

Design Objective Analysis:

A1:

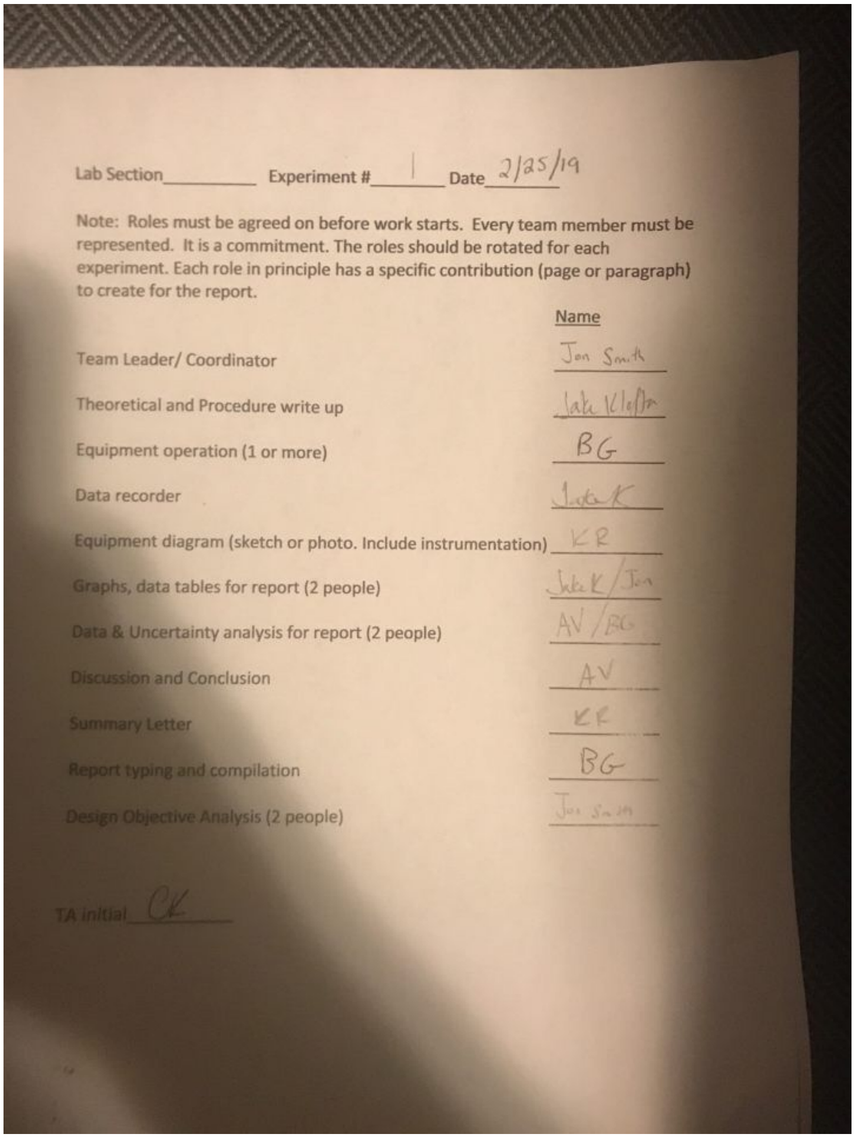
Based on the experiment, certain parts of the rod can easily get hot enough to damage the cable. In our testing, the surface of the rod reached a maximum temperature of 103.7C with an ambient temperature of 23.1C. The wall temperature, according to the ship's engineers, could reach temperatures of 160C with an ambient temperature of 40C. Comparing these numbers to the maximum temperature the cable can withstand, 115C, the cable will not survive in the worst case scenario conditions. Based on our experiment, changes must be made to the rod. The rod can be insulated to prevent of lower the thermal energy that is transferred to the ribbon cable. In addition, the cable could be placed farthest away from the hot wall, allowing it to rest on the cooler end of the brace rod, or could be elevated off the direct surface of the rod through an insulating spacer or guard. These changes will prevent the cable from exceeding the maximum service temperature.

AA1:

From what we learned through experiment AA1, when the heat is pushed through a narrow pipe the heat rapidly drops off as the length increases. In this experiment our initial temperature at the mouth of the fan dropped off at nearly 63 degrees celsius per meter of pipe. Therefore, with an initial temperature of 200 degrees celcius the heated air flowing through the pipe 5 meters away from the source would dissipate before the hot air would reach the cabin. So instead of using a straight uniform pipe of 6061 T6 aluminum I would recommend adding insulation along the 4 additional meters of pipe to reduce the heat loss from engine room to cabin to insure warm air reached their room during the northerly journeys.

Appendices:

Appendix A: Lab Roles



Lab Section________ Experiment # 1 Date 2/25/19

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	Jon Smith
Theoretical and Procedure write up	Jake [illegible]
Equipment operation (1 or more)	BG
Data recorder	Jake K
Equipment diagram (sketch or photo. Include instrumentation)	KR
Graphs, data tables for report (2 people)	Jake K / Jon
Data & Uncertainty analysis for report (2 people)	AV / BG
Discussion and Conclusion	AV
Summary Letter	KR
Report typing and compilation	BG
Design Objective Analysis (2 people)	Jon Smith

TA initial CK

Appendix B: Data Sheets

Lab XI

Ambient temp: 22.1°C

Voltage: 20V $\rightarrow$ 18V

Temp (closest to box)

1	2	3	4	5	6	7	8	
103.7	78.2	61.6	48.4	41.3	36.2	34.6	32.5	23.1

CK

Design objective:

LAB # 23LA1

Ambient 22°C

$Q = m \times C_p \Delta T$

Fan only: 0.47 Amps
Voltage: 120.8 V

Fan & heater: 10.12 Amps

Outlet: 187°C
0.705 m: 210°C
0.47 m: 219°C
0.235 m: 227°C
0 m: 256°C

CK