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Powder Coating Oven

Heat Transfer Analysis

Introduction

One of the teams in the capstone mechanical engineering I (ME 476C) class is designing an oven to powder coat material for the BAJA club at Northern Arizona University and will be stored outside of the renewable energy lab. The oven must be large enough to fit the parts of the BAJA team, which is approximately 30.73 in. x 85 in. x 50 in. and must heat up to approximately 400 degrees Fahrenheit to properly cure the product. The team from ME 476C is conducting multiple technical analyses to ensure the material chosen meets the criteria for the engineering requirements of the design. One of the engineering requirements is to withstand the maximum temperature without having the material burn red and to not have a large heat loss from the insulation. The team plans to analysis this requirement by observing the heat transfer analysis through a sample of the oven wall. This will determine if the team selected the right materials for the oven to hold the hot air in.

Method

The material used for the analysis are:

- Two 1 ft. x 1 ft. 25 gauge cold rolled steel plates.
- 10in. x 11in. R15 mineral wool insulation (3.5" thick)
- Synthetic rubber Maxx foam that withstands 300-375 degrees Fahrenheit
- High temperature vinyl tape that withstands 400 degrees Fahrenheit

The team cut the Maxx foam to three pieces of 12 in. x 4 in. The 4 in. width represents the thickness of the steel beams that will be placed as a frame in the oven. The foam pieces are attached to the three sides of the steel plates using high temperature vinyl. The insulation is then placed inside the box shape of the wall. Figure 1 shown below shows the design of the oven wall sample.

Figure 1: Sample of Oven Wall

The team then set up LabVIEW and the DAQ acquisition system for the thermocouples to read the temperature. The team followed the lab 04 manual set-up of experimental thermos-fluids class (ME 495) [1]. The team set the DAQ system by placing the 4 k thermocouples into the oven wall, shown below in Figure 2, and the fifth thermocouple temperature to be ambient.

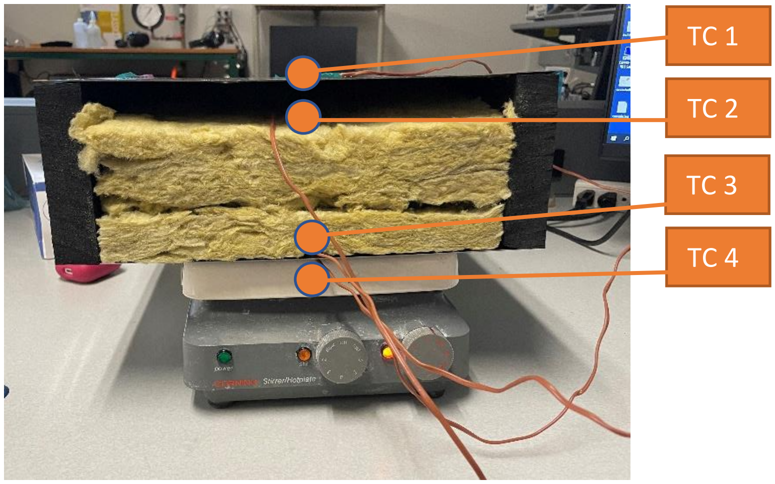

Figure 2: Thermocouple Locations

The team analyzed the temperature change through the wall for approximately 40 minutes and recorded the readings every 2-3 minutes. The team is recording temperature to be able to calculate heat loss between 3.5” insulation and 4” insulation.

To accomplish the analysis, the following governing equation are needed:

$$R_{tot} = 2R_{steel} + R_{insulation} + R_{air}$$

The R value is material resistance to heat flow. The R value is calculated for the steel, insulation, and the air outside of the oven. The steel has a value of 2 in front because of the steel on the top and on the bottom.

$$R_{steel} = \left(\frac{L_{steel}}{k_{steel} * A}\right)$$

L is the length of the steel [m], k is the thermal conductivity of the steel $[W * m/k]$, and A is the area of the steel $[m^2]$. The steel is thin, that area will be neglected.

$$R_{insulation} = \left(\frac{L_{insulation}}{k_{insulation} * A}\right)$$

L is the length of the insulation [m], k is the thermal conductivity of the insulation $[W * m/k]$, and A is the area of the insulation $[m^2]$.

$$R_{air} = \frac{1}{h_{air} * A}$$

The variable h is the specific heat constant of air $[W * m^2/K]$ and A is the area $[m^2]$ of the air but will be neglected.

$$q" = \frac{T_\infty - T_s}{R_{tot}}$$

q" is the heat flux in the oven wall $[W/m^2]$, T_∞ is the temperature of the air surrounding the oven wall (T ambient) and T_s is the temperature of the surface, the inside of the wall at thermocouple 1. R_{tot} is the summation of the R values.

The team is using a two-dimensional model of the oven wall to analyze the thermal resistive network of the two different insulations.

Results

The team analyzed the temperature change of the oven wall using 3.5" insulation and then 4" insulation. Figure 3 shows the 3.5" insulation and Figure 4 shows the 4" insulation. Shown in these graphs, it is shown that temperature increases in thermocouple 1 and thermocouple 2 because it is close to the heat plate, while thermocouple 3 and thermocouple 4 are not and read close to ambient temperature.

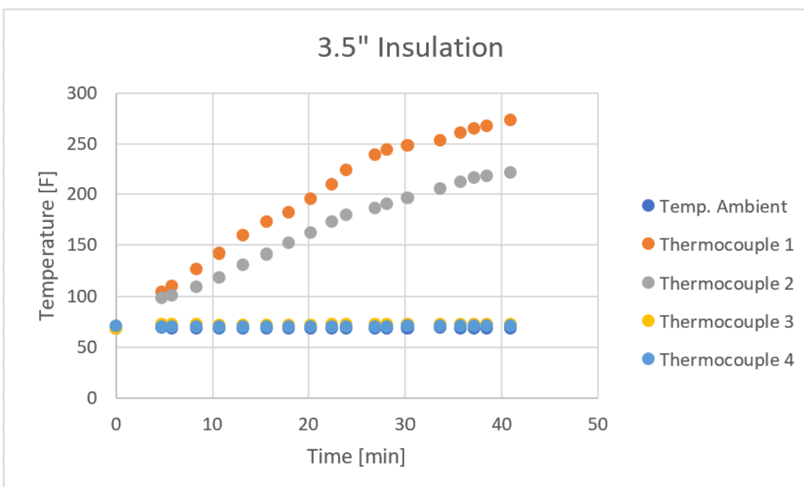

Figure 3: 3.5" Temperature Recordings

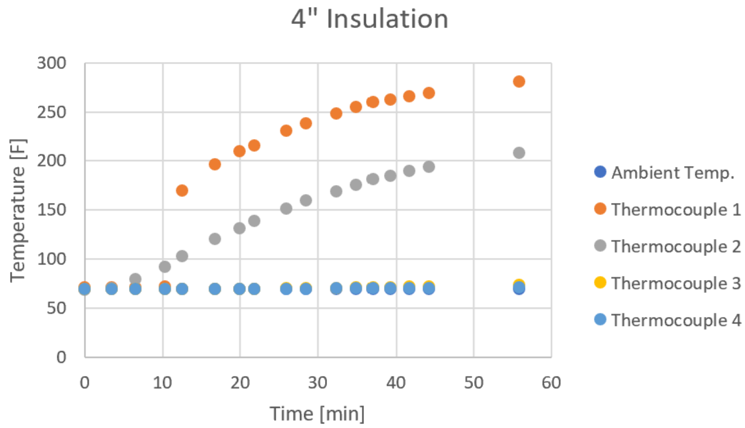

Figure 4: 4” Temperature Recordings

To calculate the thermal resistive network of the oven wall, the average temperatures were calculated for each thermocouple, shown in Table 1, in the time span of approximately 40-50 minutes. The team used the average temperatures of thermocouple 1 and ambient to calculate heat loss. The 3.5” insulation average temperatures are found in appendix A.

Table 1: Recorded Temperatures and Averages for 4” Insulation

		Average Temperature [F]				
Reading Set	Time [min]	TC (AMB)	TC 1	TC 2	TC 3	TC 4
0	0	69.01	70.6	67.95	68.98	69.12
1	3.47	68.98	70.6	69.52	68.87	68.83
2	6.54	69.11	70.76	78.76	68.8	68.73
3	10.34	69.15	71.54	91.96	69.22	69.23
4	12.59	69.18	169.12	102.75	69.08	68.96
5	16.76	69.33	195.93	119.95	69.06	68.99
6	19.93	69.42	209.79	130.59	69.13	69.06
7	21.86	69.27	215.68	138.4	69.22	69.11
8	26.01	69.26	230.85	150.9	69.51	69.29
9	28.53	69.05	237.84	159.27	69.74	69.36
10	32.46	68.83	247.96	168.92	70.13	69.5
11	34.99	68.92	254.75	175.63	70.64	69.75
12	37.09	68.74	259.79	180.88	70.88	69.91
13	39.29	68.83	262.4	184.44	71.01	69.92
14	41.71	68.85	265.89	189.75	71.3	70.03
15	44.24	68.81	269.2	193.89	71.56	70.13
16	55.89	68.76	280.89	208.24	72.9	70.42
Average:		69.03	199.03	141.87	70.00	69.43

Discussion

Calculating the thermal resistive network of each component involved finding the k and h values. The team found the thermal conductivity for insulation to be 0.41 $W * m/k$ for both cases because the average temperature between thermocouple 1 and 4 was to be approximately 330 K [2]. The thermal conductivity for steel is assumed to be 0.5 $W * m/k$ from research [3]. The h value is a complex number to calculate, based on research, the team assumed h to be 13.75 $W * m^2/K$ [4]. The data and calculations are found in Appendix B.

The team calculated the thermal resistive network through all five thermocouples and found the 3.5" insulation to be -2.08 W/m^2 and the 4" insulation to be -2.40 W/m^2. Since the values are close upon observation the difference in minimal heat loss is considered negligible. The heat flux is then analyzed between thermocouple 1, which is between the plate and steel and thermocouple two, which is between the steel at the bottom and insulation. The next heat flux was analyzed at thermocouple 4, which is between the steel at the top and open air and then thermocouple ambient (5).

The q" from thermocouple 1-2 for the 3.5" insulation is found to be 31.88 W/m^2 and the 4" insulation is 52.10 W/m^2. At the end of the thermal resistive network, between thermocouples 4-5, the heat flux for the 3.5" insulation is -14.83 W/m^2 and the 4" insulation is -3.07 W/m^2. From these heat flux values between the two different points, the team analyzed that the 4" insulation has a minimal heat loss.

Conclusion

The team observed two different insulations to analyze which thickness would withstand a high temperature of approximately 300 degrees Fahrenheit and produce minimal heat loss through the wall. The team wants to ensure that the heat that the propane fueled torpedo heater releases stays inside of the oven. The team then analyzed a 2D thermal resistive network of the oven wall to calculate heat flux. Since the heat minimal heat loss is negligible the team will use the 3.5" insulation to accommodate the use of 2x4 structural beams.

References:

[1] Northern Arizona University, "ME 495 – Intro to Data Acquisition with NI & Arduino," Flagstaff, AZ, 2022

[2] “Mineral Wool Insulation,” *Engineering ToolBox*. [Online]. Available: https://www.engineeringtoolbox.com/mineral-wool-insulation-k-values-d_815.html. [Accessed: 30-Apr-2023].

[3] Dan, “Calculating the developed length of a rolled cylinder,” *The Chicago Curve*, 22-May-2016. [Online]. Available: https://www.cmrp.com/blog/plate-rolling/calculating-the-developed-length-of-a-rolled-cylinder.html#:~:text=The%20AutoCAD%20default%20K%20value,your%20software%20to%20K%20%3D%200.50. [Accessed: 30-Apr-2023].

[4] “Convection heat transfer coefficient,” *Convection Heat Transfer Coefficient - an overview | ScienceDirect Topics*. [Online]. Available: https://www.sciencedirect.com/topics/engineering/convection-heat-transfer-coefficient. [Accessed: 30-Apr-2023].

Appendix:

Appendix A:

Table 1.A: Recorded Temperatures and Averages for 4" Insulation

Reading Set	Time [min]	Average Temperature [F]				
		TC (AMB)	TC 1	TC 2	TC 3	TC 4
0	0	68.65	68.48	68.59	68.19	70.50
1	4.78	68.68	104.33	98.16	72.17	70.23
2	5.84	68.08	110.4	100.46	72.13	70.14
3	8.31	68.04	126.63	108.90	72.04	70.12
4	10.76	68.04	141.54	118.29	71.82	70.09
5	13.16	68.09	159.73	131.15	71.84	70.11
6	15.63	68.12	172.55	141.19	71.96	70.12
7	17.96	68.5	181.62	151.50	71.98	70.19
8	20.21	68.56	195.04	162.08	72.00	70.19
9	22.44	68.54	209.52	172.98	72.16	70.24
10	23.89	68.5	223.78	179.17	72.19	70.28
11	26.89	68.49	238.67	185.94	72.31	70.32
12	28.15	68.46	243.87	190.06	72.38	70.30
13	30.27	68.58	247.71	196.61	72.30	70.41
14	33.65	68.76	253.00	205.25	72.14	70.55
15	35.77	68.58	260.21	211.84	72.03	70.67
16	37.10	68.4	265.07	216.06	72.41	70.76
17	38.43	68.48	267.5	218.08	72.50	70.82
18	40.88	68.65	272.8	221.45	72.46	71.04
Average:		68.43	196.97	161.99	71.95	70.37

Appendix B:

Table 1.B: Thermal Resistive Network for 3.5" Insulation

k_steel	0.5	[W/mK]	R_Steel	0.61
k_insulation	0.41	[W/mK]	R_insulatio	32.92
T_avg (ins)	133.67	[F]	R_air	0.07
	329.63	[K]		
h_air	13.75	[W/m^2K]	R_tot	34.21
A_insulation	35	[in^2]		
	0.023	[m^2]	q" [1-5]	-2.09
L_steel	0.3048	[m]	q" [4-5]	-14.83
L_insulation	0.254	[m]	q" [1-2]	31.88

Table 2.B: Thermal Resistive Network for 4" Insulation

k_steel	0.5	[W/mK]	R_Steel	0.61
k_insulation	0.41	[W/mK]	R_insulation	28.81
T_avg (ins)	134.23	[F]	R_air	0.07
	329.95	[K]		
h_air	13.75	[W/m^2K]	R_tot	30.10
A_insulation	40	[in^2]		
	0.026	[m^2]	q" [1-5]	-2.40
L_steel	0.3048	[m]	q" [4-5]	-3.07
L_insulation	0.254	[m]	q" [1-2]	52.10