Project 1.0 :	Material Selection - Refrigerator Condenser
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To:	Future Employer

Abstract - The energy utility of a refrigerator system is dependent on the condenser pipe thermal conductivity. This report examines different materials to select the most thermally conductive material. The materials examined are Aluminum, Nickel, Steel, and two alloys. The most economical material for the heat flow requirement of 0.5 KW for the McKinstry refrigeration system is aluminum with a cost and conductivity of $0.82 / lb and 0.19 $W*m^{-1}*K^{-1}$.

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Introduction

Condensers are pipes in the refrigerator that allow heat to transfer from the fluid to the pipe to the environment. In refrigerators, a refrigerant is a very low temperature fluid used in the pipes. The refrigerant temperature is lower than the inner fridge temperature. The refrigerant gains its heat from the inner fridge heat. Then, the refrigerant is compressed by a compressor. This will increase the pressure and heat of the refrigerant greater than the room environment so heat can travel from the fluid to the room environment. As stated above this transfer occurs with the condenser piping. Afterwards, the fluid travels through an expansion valve that decreases the pressure and temperature of the fluid. So, that sums the processes of 1 cycle of the refrigeration system.

The pipe material of the condenser governs the heat transferred to the environment. More transfer of heat will result in either less electrical energy use or cooler refrigerants. The less electrical energy use results stems from the increase in ease of heat transfer. The more heat transferred, the less pressure required from the pump to cause the necessary heat transfer. The cooler refrigerant results will occur in general with the greater thermally conductive material since more heat will transfer from the refrigerant to the environment in the condenser part of the process.

The materials examined for the condenser piping are aluminum, nickel, steel, and 2 alloys. The thermal conductivity of each material is measured for a sphere filled with a refrigerant. The initial temperature of the fluid is controlled. The time required to change the temperature by 30 degrees C was recorded. The verification method is a rectangular box made of insulating materials. There is one thin conductive plate in the center of the box. The plate is made of the piping materials. The required time to change the temperature of the environments separated by the thin plate verifies the thermal conductivity order of the piping materials.

The costs of piping materials that meet the 0.5 KW requirement are categorized in the analysis section. The cheapest material is stated.

PROCEDURE

Experiment 1 - Temperature Sphere

Measuring Equipment

- BestMed Thermometer
  - Definition: A device that senses changes in temperature at the tip of the device.
  - Tolerance: +/- 0.1 degrees C.
- Accusplit Pro Survivor A601X Stopwatch
  - Definition: A device that measures the time duration of an event.
  - Tolerance: +/- 0.01 seconds.

Steps

1. The room should be set to 15 degrees C.
2. The sphere should have a drain. Plug a hose to the drain and fill the sphere with refrigerant. Then close the valve of the drain.
3. There should be a plug on the other side of the sphere. Remove the plug and place the BestMed Thermometer tip in it. The tip should be in the sphere and not touching the inner edge of the sphere.
   a. *Note: The refrigerant input process and the thermometer input step should be complete after a time duration equal for each material test.*
4. Start the stopwatch once the thermometer is fixed in the sphere.
5. Record the time it takes for the thermometer to change from the 15 degrees C to -15 degrees C.
6. Drain the refrigerant.
7. Wait for the sphere to reach room temperature.
8. Repeat steps 1-7 a few more times and find the average time.
9. Repeat steps 1-8 for the other piping materials.

Experiment 2 - Insulated Box

Measuring Equipment

- BestMed Thermometer
  - Definition: A device that senses changes in temperature at the tip of the device.
  - Tolerance: +/- 0.1 degrees C.
- Accusplit Pro Survivor A601X Stopwatch
  - *Description in last section.*

Steps

1. Cut out one side of the box. Then insert a thin metal plate that is 0.0254 m thick into the box. There should be a tight fit.

   a. *Note: The surface of the plate should be normal to the axis in which the plate translates.*
2. Then wait until the side of the box with the open end is at 15 degrees C.
3. There should be a valve and a plug on the outside of the box. Insert refrigerant into the pump/drain valve.
4. Then, remove the plug and place the BestMed thermometer inside.
   a. *Note: The refrigerant input process and the thermometer input step should be complete after a time duration equal for each material test.*
5. Start the stopwatch once the liquid in the box changes the temperature to -15 degrees C.
6. Record the time it takes for the thermometer to change from the -15 degrees C to 15 degrees C.
7. Drain the refrigerant.
8. Repeat steps 1-7 a few more times and find the average time.
9. Repeat steps 1-8 for the other piping materials.

EXPERIMENTAL RESULTS

Table 1 - Experiment # 1: Sphere Conductor

Material	**Trial 1 (s)**	**Trial 2 (s)**	**Trial 3 (s)**	**Trial 4 (s)**	**Trial 5 (s)**	**Average (s)**
Aluminum	8	11	9	7	8	8.6
Nickel	22	20	17	23	20	20.4
Steel	36	33	29	37	38	34.6
Yellow Brass	15	16	15	18	25	17.8
Red Brass	12	13	14	13	12	12.8

Table 2 - Experiment # 2: Box Conductor

Material	**Trial 1 (s)**	**Trial 2 (s)**	**Trial 3 (s)**	**Trial 4 (s)**	**Trial 5 (s)**	**Average (s)**
Aluminum	13	14	13	14	14	13.6
Nickel	31	33	32	33	35	32.8
Steel	47	45	44	48	49	46.6
Yellow Brass	25	26	27	25	28	26.2
Red Brass	16	17	20	17	18	17.6

ANALYSIS

The thermal conductivity of the piping materials is calculated by the transfer of heat per second per meter times kelvin. The equation is shown below:

Eq. 1:

$$Q' / (1\ m * 1\ K)$$

The Kelvin represents the infinitesimal temperature difference between two locations on the piping material. The meter is derived from the meters squared units. The m^2 units change because it is multiplied by the delta-T / delta-X units represented by the K/m unit. Q' represents the rate of heat transferred from the refrigerant to the environment/metal sphere.

In order to calculate the amount of heat transferred, equation 2 is used to quantify the heat transferred.

Eq. 2:

$$Q = m\ c_p\ dt$$

The rate of heat transferred with respect to time is equal to the amount of heat transferred divided by the amount of time it takes to transfer the heat. The value Q for each experiment and material is the same since the refrigerant and the change in temperature are the same. The calculation of Q is shown below:

C_p = specific heat for superheated fluid = 0.86 KJ/ (C * kg) at 200 kPa and 15 degrees C.

C_v = 0.75 KJ/ (C * kg) at 200 kPa and 15 degrees C.

C_p/C_v = 1.14

V_s = specific volume = 0.194 m^3 / kg.

V_{sphere} = volume of sphere = 0.092 m^3

m = mass = V_s^{-1} *(0.092 m^3) = .47 kg

Q = 0.47 kg * 0.75 [KJ/ (C*kg)] * 30 C

= - 10.6 KJ

Table 3 - Experiment 1: Rate of heat transfer through sphere.

Material	**Q' = (Q/delta-t)**
Aluminum	-1.23255814
Nickel	-0.5196078431
Steel	-0.3063583815
Yellow Brass	-0.595505618
Red Brass	-0.828125

Table 4 - Experiment 2: Rate of heat transfer through plate.

Material	**Q' = (Q/delta-t)**
Aluminum	-0.7794117647
Nickel	-0.3231707317
Steel	-0.2274678112
Yellow Brass	-0.4045801527
Red Brass	-0.6022727273

Since 1/m*K is controlled, then it will remain a constant for both experiments and all materials. Therefore the Q' values are sufficient to compare order of thermal conductivities of materials.

Upon ordering the materials from most thermally conductive to least, aluminum was the first in the sequence. The sequence is aluminum, red brass, yellow brass, nickel, steel.

The materials that meet the power requirement in experiment 1 are aluminum, nickel, yellow brass, and red brass. The materials that meet the power requirements in experiment 2 are aluminum and red brass.

According to Table 5, the cheapest material for condenser pipes is 1040 carbon steel. It costs about $.32 / lb. Steel is superior in terms of cost. However, it does not meet the 0.5 KW power requirement. The most cheap material that meets this requirement is aluminum.

The most suitable material for condenser pipes is aluminum. Aluminum meets the energy requirement. It is the most thermally conductive material. Also, it is the cheapest material within the sequence of materials that at least meet the greater than 0.5 KW power requirement.

Table 5 - Cost of all materials

Material	Cost per pound ($ / lb)
Aluminum	.82
Nickel	4.5
Steel	.32
Red Brass	1.35
Yellow Brass	1.20

Table 6 - Uncertainty U_Q for the heat transfer measurements for experiment 1.

Time Variable	Q' Error (+/-)
8.6	0.004341068017
20.4	0.00174652572
34.6	0.001022608468
17.8	0.002008266368
12.8	0.002828533397

Table 7 - Uncertainty U_Q for the heat transfer measurements for experiment 2.

Time Variable	Q' Error (+/-)
13.6	0.002654222903
32.8	0.001079180971
46.6	0.0007580036703
26.2	0.001354211109
17.6	0.002031728603

The uncertainty of the heat flow measurements are stated in the previous 2 tables with the largest uncertainty approximately equal to +/- 4.34 W. The uncertainty does not affect the order of the material sequence since it is below 0.03 KW of difference which is a difference that is smaller than all other differences in the material. There are other variables that affect thermal conductivity that do not affect heat flow. These variables are temperature between points and area of material. These variables are vital for a more accurate statement of the error involved in thermal conductivity.

There is no standard method of incorporating the two additional variables into the accumulated uncertainty. The individual uncertainties are known however. The created method uses the maximum values of the variables due to the uncertainties associated with each variable. Then, the resulting value of conductivity will be the boundary of that particular measurement. This is repeated for the minimum value. The largest deviation of the resulting value of conductivity is then used as the uncertainty magnitude for the particular conductivity measurement.

As seen in table 8, the value for the thermal conductivity was calculated. This is necessary because it is a variable in calculating the uncertainty of conductivity. The maximum value for the conductivity was found with equation 1 on page 5; the numerator increased in magnitude as the denominator was decreased by including the uncertainty to the measured values that would result in large numerators and small denominators. A similar method was used to calculate the smallest value of conductivity. Then, the interval from the measurement to the extreme values are calculated. Afterwards, the largest interval is used as the absolute interval for safety measures.

The error of conductivity is smaller than the error of heat flow. The error of conductivity is +/- 1.21 W/m*K. This interval is approximately 75% less than the heat flow error. Nonetheless, the error is not large enough to alter the order of the piping material sequence nor does the error noticeably change the feasibility of other materials surpassing aluminum as the prime thermal conductor.

Table 8: The Uncertainty of Conductivity is presented in the last column.

Function Value	Boundary Value 1	Boundary Value 2	Interval 1	Interval 2	Largest Interval-Uncertainty
-0.00822	-0.00943	-0.00727	0.00121	0.00094	0.00121
-0.00346	-0.00397	-0.00307	0.00051	0.00040	0.00051
-0.00204	-0.00234	-0.00181	0.00030	0.00023	0.00030
-0.00397	-0.00456	-0.00351	0.00059	0.00046	0.00059
-0.00552	-0.00634	-0.00489	0.00081	0.00063	0.00081
-0.00520	-0.00596	-0.00460	0.00077	0.00060	0.00077
-0.00215	-0.00247	-0.00191	0.00032	0.00025	0.00032
-0.00152	-0.00174	-0.00134	0.00022	0.00017	0.00022
-0.00270	-0.00309	-0.00239	0.00040	0.00031	0.00040
-0.00402	-0.00461	-0.00355	0.00059	0.00046	0.00059

DISCUSSION

What causes increases in thermal conductivity?

- Electrical conductivity.
- Increases in internal temperature differences.
- Increases in external temperature differences (The larger the difference, the larger the temperature bounds of an object are and the larger the internal gradient can be).
- Metals.
- Softness.
- Crystal Structure (at least +90 % of all noticeably conductive materials have a FCC structure)

What differentiates heat capacity from conductivity? Also, are the two concepts dependent on the same behavior of the ability of a material to adapt its internal temperature to heat?

- Heat capacity is the property of the material and it measures the material's ability to absorb/release heat with respect to the magnitude of heat applied to the system. The heat is typically heated 360 degrees all around.
- Thermal conductance depends on the material to move heat between environments as a medium of transfer. This implies that the material is heated on one side. Eventually, the material reaches its steady state.
- The ability of the material to absorb heat (capacity) is related to its ability to move the heat from the hot to the cold environment. Imagine a heat wave wanting to move from hot to cold. If the material has atoms that absorb heat easily, then the heat will have ease traveling from hot to cold. So, capacity and conductivity are directly proportional.

Why are metals more thermally conductive that non-metals?

- Conduction band theory that states that the levels of atoms are closer than others.

What alloys would work best for thermal conduction?

- Nickel Mixture
- Palladium Mixture
- Platinum Mixture
- Vanadium Mixture
- Silver Mixture

Why would I increase the heat only to want to decrease it?

- The heat is not increased; the pressure is increased. This increases the temperature focus which allows a region to be noticeably hot and a difference in temperature to exist. Then, there is a transfer from the hot region to the cold region. After the heat is transferred, the pressure returns to normal. So, I am not adding heat; I add pressure.

Also if I increase the heat, will not the decrease in heat level off at room temperature since at this point no more heat may be transferred?

- Yes, not all of the heat is transferred from the refrigerant to the environment. However, enough is transferred to result in a noticeable difference in temperature.

The key answer is that pressure is increased rather than heat. The heat is more concentrated which results in higher temperatures in certain regions without a gain in heat. Afterwards, the pressure is reduced again maybe by the previous increased amount. So, there would be a net loss of energy from the refrigerant.

CONCLUSION

Aluminum is the most thermally conductive material in the sequence of materials surveyed for condenser piping. The thermal conductivity is equal to c* -1.23 KW, and c is equal to 1/(k*m). Aluminum averaged approximately 300 more Watts than its competitor red brass. 300 more Watts is 60% more Watts than the minimum requirement of power desired for the condenser pipes.

Even though thermal conductivity was not explicitly measured, a variable with a directly proportional linear relation with thermal conductivity was measured. The variable was thermal power. The order of the thermal conductivity is the same as the order created by the thermal power measurements. So, the order and the quantified relations of materials in terms of thermal conductivity is correct from the measurements of thermal power.

The next plan is to observe new materials based on copper. It is the most used thermally conductive material on the market. It may have more conductive alloys. In this report, I will define what is needed for really great conductivity in hopes of hypothesizing which elements combinations will result in a feasible candidate.

The following plan is to observe liquids and gases as inner boundary material.

REFERENCES

http://www.et.byu.edu/~rowley/ChEn273/Topics/Energy_Balances/Energy_Balance_Open_Systems/Ex_Four.htm