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PHYS 229: Convective and Radiative Cooling

Introduction: In this lab, we investigate the three main mechanisms of heat transfer by measuring the temperatures of cooling aluminum rods as a function of time. The three mechanisms are: conduction, radiation, and convection.

The equation for conduction is : $\frac{dQ}{dt} = -kA\frac{dT}{dx}$

The equation for radiation is: $\frac{dQ}{dt} = -Ae\sigma T^4 + Ae\sigma T_0^4$

The equation for convection is: $\frac{dQ}{dt} = -hA(T - T_o)$, where $h = 1.32\frac{J}{m^{7/4}s\,K^{5/4}}\left(\frac{T - T_0}{D}\right)^{1/4}$

The equation that relates heat flow to the rate at which a body cools is:

$$\frac{dQ}{dt} = MC\frac{dT}{dt} = \rho VC\frac{dT}{dt}$$

Procedures: We heated up three aluminum rods in boiling water until they reached approximately 85 ºC. Rod 1 was just a normal rod, rod 2 was polished and rod 3 was lacquered. We placed the rods vertically on a stand wooden stand, ensuring that there was approximately 30cm of space between the rods. We then inserted an analog thermometer into each rod and monitored the temperature every 2 minutes. When the temperature difference was about 2ºC between measurements, we switched to taking measurements every 5 minutes. This happened after 24 minutes.

Data:

Room temperature: 25ºC ± 0.5ºC
Rod length: 34.5cm ± 0.05cm
Rod diameter: 2.52cm ± 0.05cm
Aluminum density: 2.70 g*cm^-3
Molar Heat capacity of aluminum: 24.20J*mol^-1*K^-1
Rod mass: 46.44kg
Rod moles = 1721.17686mol
Specific Heat Capacity: 41652.48J*K^-1

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*The rod length was measured with an analog ruler. The diameter was measured with an analog caliper. Density and heat capacity are accepted values taken from the online chemistry and physics handbook.

Time (min)	Temp1 (normal)	Temp2 (polished)	Temp3 (lacquered)
0	82.5	85	83.5
2	79.5	83.5	79
4	74.5	79.5	73.5
6	70	76	68.5
8	61	72.5	64
10	62.5	70	60.5
12	59.5	67	57.5
14	56.5	64.5	54.5
16	54	62.5	51.5
18	51	60	49
20	49	57.5	46.5
22	46.5	56	45
24	45	54	42.5
29	40.5	49.5	38.5
34	37	45.5	35.5
39	34.5	42.5	33
44	32	40	31
49	30.5	37.5	29.5
59	28	34	26.5
69	26	31	25.5
79	25	29.5	24.5

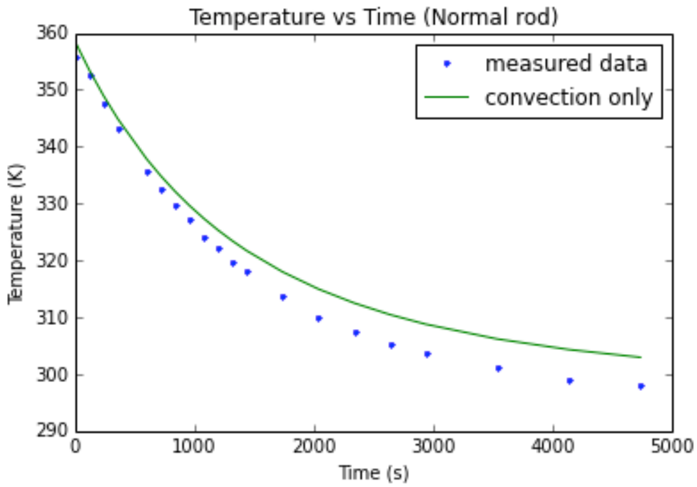
All temperatures measured in ºC.

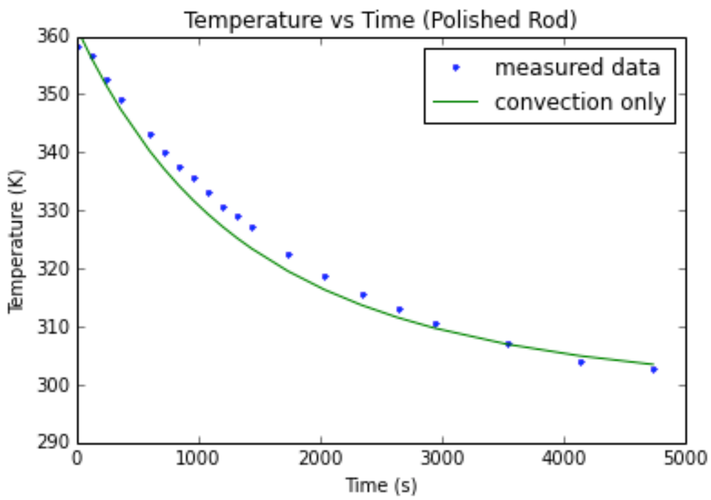
From the pre-lab, we solved the differential equation for convection only cooling and obtained the equation: T = (kt + (Ti-T0)^-.25)^-4 + T0

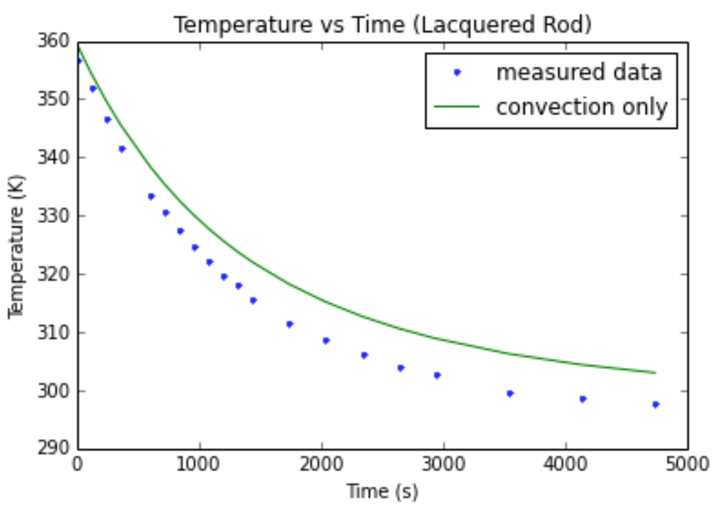
Where:

- T0 is the room temperature = 25ºC = 298K
- K is a constant = 1.32A/(pVC(D^.25)) = 2.6306 * 10^-4
    - For calculations of area (A), we neglected the ends of the cylinder because one end was resting on wood (a poor conductor of heat) and the other end had a large cavity in which we inserted the thermometer.
- Ti is the initial temperature

We then plot our data and compared it qualitatively with the expected cooling from convection only.







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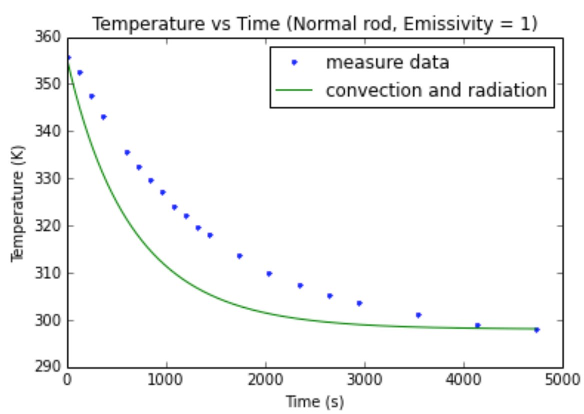
The graphs above show that although the convection model has a similar shape as the measured data, it is not enough to account for all the cooling (i.e. the other mechanisms of heat transfer are not negligible). It is interesting to note that the polished rod cooled much slower than expected and that only taking convection into account is already too much cooling. This may be because the surface area of the polished rod is smaller than the other two rods and that some approximations to the convection model were used (in particular the surface area, the ambient temperature and the mass). Also, note that lacquer cooled the fastest of the three bars.

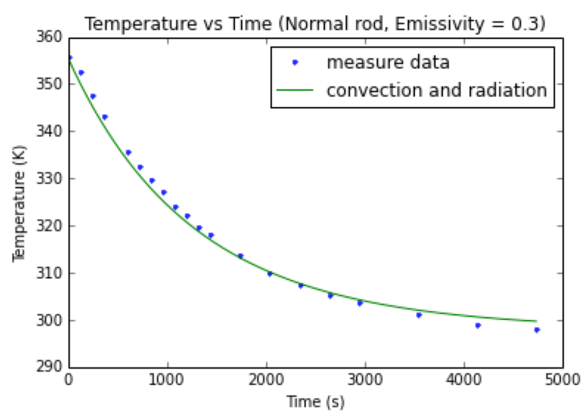
Next, we modelled the cooling with both convection and radiation. Combining the equation for convection and radiation given above, we get.

$$\frac{dT}{dt} = \left[\frac{1}{\rho V C}\right]\left[A\epsilon\sigma(T_0^4 - T^4) - \frac{1.32A}{D^{\frac{1}{4}}}(T - T_0)^{\frac{5}{4}}\right]$$

The equation could not be solved analytically and so we used numerical methods (by writing a loop in Python that uses Euler's method with steps of 1 second).

In Python, we first tried to simulate emissivity = 1 (which did not work at all) and just tried different values for emissivity until it looked like a good fit. We gave the lower points more weight in our fit because the slower cooling rates made those measurements more accurate than the initial measurements when the rods were cooling much quicker. We could not use Python to fit because we could not solve the differential equation. Unfortunately, using this method of guessing and checking, we were able to obtain emissivity values with a precision of only one significant figure.





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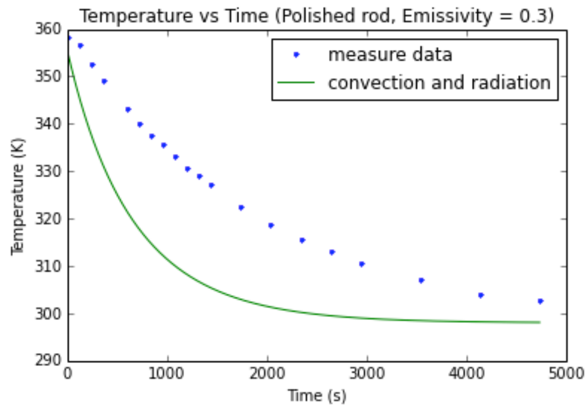

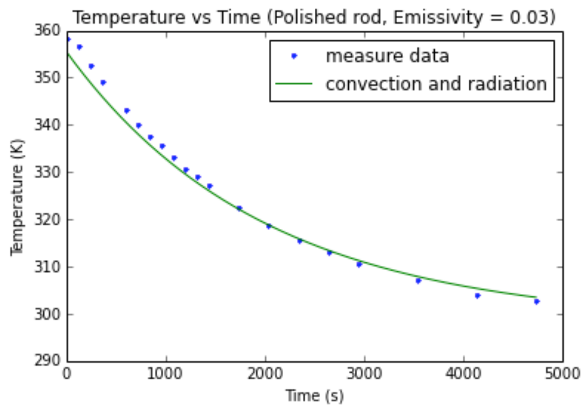

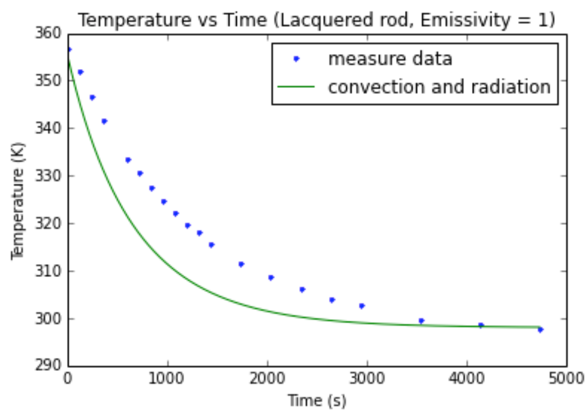

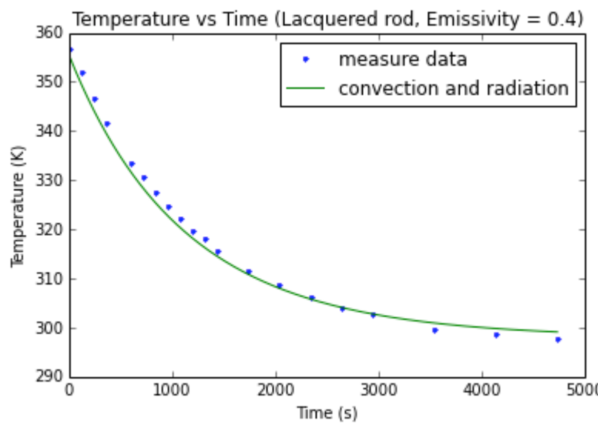

Normal: 0.3 ± 0.05
Polished: 0.03 ± 0.005
Lacquered: 0.4 ± 0.05

We note that emissivity should increase as surface area increases because heat can dissipate more easily if more of the object is exposed to the air. Therefore, we should expect the normal (rough) rod to have the highest emissivity of the three. However, we note that lacquer, which might have been expected to reduce the emissivity by making the surface smoother, actually increased it by a significant amount. This is unexpected and indicates that lacquer has a higher emissivity than normal (rough) aluminum.

Conclusions:
Although there are three main mechanisms of cooling, (conduction, radiation, and convection), modelling temperature change of aluminum rods can be well approximated by only including radiation and convection. Using our radiation and convection model with our data, we found that the emissivity of the unpolished aluminum rod to be 0.3 ± 0.05, the emissivity of the polished aluminum rod to be 0.03 ± 0.005 and the emissivity of the lacquered aluminum rod to be 0.4 ± 0.05.