Experiment of the Month

Black Body Radiation and the I-V Characteristics of an Incandescent Lamp

Our labs do not have written instructions. In keeping with this spirit, the description given here will be brief and general. The intent is that each performance of the lab will be unique; in each nature will reveal a slightly different face to the observer.

The first time that this intermediate laboratory experiment was performed, it was primarily an exercise in automatic data collection, using Commodore-64 computers (!)

The computer recorded two voltages, one proportional to the current through a 12V incandescent lamp, and one which reflected the voltage across the lamp. A plot of the potential difference (voltage) across the lamp, versus the current through the lamp was concave, downward. Students were familiar with this result from our Physics 232 laboratory. There, the lamp was presented simply as a device which failed to obey Ohm's law.

The experiment extended the elementary result by starting with the lamp glowing brightly. The rapid computer data collection was started and the power supply was abruptly turned to zero. In this case, a plot of potential versus current was a straight line.

The slope of the straight line represented the (temperature dependent) resistance of the filament at the elevated temperature that made the lamp glow. By taking data rapidly, students can measure the Ohmic character before the temperature has time to change.

In the past few years we have extended the analysis of the experiment to follow the power flows in the system. The power input is simply the product of current through times potential across the lamp. Power leaves the lamp filament in several ways, however. The two mechanisms upon which we focus are heat conduction (via the gas and glass envelope and the filament supports) and electromagnetic radiation.

The rate of heat conduction is proportional to the temperature difference between the filament and the room air which absorbs the heat. The rate of electromagnetic power radiation follows the rules for black body radiation. It is proportional to the difference in the fourth power of (absolute) temperature between filament and room. To make meaningful connection between experiment and analysis, we need an estimate of the temperature of the filament.

We return to the original qualitative observation that, when the bulb is hot, the resistance is higher than when the bulb is cold. We try a first order Taylor series expansion, treating the resistance as function of temperature. In first order, the resistance is proportional to the temperature. The only question is the range of temperatures over which this is true. (Eventually the higher order terms of the expansion must become important.)

We test the linear approximation by using it to model the experimental relation of current to potential. To make the model as simple as possible, we further assume that the filament resistance is zero at a temperature of absolute zero.

The two equations that describe the model relation of current (I) to potential difference (V) are

$IV = A(T-T0) + B(T^4-T0^4)$ and

$T = GR = GV/I$

where T is the (absolute) temperature, T0 is room temperature (absolute), R is filament resistance at a particular temperature, and A, B, and G are empirical constants.

To test the model, we first try ignoring the black-body radiation term: We set B=0. In that case, we quickly find that that the slope of the predicted plot of current versus potential changes too quickly to fit the data. We next include the black-body term and consider the limiting case of high temperature. In this case, the T^4 term will dominate the right hand side of the equation, leaving us with

$IV = BG^4(V/I)^4$

Thus the model predicts that a plot of ln(I) versus ln(V) will be a straight line with slope 3/5=0.6. This unusual slope is verified experimentally, justifying the model, at least in the high temperature limit. Most interesting is the experimental support for our assumption that the filament power radiation is proportional to the fourth power of its temperature.

Our confidence bolstered, we calculate G using the room temperature resistance of the filament and use that to estimate the temperature of the filament when it is hot, using the measured hot resistance. The results have the same order of magnitude as the "color temperature" of the filament.

As a follow-up, while students begin a new series of experiments, we demonstrate a measurement of the temperature dependence of the filament resistance at low temperatures, using our cryostatic refrigerator, which takes us down to within 7 degrees of absolute zero.