PHYS 232: Blackbody Radiation

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Introduction

All surfaces at a finite temperature emit electromagnetic radiation at all wavelengths/frequencies. The intensity and peak wavelength of the emitted radiation are strongly temperature dependent. At room temperature the emitted radiation is predominantly in the far infrared part of the electromagnetic spectrum. The power radiated increases as the *fourth* power of temperature. This relationship is given in the Stefan-Boltzmann Law:

$$P = A\varepsilon\sigma T^4, \tag{1}$$

where P is the emitted power (energy per unit time), A is area of the surface emitting the radiation, ε is a material property of the emitter called the emissivity, T is temperature, and:

$$\sigma = \frac{2\pi^5 k_{\mathrm{B}}^4}{15c^2h^3} = 5.67 \times 10^{-8}\ \frac{\mathrm{W}}{\mathrm{m}^2\mathrm{K}^4}, \tag{2}$$

is the Stefan-Boltzmann constant, k_{B} is Boltzmann's constant, c is the speed of light, and h is Planck's constant.

In this experiment we will be interested in the intensity of the electromagnetic radiation emitted by a *blackbody*. A blackbody is an object that perfectly absorbs all incident radiation. A nearly perfect blackbody absorber can be made by drilling a small hole into a hollow cavity. See Fig. 1. Any radiation that enters through the hole will bounce around inside the cavity until it is completely absorbed. All materials have an emissivity somewhere between zero and one. Those that are highly reflective, like polished copper, do not absorb well and have a low emissivity. An ideal blackbody has an emissivity $\varepsilon = 1$.

A body will *emit* electromagnetic radiation exactly as well as it absorbs radiation. To see why, imagine a room full of objects all at the same temperature. Assume that each of these objects emits

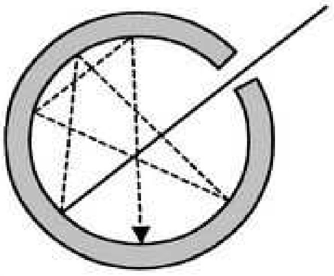

Figure 1: Radiation incident on the hole in the cavity undergoes multiple reflections. The radiation loses energy at each reflection until it is completely absorbed.

radiation as well as it absorbs radiation. Now suppose an object that absorbs better than it emits in introduced into the room and that it is initially at the same temperature as the other objects. This object would heat up because it is gaining energy faster than it loses energy. On the other hand, the room is losing net energy and it would cool down. This type of scenario would violate the second law of thermodynamics which, among other things, states that in a closed system the temperatures of the bodies in the system tend to equilibrate.

The Planck Radiation Law gives the intensity of the electromagnetic radiation emitted by a blackbody as a function of temperature and wavelength:

$$I_\lambda(T,\lambda) = \frac{2c^2h}{\lambda^5}\left[\frac{1}{e^{\frac{hc}{\lambda k_\mathrm{B} T}}-1}\right] \tag{3}$$

Figure 2 plots I_λ as a function of λ for a number of different temperatures. Notice that the peak wavelength increases with decreasing temperature. A quantitative statement of this qualitative observation is made using Wien's displacement law: $\lambda_\mathrm{max} \propto T^{-1}$.

Further Reading

There is a very good description of blackbody radiation available in the supplemental materials for this lab. This document provides a qualitative description of the absorption and emission of electromagnetic radiation as well as differences between transparent and opaque materials and insulating and conducting materials. The document also provides some historical insights into the development of the theory of blackbody radiation and its significance. For the interested reader, there is also some detailed quantitative analysis/derivations (some of the analysis requires a background in statistical mechanics and quantum mechanics).

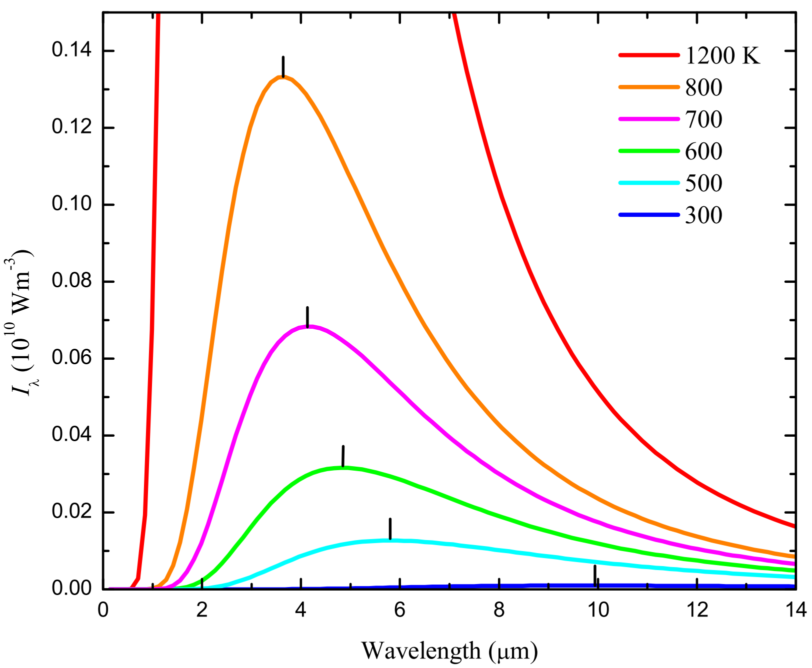

Figure 2: Intensity curves for blackbody radiation for a number of temperatures spanning 300 to 12000 K.

Pre-lab Assignment

In this experiment you will use a furnace to achieve high temperatures. The temperature of the furnace will be measured using a thermocouple. Imagine you have two wires made of different materials. The wires are joined together at one end and a voltmeter attached to the free ends. If the temperature difference exists across the lengths of the dissimilar wires a nonzero voltage will be read by the voltmeter and the magnitude of the reading will depend on the size of the temperature difference. See the supplemental material for this lab for an introduction to thermocouples.

Question 1: The thermocouple that you will use is called a type K thermocouple. The positive lead is made of a nickel-chromium alloy and has yellow insulation and the negative lead is a nickel-aluminum alloy and has red insulation. A calibration table used to convert the measured voltage to temperature is provided within the supplemental material for this lab. Plot the calibration data over the temperature range 100 to 1100°C. Fit the data to a polynomial that expresses the temperature as a function of thermocouple voltage. You will use this expression to convert your thermocouple measurements to temperature.

Question 2: Make an approximation to Eq. 3 at allows you to write $\ln I_\lambda$ as a linear function of $1/T$. What condition must be met in order for this approximation to be valid? Plug in some numbers to test whether or not the approximation is valid (for example, choose λ of red light and any reasonable temperature). What is the slope of a plot of $\ln I_\lambda$ as a function of $1/T$ in terms of c, h, k_B, and λ?

Experiment

The radiation emitted by the furnace will be collected by a fibre optic and transported to a *spectrometer* that can measure the intensity of the light in the visible range of the electromagnetic spectrum. To avoid damage, the end of the fibre that is close the furnace opening must not be heated. The fibre is mounted within a brass cylinder that is surrounded by copper pipe through which cooling water can flow. **The cooling water must be flowing before power is supplied to the furnace**.

1. Ensure that the fibre is mounted properly and pointing at the opening in the furnace.
2. Turn on the cooling water.
3. Turn on the variac and set it to 100 V.

The thermcouple voltage will be monitored and collected using an Aglient 34401A digital multimeter in combination with a program written using LabVIEW. The intensity data will be collected by the spectrometer controlled by Logger Pro. Open the Logger Pro and LabVIEW programs. Setup Logger Pro to measure the intensity of radiation as a function of time. Have Lopper Pro record the intensity of the radiation of emitted at 900 nm, 850 nm, 800 nm, and 750 nm every 15 seconds. Also setup the LabVIEW program to record the furnace temperature every 15 seconds. Start collecting the temperature and intensity data at the same time. Once the temperature is approximately stable and the intensity is no longer increasing (or increasing very slowly), you can increase the variac voltage to 110 V. Stop the data acquisition programs once the intensity measurements at all four wavelengths have saturated at a relative intensity of 1. The LabVIEW program will write the data to a file. Export the Logger Pro intensity data to a data file.

Use your data to generate a plot of $\ln I_\lambda$ as a function of $1/T$. You can import your data files into Python. Take a look at example Jupyter notebooks provided on the course website to see how to import your data into Python. Use a straight line fit to extract Planck's constant h from your data at each wavelength.

Time permitting, you can also use Logger Pro to measure the intensity spectrum of the radiation. Allow the furnace to reach a suitable equilibrium temperature. Then setup Logger Pro to measure the intensity over the entire available range of wavelengths. Can you determine how to extract h from this set of data?