

# Black-body Radiation

## 1. Introduction

All surfaces at a finite temperature emit electromagnetic radiation, but at room temperature this energy emission is weak and almost entirely distributed in the far infrared spectrum. With increasing temperature the total radiated power increases rapidly, proportional to the fourth power of the absolute temperature (Stefan's Law).

The fundamental concept is of cavity radiation: the isotropic distribution of intensity versus wavelength in a cavity whose walls are at a uniform temperature  $T$  (Kelvin). The radiation field is in thermal equilibrium with the walls of the enclosure and the distribution of energy as a function of wavelength is given by the Planck Radiation Law in which each of the parameters is a well-known physical constant,

$$I_{\lambda} = 2\pi c^2 h / [\lambda^5 (e^{hc/\lambda k_b T} - 1)] \quad (1)$$

where the spectral intensity  $I_{\lambda}$  is such that the power per unit area is  $I_{\lambda} d\lambda$  ( $W/m^2$ ). The total power (energy per second) falling on area  $\Delta A$  is

$$\Delta A \int I_{\lambda} d\lambda$$

The areas involved here may be either real areas of the cavity walls or one side of a mathematically postulated area within the space of the cavity. The spectral intensity given by this equation peaks at a particular wavelength (see Figure 1), and this wavelength is inversely

proportional to the temperature in Kelvin (Wien's Law). From everyday experience we are aware that different surfaces made from different materials radiate 'heat' at different rates; dull black surfaces radiate more effectively than polished and shiny surfaces.

However, good radiators are also good absorbers - and therefore poor reflectors. You might have thought that a cavity made from dull black material would have a higher spectral intensity than a shiny cavity at the same temperature, since the former surface radiates more power. But when you 'look' at the surface (or point an instrument to take a measurement), the total radiation that you 'see' or measure is the sum of the emitted and reflected parts. A dull black surface emits a lot but reflects little; for a shiny surface this is reversed.

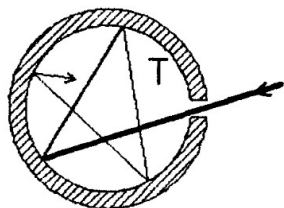


Figure 2: Cavity at temperature  $T$  absorbing like a black-body.

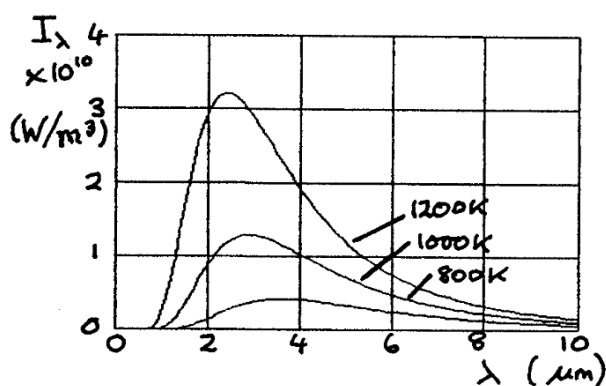


Figure 1: Intensity curves for blackbody radiation at 1200K, 1000K, and 800K.

In fact, the spectral intensity is the same, regardless of the material of the cavity walls exactly as shown by the equation above - and there is a good thermodynamic argument to support this, based on the Second Law. In fact the spectral intensity is a function of  $T$  only, which makes it a property worthy of study in thermodynamics.

Real surfaces emit radiation at rates that are less than that given by (eq. 1), and the ratio of the radiated spectral intensity to  $I_{\lambda}$  is called the emissivity  $e$  ( $<1$ ). A 'perfect radiator' ( $e=1$ ) is also a perfect absorber that gives no reflected radiation; the emitted radiation for

the perfect absorber is given by (eq. 1), and this explains the other term used for  $I_\lambda$ , 'Black-Body Radiation'.

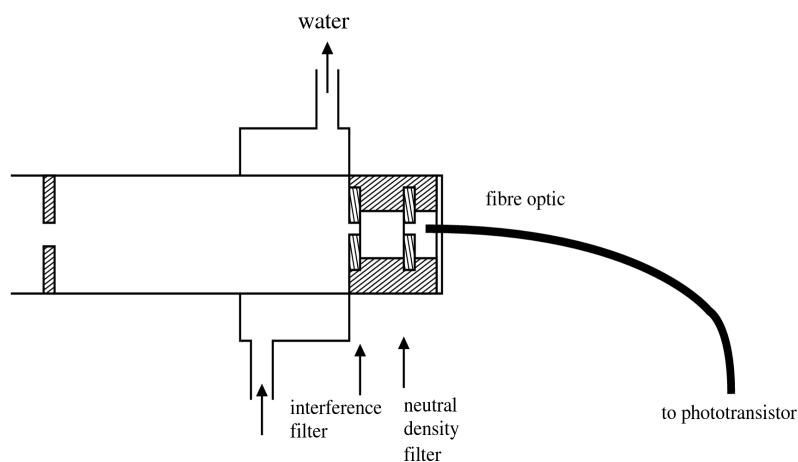
The classical theory of radiation treats the normal modes of the waves in the cavity as each having energy  $kT$  (given by the Law of Equipartition of Energy). At a given temperature this predicts values of  $I_\lambda$  that are reasonably accurate for long wavelengths, but for short wavelengths the theory leads to the 'ultra-violet catastrophe' -  $I_\lambda$  tends to infinity as  $\lambda$  tends to zero because the number of available states also tends to infinity. The classical statistics of Boltzmann has to be replaced by the appropriate quantum version in order to get the correct result of equation 1.

In 1899 Planck arrived at eq. 1 through a model in which the cavity wall was supposed to be made of quantum oscillators with discrete energy levels. Einstein interpreted the success of the model literally, and so 'invented' the photon, the quantum of radiation energy. It is ironic that Planck, the man who actually discovered quantum theory, refused to believe in it to his dying day, thinking that some explanation from classical physics would eventually vindicate his strange success. With the benefit of hindsight it seems surprising that the quantum was discovered through a correction to a classical theory involving a continuous energy distribution; now it seems self-evident that spectral lines (well-known at the time) should have been seen as obvious markers of discrete quantum states. But the Bohr theory of the atom was still fifteen years away when Planck published his results.

As explained above, cavity radiation is a proper subject for thermodynamic study. To make this system available for experimentation with detectors that are not subjected directly to the high temperatures of the cavity it is convenient to make a small hole in the cavity wall and observe the radiation that is emitted. The radiation falling on the orifice on the inside (and transmitted outside) should be close to ideal cavity radiation. Notice that in principle the hole is indeed an almost perfect 'BlackBody' absorber since any radiation that falls on it from the outside, goes into the cavity and must be essentially absorbed after multiple reflections from the internal walls before any significant part of it emerges again from the orifice.

### Apparatus:

In the present experiment the 'cavity' is a 12-mm hole bored in a 25-mm steel rod placed axially in the electric furnace. The detector 'looks' along the axis into this hole, and though this is not an ideal situation (since the orifice is not small in comparison with the cavity dimensions so that the radiation loss may be significant), it is at least a reasonable attempt to simulate true cavity radiation. A chromel-alumel thermocouple monitors the temperature of the furnace. You may notice that the thermocouple reference junction is actually three junctions. You should be able to explain why.



The detector is a phototransistor that is connected to a digital voltmeter (DVM). The radiation input is filtered by an interference filter that transmits only a very narrow wavelength band around 751.5 nm; a graph of the transmitted spectrum is provided. The output of the photodiode is a very non-linear function of the incident intensity, and is calibrated later (step 5). For this purpose there is a mounted filter wheel that you can use to attenuate the light in known steps.

## Prelab Questions:

1. Tables are available to calibrate the chromel-alumel thermocouple used to measure temperature in this experiment. Tables are in the lab or found in several handbooks, including chemistry's CRC Handbook and are also readily found on the web. Refer to one of these tables and use the data to fit to a polynomial in the temperature range of your experiment (about 800 to 1100 C). This fit to the calibration table will be useful in the performance of your experiment and the subsequent analysis.
2. Write a program, or use a spreadsheet to calculate  $I_\lambda$  and plot the values versus wavelength  $\lambda$  as shown in Fig. 1. Next, plot  $I_\lambda$  versus temperature at several, fixed  $\lambda$ , including a plot at the measurement wavelength that will be used in this experiment. Show that over some range of temperatures,  $\ln I_\lambda$  is nearly linear when plotted vs  $1/T$ . Analytically, what is the condition on the parameters in Eq. 1 that gives this linear behaviour in a semi-log plot? Show how such a plot can be used to determine the value of the fundamental constant  $h$ .

## Procedure:

1. Switch the furnace control to 'high' if this has not been done already; warm-up time is about 1.5 hours.
2. Turn on the water-cooling to the radiation detector to give a strong flow; the flow must be unchanged throughout the experiment, including the detector calibration (step 4). Direct the input-tube of the detector into the end of the furnace. If the stainless steel calibration adapter was left on the input tube, remove it first. The furnace temperature is to be allowed to reach **1100°C, but no higher** (you can destroy the furnace elements).
3. Two multimeters are used to measure the emf of the thermocouple and the signal from the photodetector. These voltages should be recorded at 20 second intervals during the main part of the experiment. You can program the multimeters with a trigger delay of 20 s so they will automatically take a new measurement every 20 s. It would be a good idea to make absolutely certain that you are confident in the functioning of the meters before starting your data collection as this experiment takes a fair bit of time to run. You have a couple of options for recording the data. You can write down each measurement as it is made (requires you take note every 20 s), or you can set the multimeters to store the measurements – recall our capacitor discharge experiment. If you set the multimeters to store the measurements, don't forget that you need to explicitly set the 'reading store' field to On each time you start. You can use the computers supplied to read the measurements out of the multimeter. There is a handout at the bench on how to do this. Ensure that the fiber-optic coming out of the photometer is seated properly in the photometer before making measurements!
4. When the furnace temperature reaches 1100°C turn off the power. Start the data recording and continue to measure down to 800°C or so.
5. Calibrate the photometer. To do this, screw the stainless steel adapter into the front of the photometer housing and point the detector towards the 100 W incandescent lamp and adjust the position so that the DVM reading is slightly greater than the maximum reading in your data-set from step 4 (so that the calibration range corresponds roughly to the range observed in the experiment). The photometer calibration is done relative to the arbitrary intensity of the lamp (for the 751.5 nm pass-band). There are 11 sections on the stepped circular filter – the first (wide) section is uncalibrated compared to the others, but the remaining 10 sections have optical densities that increase in steps of 0.2, meaning the intensity of light transmitted decreases by a factor of  $10^{-0.2} = 0.63$  in going from one step to the next so that  $I/I_0 = 0.63^n$  where  $n$  is the number of the filter section. Taking the natural log,  $\ln(I/I_0) = n \ln 0.63$ . Plot  $\ln(I/I_0)$  vs. the voltage. By regression analysis you can express the dependent variable  $\ln(I/I_0)$  in terms of the observed voltmeter readings. For this 'calibration' is it appropriate to use a linear regression or some higher order, or some other function?
6. Using the calibration of step 5, you can now construct a plot of  $\ln I_\lambda$  versus  $1/T$  and thus determine  $h$ .