Thermal Radiation

Modern Physics Lab - Rochester Institute of Technology*

Theory

An ideal blackbody is an object that absorbs all radiation and, in an equilibrium state, emits radiation in a manner that is determined by its physical properties such as temperature, surface area, and emissivity. In this experiment we will be using an incandescent light bulb as our heat source. Which this is obviously not an ideal thermal radiator, it does follow the physics below surprisingly well.

The Planck law gives the specific intensity (sometimes called 'spectral radiance') of a blackbody as a function of wavelength as:

Where is pi?

$$I(\lambda) = \frac{1}{A}\frac{d^2P}{d\lambda d\Omega} = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \tag{1}$$

where $I(\lambda)$ is defined as the power emitted per unit area (A) of emitting surface, per unit of solid angle (Ω) radiated into, per unit of wavelength (λ), h is Planck's constant, c is the speed of light, k is Boltzmann's constant, and T is absolute temperature. Blackbody curves for T=300 K and 1200 K is shown in Figure 1.

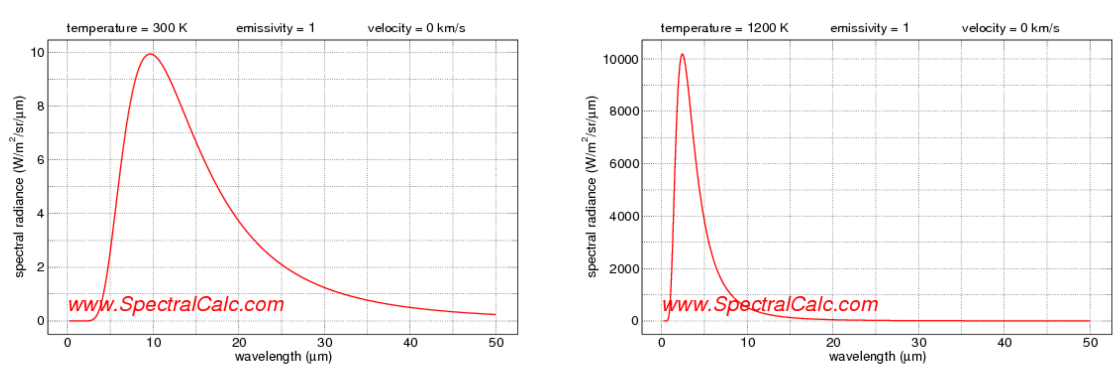

Figure 1: Theoretical blackbody curve for T=300 K and 1200 K. Note the different power scales for the two temperatures, and that there is very little radiation in the visible regime for either temperature.

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Integrating Equation 1 over λ yields the total power emitted into a solid angle Ω per area of emitting surface A. This is the well known Stefan-Boltzmann law:

$$\frac{P}{A\ \Omega} = \frac{\sigma}{4\pi} T^4 \tag{2}$$

where the Stefan-Boltzmann constant $\sigma = 5.67037$ x 10^{-8} W/m^{2}K^4 and T is absolute temperature in Kelvin. If a detector at a finite temperature is used to collect the radiated power from the source, care should be taken to correct for the amount of power that the detector radiates back into the environment. Thus Equation 2 becomes

$$\frac{P}{A\ \Omega} = \frac{\sigma}{4\pi}(T^4_{source} - T^4_{detector}) \tag{3}$$

For a blackbody at a fixed T, the wavelength at which the most power is radiated is given by the Wien displacement law:

$$\lambda_{max} T = 2898\ (\mu\text{m K}). \tag{4}$$

For $e^{hc/\lambda kT} \gg 1$, the Planck law can be approximated by

$$I(\lambda) = \frac{2hc^2}{\lambda^5} e^{-\frac{hc}{\lambda kT}} \tag{5}$$

Week 1: Stefan-Boltzmann

Apparatus for Stefan-Boltzmann

Thermopile

Converts variations in a physical quantity into an electrical signal or viceversa

A thermopile is a device (transducer) which measures total power captured by its absorber and convert it to a voltage proportional to the measured power. It has a spectral response that is nearly uniform over all wavelengths, due to the detector element being coated with a carbon black absorbing layer. See the data sheet for the Kipp-Zonen thermopile.

Thermopiles are sensitive to all thermal radiation in the room, so care must be taken to minimize distance to the blackbody source and maintain proper alignment to the lightbulb filament. For all experiments with the thermopile, you must determine and subtract the background signal level with the thermopile in place and the light bulb off, at room temperature. Determine if the room lights impact your measurements.

The thermopile measures total irradiance incident upon it, over all wavelengths from 0.3 to 3 μm with the window attached, and 0.2 to 50 μm with the window removed (we will use it with the window removed, so as to capture the largest possible range of wavelengths).

The thermopile should be connected to the Keithley microvoltmeter that reads their DC voltage output.

Light Source

We use an incandescent lightbulb as our black body radiator. Typical lightbulbs run with filament temperatures of 2000 K to almost 3000 K. They become barely visible, glowing dull reddish, at about 1000 K.

The lightbulb is run with an ammeter in line and is plugged into a Variac. The Variac is an autotransformer that takes 120 V RMS AC line voltage and cuts it down to some percentage of that value, the percentage is shown on the dial. With this setup, the voltage and current to the lightbulb can be determined; the voltage is the Variac setting (percent) times 120 VAC, the current is measured AC. Both are RMS values. The ammeter should be set up on the 10A AC scale.

Careful handling wiring to bulb! AC "house wiring" is always a shock hazard.

Week 1 Pre-Lab

Traditional incandescent bulbs, like the one used here, have tungsten filaments. By measuring the resistance of the filament, we can deduce the temperature of the bulb, since the resistance of tungsten is a well known function of temperature.

1. What is the melting temperature of Tungsten (look it up online) and compare it with some other metals. Comment on why tungsten makes a good filament material.

2. The resistance of tungsten is given in many sources, such as

   `http://hypertextbook.com/facts/2004/DeannaStewart.shtml`.

   This tungsten resistance data is available in a text file "tungsten.txt" on MyCourses. Plot it. This data is typically fit to a power law, that is,

   $$\frac{T}{T_o} = \left[\frac{R}{R_o}\right]^c \tag{6}$$

   where T_o is 300 K and R_o is the resistance at 300 K.

   Perform this fit and determine the power exponent c. This will be your calibration, that allows you to convert measured resistance R to filament temperature T.

3. Measure the room temperature resistance of the bulb R_o. Use the Keithley 2000 high precision multimeter to measure Ohms. You should get a resistance between 4 Ω and 6 Ω. Unscrew the lightbulb from the socket and measure it directly. Note that an incorrect R_o will change all of your calculated temperatures!

4. Wire the lightbulb and meters as described above. Turn the lightbulb on with about half power. Determine the voltage from the Variac percentage setting (percentage of line voltage 120 VAC RMS). From the measured current, find the resistance.

5. Compute the temperature.

6. Using the uncertainty in your fit c, and in your measured R_o, compute the uncertainty in temperature. Do you think the uncertainty in voltage or current matters?

Thermopile Calibration

Before you begin taking data, you will first need to do some calibration measurements.

1. Attach the Kipp-Zonen thermopile to the Keithley 2000 multimeter. Aim the thermopile away from all heat sources. Set up the Keithley to read DC voltage, and let it stabilize. Now place your hand in front of the thermopile. Does the thermopile detect the heat signature (IR radiation) of your hand?

Response time: 18s

2. Set up a stopwatch or timer. Aim the thermopile at the lightbulb, and turn it up to about half power. Record the thermopile response as a function of time. Note the response time that is given on the spec sheet for this thermopile. Continue measurements considerably longer than the nominal response time. Plot the response as a function of time. Decide how long you will need to wait, when taking data.

Stefan-Boltzman Experiment

Before you begin, **confirm with your instructor that you have decided on an acceptable waiting time**. Then, measure the radiated power from the lightbulb, with the thermopile, as a function of the bulb temperature. Span the range from 20% to 100% on the Variac, and note the bulb voltage, bulb current, and power at the thermopile.

Note that the thermopile is sensitive to geometry, obviously, from the solid angle in Equations 2 and 3. Once you have the thermopile aimed at the bulb, do not disturb the geometry. Experiment and decide if the room lights matter.

Compute filament temperatures for all of your measurements using your fit to the tungsten resistance data.

Note: The output voltage from the thermopile is directly proportional to net incident power, that is, the left side of Equation 3. You do not have to convert thermopile voltage to power, it already *is* a measurement of power. (A thermopile is a *transducer*; transducers produce a voltage that is proportional to some physical quantity like optical intensity, temperature, length, or in this case power).

Week 1 Check in

Choose appropriate variables to test your data against the prediction of Equation 2 (that is, ignoring the second term in Equation 3). Since this is a power law, if we use a log-log plot the data should be linear. Computers often have trouble fitting power laws, so instead plot $ln(P)$ vs $ln(T)$. The slope of this line is the exponent we're interested in.

Do your results agree with the Stephan Boltzmann law, that is, a T^4 dependence?

Stefan-Boltzman Analysis

- Make sure you are satisfied with your plot and results from the Check in section above.
- What additional information would you need in order to use this data to find the Stephan Boltzmann constant, σ?
- Plot the radiated power observed on the thermopile as a function of the RMS electrical power you supplied. Is it what you would expect? The light bulbbpackage says 200 W, does this agree with the observed maximum electrical power that you provided to the lightbulb?

Week 2: Planck Law

The Planck radiation law, Equation 1, shows a broad peak in the Near Infrared (NIR) wavelengths, for all temperatures that can be reached by the simple incandescent light bulb. For example, Figure 2 shows a detailed look at the Planck law prediction for the NIR, for a 2000 K source.

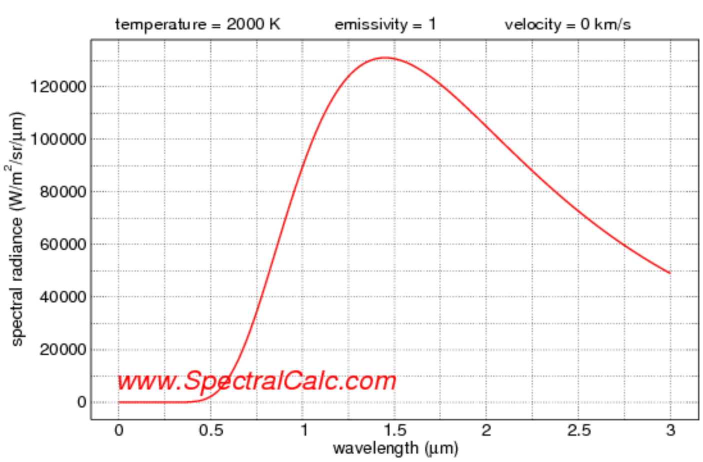

Figure 2: Theoretical blackbody curve for T=2000 K in the Near Infra Red (NIR)

Unfortunately, detectors sensitivities vary wildly with wavelength. This renders it seemingly impossible to simply measure the expected Planck curve, as shown in Figure 2.

Planck Apparatus

Lightsource

The same lightbulb arrangement that was used for the Stefan Boltzmann measurements will be used again. The monochromator has been placed on a carefully calibrated stack of books that should align the lightbulb filament with the input slit.

Monochromator

You will use the 1/8 meter Oriel monochromator, model 77250.

A grating monochromator is used to produce monochromatic light. This monochromator has interchangable gratings that allow measurements in the visible (VIS) or near IR (NIR). The grating angle is adjusted with a hand crank, a dial provides readout proportional to wavelength.

A grating can operate in first, second, or higher orders. The light must satisfy the Bragg condition;

$$d \sin \theta = m\lambda \tag{7}$$

where m is the order. Thus a grating system like this will pass 1.0 μm in first order and 500 nm in second order and 333 nm in third order, etc; for each, the product $m\lambda$ is the same and satisfies the Bragg condition.

The monochromator also uses different gratings that are optimized for different wavelength regimes.

In all cases, the light source is placed near the entrance slit to the monochromator, and the detector is placed at the exit slit. For visible light, your eye is an excellent detector, simply look into the exit slit. Obviously this is only sensible for a light bulb source, not a high intensity one!

Order-Sorting Filters

In order to know in what order a grating monochromator is operating, *order sorting* filters are used. These filters cut off the short wavelengths, and pass longer ones, so that one can be sure to be operating in first order. The *cut on* wavelength is very sharp and well defined for these filters. See the Thorlabs spec sheet for filter characteristics.

Detectors

A visible light photodiode as well as the FGA10 and FGA20 InGaAs photodiode detectors (NIR) are used. All photodiodes produce a small voltage proportional to incident light intensity; however, the proportionality is strongly dependent on wavelength. Thus it would be extremely difficult to figure out "absolute intensity" as a function of wavelength due to the varying detector sensitivity. Spec sheets for these photodiodes are posted. The photodiodes should be wired directly to a Keithley 2000 microvoltmeter; the DC voltage output is proportional to the product of the light intensity and the detector sensitivity response.

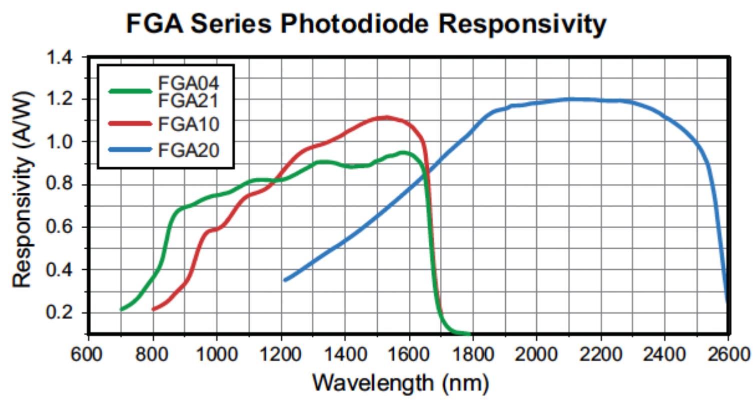

Figure 3: Response curves for two of the photodiodes we use (FGA10 and FGA20). Note that while they have wavelengths where they work best, these responses are not very flat.

Week 2 Pre-Lab

For this pre-lab you will be designing the experiment that you will perform next week. Because we would like to measure over a large array of wavelengths, we have to use multiple detectors. These photodiodes only have a small range over which they are useful so we will have to mix and match photodiodes depending on the wavelength. The VIS detector is good for wavelengths under 1000 nm and the responses of the IR detectors are shown in Figure 3.

Further complicating matters is that at higher wavelengths you will see strong second order transmission peaks (see above). For example if you are trying to measure the transmission at 1200 nm you will see a strong transmission for the second order 600 nm light. To block these lower wavelength higher order light, we have IR filters as shown in Figure 4. In general these filters have very sharp cutoffs.

We will also be using two gratings, as our monochromator has a limited range of rotation. The dial on the monocrhomator reads between 0 and 1000. When the VIS grating is used, the dial on the monochromater reads out exactly which wavelength is being selected. The IR grating changes this so that the dial actually reads out 1/4 of the wavelength that should be selected by the monochromator (this is done by having a different grating spacings).

For the pre-lab, fill out Table 1 with the needed dial, grating, filter, and detector for each wavelength. You will need to check with your instructor before you actually take data to make

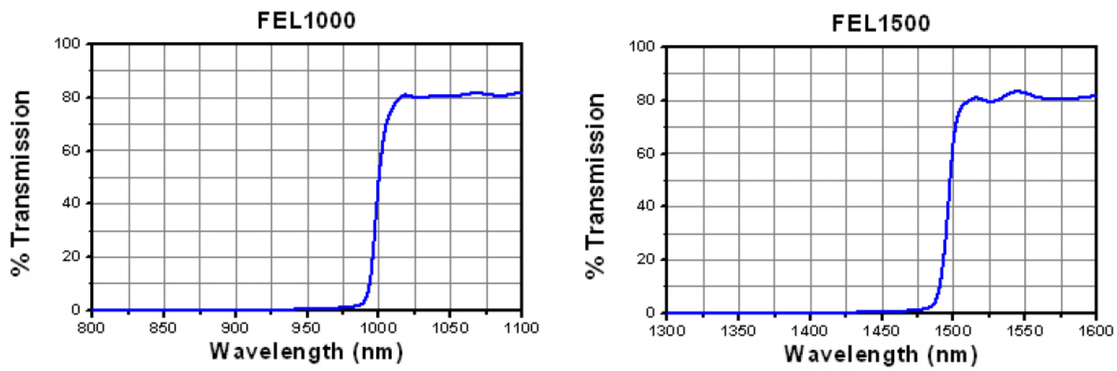

Figure 4: Transmission curves for the two IR filters

sure you are using the right combinations. As a reminder you have available two gratings (VIS and NIR), two filters (FEL1000 and FEL1500) and three detectors (VIS, FGA10, and FGA20).

$\lambda(\mu\text{m})$	dial	grating	filter	detector
0.6				
0.8				
1.2				
1.6				
2.0				
2.4				

Table 1: Experimental design table

In this lab you will need the brief use of a digital spectrometer. If you have not yet downloaded the software (from the Atomic Spectra lab) please do using the instructions below:

In order to operate the digital spectrometer you will have to download free software to your computer. Please visit `https://www.oceaninsight.com/support/software-downloads/oceanview-downloads/oceanview-form/` to download a free version of the OceanView software. This version of OceanView contains a lite version of the software that despite its name will work indefinetly (and no need to "activate" the trial).

You will use this software in other labs so it's worth it to put the (lightweight) software on your personal laptop. While you won't be able to test the software with a spectrometer, please get this installed before coming to lab.

Planck Law Equipment

Pull the lid off the monochromator, and see the parts inside. Align the bulb at the entrance slit, make sure the VIS grating is installed, set the monochromator dial for 500 nm. As you turn the crank, do you see the grating move? Put the lid on, and turn out the lights. What color is visible at the exit slit? Optimize the position of the bulb near the entrance slit.

Practice changing gratings. Dial until 000 is reached, before changing gratings; this sets up the grating nice and square and easy to handle. *Have your instructor help you change gratings the first time!* Pull the spring lever back, and hold it (or it will snap at you just as you put the grating in). Using the tab on the grating mount only - **NEVER TOUCH THE GRATING SURFACE** - remove one grating and set the new one in. Gently push the spring lever forward to hold the grating.

Now take the Ocean Optics spectrometer, and use it as a detector at the outlet slit of the monochromator. Put the lightbulb near the entrance slit and turn it on fairly bright. Set the monochromator dial to its maximum reading, and use the NIR grating. Take a spectrum with the Ocean Optics spectrometer at the outlet slit. Looking at the Ocean Optics spectrum, do you see both the first order and the second order peaks (or maybe even more)? Save the spectrum and explain; identify which peak is which order. This should emphasize to you why we need those cut-off filters.

Planck Law Measurement

When intensity is measured *at fixed wavelength* then the detector sensitivity is a constant for that wavelength. The Planck distribution, approximated for $e^{hc/\lambda kT} \gg 1$ as shown in Equation 5, with an arbitrary sensitivity of the detector at fixed wavelength, gives a detector output voltage V of

$$V \propto e^{-\frac{hc}{\lambda kT}} \tag{8}$$

Set up the monochromator with the VIS grating, and put the lid on. No filter is needed for visible light. Place the lightbulb a few inches away from the input slit. Do *not* adjust the slits at either the input or output; they are set very wide open so as to pass the maximum amount of light. Set the monochromator dial to 800; this is 800 nm wavelength with the VIS grating. Arrange the VIS detector at the output side, treat it gently. You will have to align it at the output side of the monochromator. Turn on the lightbulb at about half maximum voltage. Take the output from the VIS detector to the Keithley microvoltmeter.

Align the lightbulb so that you get a maximum signal. The monochromator is very sensitive to the position of the lightbulb; you will get a very much stronger signal if the filament is directly lined up with the input slit. Always keep the bulb a few inches away from the input slit, just adjust its position back and forth at fixed distance away until you get a strong signal. You want enough distance between the bulb and the entrance slit that (later) you can insert a filter here, without bumping into the bulb.

Take data for detector output as a function of lightbulb intensity; for each setting on the Variac, record the variac setting, the current to the lightbulb, and the detector output. Run from 30% to 100% on the Variac. Don't bump the lightbulb position or you'll have to start over!

Repeat this measurement for the rest of the wavelengths on your chart. If you need to switch between the NIR and VIS grating have your instructor help so that you don't scratch the surface. Also please note that the diode elements for the detectors may be exposed, and should be handled with care.

Important: The IR detectors can easily saturate. This means an increase in light is not represented by an increase in the signal. If the Photoelectric lab is not using them, you can borrow the set of neutral density filters to dim the light entering the monochromator. Otherwise you will have to move the bulb back until the light entering the monochromator is no longer saturating the detector. The saturation happens at values above 100 mV on the Keithly meter, but you can only really tell once you plot your data. (Recording data that you find later to be saturated, and having to go back to get it again is a common exercise in science). So before you take data with one of these detectors, be sure that the maximum signal you get is below 100 mV and adjust accordingly.

Change back to the VIS grating and put away the filters.

Planck Law Analysis

Compute filament temperatures for all of your measurements using your tungsten resistance fit.

For the monochromator data, if Equation 5 is correct, we would expect that the log (natural) of the detector output would be a linear relationship with $1/\lambda T$. However, since the detectors have a response that is a strong function of λ and in fact we used three different detectors with no attempt to calibrate one against the other, we cannot use this form.

All data were taken at fixed λ. Equation 8 predicts that the detector output is an exponential in $1/T$. Plot log detector output vs. $1/T$ for each wavelength and extract the slopes, with uncertainty. You need to look at your data; do the very low-intensity data points look right? If not, the detector simply isn't good enough for those low light levels, and you should make judicious decisions about what data to use for your fit of the slopes.

Now, those slopes are supposed to be equal to $hc/\lambda k$. Plot the slopes as a function of $1/\lambda$. What should the slope of this be equal to? Compare your data to the known value.

This two-step data analysis procedure allows us to completely disregard the fact that at each wavelength the detectors have different response functions. By using the slopes from a log plot, the multiplicitive factor of the detector sensitivity, is irrelevant. Your data should both confirm the form of the Planck law, Equation 1, and find a value for the ratio of fundamental constants hc/k.