Chapter 1

Blackbody Radiation

Experiment objectives: explore radiation from objects at certain temperatures, commonly known as "blackbody radiation"; make measurements testing the Stefan-Boltzmann law in high- and low-temperature ranges; measure the inverse-square law for thermal radiation.

Theory

A familiar observation to us is that dark-colored objects absorb more thermal radiation (from the sun, for example) than light-colored objects. You may have also observed that a good absorber of radiation is also a good emitter (like dark-colored seats in an automobile). Although we observe thermal radiation ("heat") mostly through our sense of touch, the range of energies at which the radiation is emitted can span the visible spectrum (thus we speak of high-temperature objects being "red hot" or "white hot"). For temperatures below about $600°C$, however, the radiation is emitted in the infrared, and we cannot see it with our eyes, although there are special detectors (like the one you will use in this lab) that can measure it.

An object which absorbs all radiation incident on it is known as an "ideal blackbody". In 1879 Josef Stefan found an empirical relationship between the power per unit area radiated by a blackbody and the temperature, which Ludwig Boltzmann derived theoretically a few years later. This relationship is the **Stefan-Boltzmann law:**

$$S = \sigma T^4 \tag{1.1}$$

where S is the radiated power per unit area (W/m^2), T is the temperature (in Kelvins), and $\sigma = 5.6703 \times 10^{-8} W/m^2K^4$ is the Stefan's constant.

Most hot, opaque objects can be approximated as blackbody emitters, but the most ideal blackbody is a closed volume (a cavity) with a very small hole in it. Any radiation entering the cavity is absorbed by the walls, and then is re-emitted out. Physicists first tried to calculate the spectral distribution of the radiation emitted from the ideal blackbody using *classical thermodynamics*. This method involved finding the number of modes of oscillation of the electromagnetic field in the cavity, with the energy per mode of oscillation given by kT. The classical theory gives the **Rayleigh-Jeans law:**

$$u(\lambda, T) = \frac{8\pi kT}{\lambda^4}$$

where $u(\lambda)(J/m^4)$ is the spectral radiance (energy radiated per unit area at a single wavelength or frequency), and λ is the wavelength of radiation. This law agrees with the experiment for radiation at long wavelengths (infrared), but predicts that $u(\lambda)$ should increase infinitely at short wavelengths. This is not observed experimentally (Thank heaven, or we would all be constantly bathed in ultraviolet light-a true ultraviolet catastrophe!). It was known that the wavelength distribution peaked at a specific temperature as described by **Wien's law:**

$$\lambda_{max} T = 2.898 \times 10^{-3} m \cdot K$$

and went to zero for short wavelengths.

The breakthrough came when Planck assumed that the energy of the oscillation modes can only take on discrete values rather than a continuous distribution of values, as in classical physics. With this assumption, Planck's law was derived:

$$u(\lambda, T) = \frac{8\pi hc\lambda^{-5}}{e^{hc/\lambda kT} - 1}$$

where c is the speed of light and $h = 6.626076 \times 10^{-34} J \cdot s$ is the Planck's constant. This proved to be the correct description.

Sometimes physicists have to have crazy ideas!
"*The problem of radiation-thermodynamics was solved by Max Planck, who was a 100 percent classical physicist (for which he cannot be blamed). It was he who originated what is now known as modern physics. At the turn of the century, at the December 14, 1900 meeting of the German Physical Society, Planck presented his ideas on the subject, which were so unusual and so grotesque that he himself could hardly believe them, even though they caused intense excitement in the audience and the entire world of physics.*"
From George Gamow, *"Thirty Years that Shook Physics, The Story of Quantum Physics"*, Dover Publications, New York, 1966.

Safety

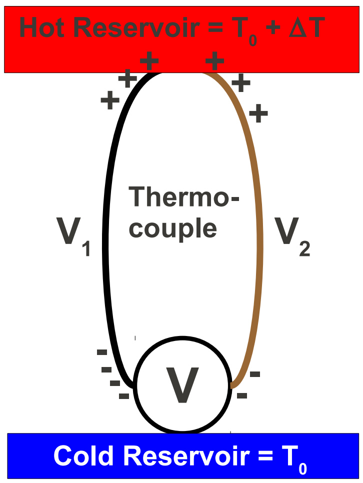
The Stefan lamp and thermal cube will get very hot - be careful!!!

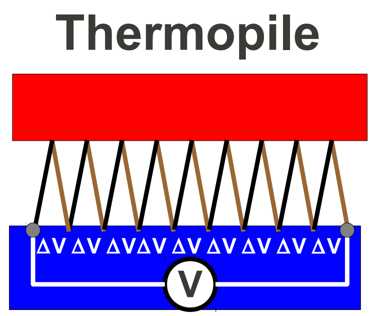
Thermal radiation rates from different surfaces

Equipment needed: Pasco Radiation sensor, Pasco Thermal Radiation Cube, two multimeters, window glass.

Before starting actual experiment take some time to have fun with the thermal radiation sensor. Can you detect your lab partner? What about people across the room? Point the sensor in different directions and see what objects affect the readings. **These exercises are fun, but you will also gain important intuition about various factors which may affect the accuracy of the measurements!**

How does the radiation sensor work?





Imagine a metal wire connected to a cold reservoir at one end and a hot reservoir at the other. Heat will flow between the ends of the wire, carried by the electrons in the conductor, which will tend to diffuse from the hot end to the cold end. Vibrations in the conductor's atomic lattice can also aid this process. This diffusion causes a potential difference between the two ends of the wire. The size of the potential difference depends on the temperature gradient and on details of the conductive material, but is typically in the few 10s of $\mu V/K$. A thermocouple, shown on the left, consists of two different conductive materials joined together at one end and connected to a voltmeter at the other end. The potential is, of course, the same on either side of the joint, but the difference in material properties causes $\Delta V = V_1 - V_2 \neq 0$. This ΔV is measured by the voltmeter and is proportional to ΔT. Your radiation sensor is a thermopile, simply a "pile" of thermocouples connected in series, as shown at the right. This is done to make the potential difference generated by the temperature gradient easier to detect.

1. Connect the two multimeters and position the sensor as shown in Fig. 1.1. The multimeter attached to the cube should be set to read resistance while the one attached to the infrared radiation sensor will monitor the potential (in the millivolt range). Make sure the shutter on the sensor is pushed all the way open!

2. Before turning on the cube, measure the resistance of the thermistor at room temperature, and obtain the room temperature from the instructor. You will need this information for the data analysis.

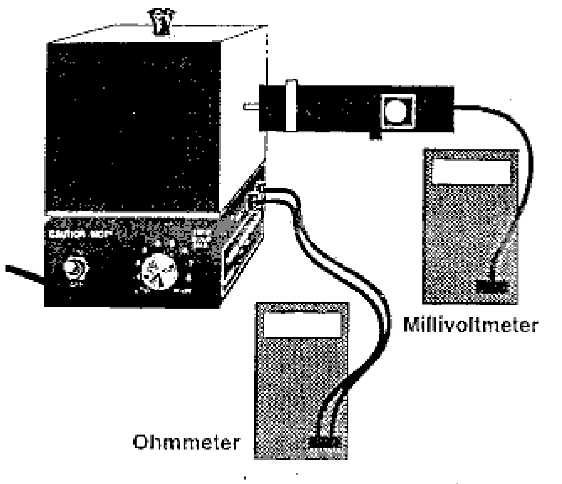


Figure 1.1: Thermal radiation setup

3. Turn on the thermal radiation cube and set the power to "high". When the ohmmeter reading decreases to 40 kΩ (5-20 minutes) set power switch to "8". (If the cube has been preheated, immediately set the switch to "8".)

> **Important**: when using the thermal radiation sensor, make each reading quickly to keep the sensor from heating up. Use both sheets of white isolating foam (with the silvered surface facing the lamp) to block the sensor between measurements.
> **Sensor calibration**: To obtain the radiation sensor readings for radiated power per unit area S in the correct units (W/m^2), you need to use the voltage-to-power conversion factor 22 mV/mW, and the area of the sensor $2mm \times 2mm$:
>
> $$S[W/m^2] = \frac{S[mV]}{22[mV/mW]} \cdot 10^{-3} \cdot \frac{1}{4 \cdot 10^{-6}[m^2]}$$

4. When the cube has reached thermal equilibrium the ohmmeter will be fluctuating around a constant value. Record the resistance of the thermistor in the cube and determine the approximate value of the temperature using the data table in Fig 1.2. Use the radiation sensor to measure the radiation emitted from the four surfaces of the cube. Place the sensor so that the posts on its end are in contact with the cube surface (this ensures that the distance of the measurement is the same for all surfaces) and record the sensor reading. Each lab partner should make an independent measurement.

5. Place the radiation sensor approximately 5 cm from the black surface of the radiation cube and record its reading. Place a piece of glass between the sensor and the cube. Record again. Does window glass effectively block thermal radiation? Try observing the effects of other objects, recording the sensor reading as you go.

Use your data to address the following questions in your lab report:

1. Is it true that good absorbers of radiation are good emitters?

Therm. Res. (Ω)	Temp. (°C)	Therm. Res. (Ω)	Temp. (°C)	Therm. Res. (Ω)	Temp. (°C)	Therm. Res. (Ω)	Temp. (°C)	Therm. Res. (Ω)	Temp. (°C)	Therm. Res. (Ω)	Temp. (°C)
207,850	10	66,356	34	24,415	58	10,110	82	4,615.1	106	2,281.0	130
197,560	11	63,480	35	23,483	59	9,767.2	83	4,475.0	107	2,218.3	131
187,840	12	60,743	36	22,590	60	9,437.7	84	4,339.7	108	2,157.6	132
178,650	13	58,138	37	21,736	61	9,120.8	85	4,209.1	109	2,098.7	133
169,950	14	55,658	38	20,919	62	8,816.0	86	4,082.9	110	2,041.7	134
161,730	15	53,297	39	20,136	63	8,522.7	87	3,961.1	111	1,986.4	135
153,950	16	51,048	40	19,386	64	8,240.6	88	3,843.4	112	1,932.8	136
146,580	17	48,905	41	18,668	65	7,969.1	89	3,729.7	113	1,880.9	137
139,610	18	46,863	42	17,980	66	7,707.7	90	3,619.8	114	1,830.5	138
133,000	19	44,917	43	17,321	67	7,456.2	91	3,513.6	115	1,781.7	139
126,740	20	43,062	44	16,689	68	7,214.0	92	3,411.0	116	1,734.3	140
120,810	21	41,292	45	16,083	69	6,980.6	93	3,311.8	117	1,688.4	141
115,190	22	39,605	46	15,502	70	6,755.9	94	3,215.8	118	1,643.9	142
109,850	23	37,995	47	14,945	71	6,539.4	95	3,123.0	119	1,600.6	143
104,800	24	36,458	48	14,410	72	6,330.8	96	3,033.3	120	1,558.7	144
100,000	25	34,991	49	13,897	73	6,129.8	97	2,946.5	121	1,518.0	145
95,447	26	33,591	50	13,405	74	5,936.1	98	2,862.5	122	1,478.6	146
91,126	27	32,253	51	12,932	75	5,749.3	99	2,781.3	123	1,440.2	147
87,022	28	30,976	52	12,479	76	5,569.3	100	2,702.7	124	1,403.0	148
83,124	29	29,756	53	12,043	77	5,395.6	101	2,626.6	125	1,366.9	149
79,422	30	28,590	54	11,625	78	5,228.1	102	2,553.0	126	1,331.9	150
75,903	31	27,475	55	11,223	79	5,066.6	103	2,481.7	127		
72,560	32	26,409	56	10,837	80	4,910.7	104	2,412.6	128		
69,380	33	25,390	57	10,467	81	4,760.3	105	2,345.8	129		

Figure 1.2: Resistance vs. temperature for the thermal radiation cube

2. Is the emission from the black and white surface similar?
3. Do objects at the same temperature emit different amounts of radiation?
4. Does glass effectively block thermal radiation? Comment on the other objects that you tried.

Tests of the Stefan-Boltzmann Law

High temperature regime

Equipment needed: Radiation sensor, 3 multimeters, Stefan-Boltzmann Lamp, Power supply.

1. **Before turning on the lamp**, measure the resistance of the filament of the Stefan-Boltzmann lamp at room temperature. Record the room temperature, visible on the wall thermostat and on the bench mounted thermometers in the room.
2. Connect a multimeter as voltmeter to the output of the power supply. **Important:** make sure it is in the **voltmeter mode**. Compare voltage readings provided by the power supply and the multimeter. Which one is the correct one? Think about your measurement uncertainties.

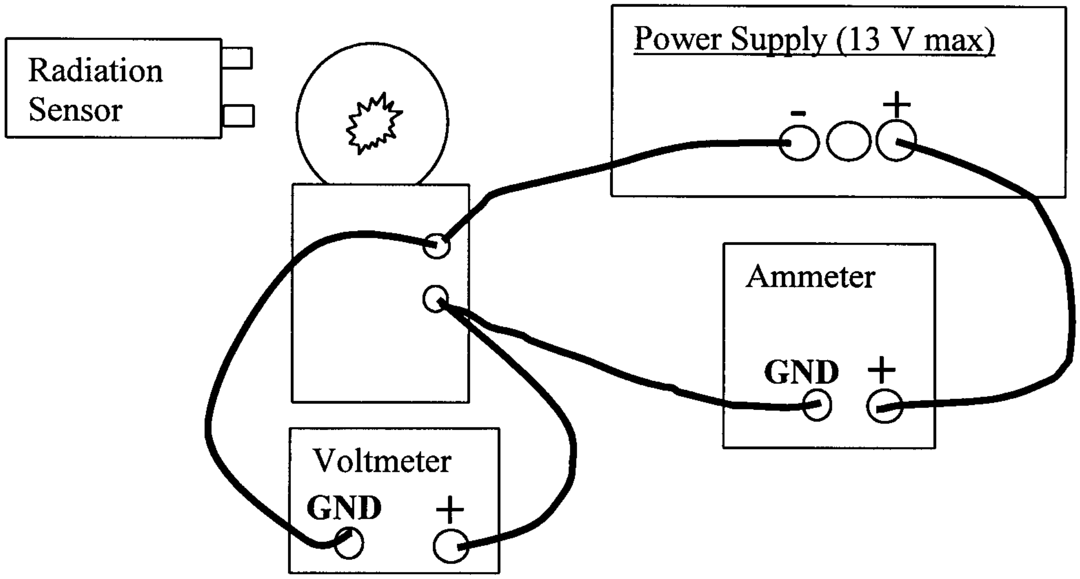


Figure 1.3: Lamp connection for high-temperature Stefan-Boltzmann setup

3. Set up the equipment as shown in Fig. 1.3. VERY IMPORTANT: make all connections to the lamp when the power is off. Turn the power off before changing/removing connections. The voltmeter should be directly connected to the binding posts of the Stefan-Boltzmann lamp. In this case the multimeter voltmeter has direct access to the voltage drop across the bulb, while the power supply voltmeter reads an extra voltage due to finite resistance of the current meter. Compare readings on the multimeter and the power supply current meters. Which one is the correct one? Think about your measurement uncertainties.

4. Place the thermal sensor at the same height as the filament, with the front face of the sensor approximately 6 cm away from the filament (this distance will be fixed throughout the measurement). Make sure no other objects are viewed by the sensor other than the lamp.

5. Turn on the lamp power supply. Set the voltage, V, in steps of one volt from 1-12 volts. At each V, record the ammeter (current) reading from the lamp and the voltage from the radiation sensor. Calculate the resistance of the lamp using Ohm's Law and determine the temperature T of the lamp from the table shown in Fig. 1.4. You can use a table to record your data similar to the sample table 1.1.

In the lab report plot the reading from the radiation sensor (convert to W/m^2) versus T^4. According to the Stefan-Boltzmann Law, the data should fall along a straight line. Do

R/R_{300K}	Temp K	Resistivity μΩ cm	R/R_{300K}	Temp K	Resistivity μΩ cm	R/R_{300K}	Temp K	Resistivity μΩ cm	R/R_{300K}	Temp K	Resistivity μΩ cm
1.0	300	5.65	5.48	1200	30.98	10.63	2100	60.06	16.29	3000	92.04
1.43	400	8.06	6.03	1300	34.08	11.24	2200	63.48	16.95	3100	95.76
1.87	500	10.56	6.58	1400	37.19	11.84	2300	66.91	17.62	3200	99.54
2.34	600	13.23	7.14	1500	40.36	12.46	2400	70.39	18.28	3300	103.3
2.85	700	16.09	7.71	1600	43.55	13.08	2500	73.91	18.97	3400	107.2
3.36	800	19.00	8.28	1700	46.78	13.72	2600	77.49	19.66	3500	111.1
3.88	900	21.94	8.86	1800	50.05	14.34	2700	81.04	26.35	3600	115.0
4.41	1000	24.93	9.44	1900	53.35	14.99	2800	84.70			
4.95	1100	27.94	10.03	2000	56.67	15.63	2900	88.33			

Figure 1.4: Table of tungsten's resistance as a function of temperature.

Data(± error)			Calculations		
V((volts)	I(amps)	$Rad(mV)$	R(ohms)	$T(K)$	$T^4(K^4)$
1.00					
...					

Table 1.1: Sample table for experimental data recording

a fit and report the value of the slope that you obtain. How does it compare to the accepted value of Stefan's constant?

Don't be alarmed if the value of slope is way off from Stefan's constant. The Stefan-Boltzmann Law, as stated in Eq.(1.1), is only true for ideal black bodies. For other objects, a more general law is: $S = A\sigma T^4$, where A is the absorptivity. $A = 1$ for a perfect blackbody. $A < 1$ means the object does not absorb (or emit) all the radiation incident on it (this object only radiates a fraction of the radiation of a true blackbody). The material lampblack has $A = 0.95$ while tungsten wire has $A = 0.032$ (at $30°C$) to 0.35 (at $3300°C$). Comparing your value of slope to Stefan's constant, and assuming that the Stefan-Boltzmann Law is still valid, what do you obtain for A? Is it consistent with tungsten? What else could be affecting this measurement?

Test of the inverse-square law

Equipment needed: Radiation sensor, Stefan-Boltzmann lamp, multimeter, power supply, meter stick. A point source of radiation emits that radiation according to an inverse square law: that is, the intensity of the radiation in (W/m^2) is proportional to the inverse square of the distance from that source. You will determine if this is true for a lamp.

1. Set up the equipment as shown in Fig. 1.5. Tape the meter stick to the table. Place the Stefan-Boltzmann lamp at one end, and the radiation sensor in direct line on the

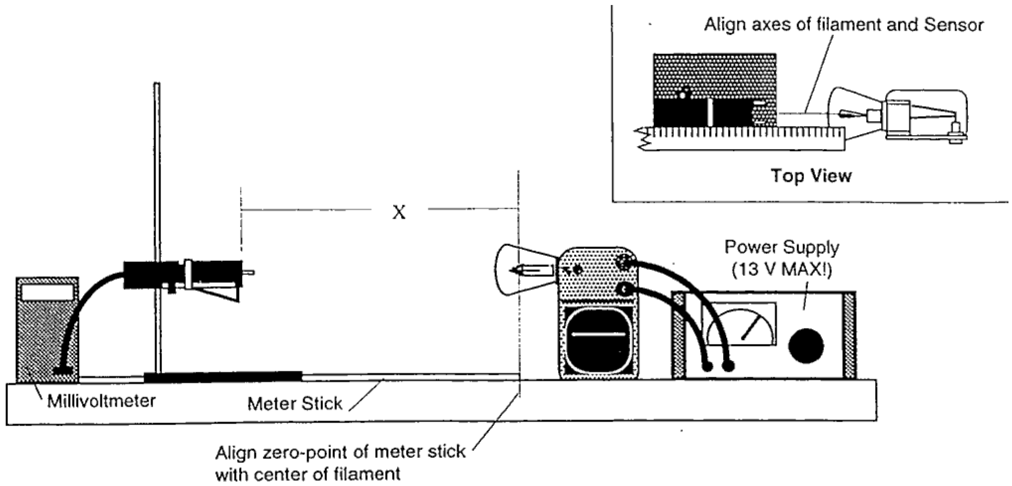


Figure 1.5: Inverse square law setup

other side. The zero-point of the meter stick should align with the lamp filament (or, should it?). Adjust the height of the radiation sensor so it is equal to the height of the lamp. Align the system so that when you slide the sensor along the meter stick the sensor still aligns with the axis of the lamp. Connect the multimeter (reading millivolts) to the sensor and the lamp to the power supply.

2. With the **lamp off**, slide the sensor along the meter stick. Record the reading of the voltmeter at 10 cm intervals. Average these values to determine the ambient level of thermal radiation. You will need to subtract this average value from your measurements with the lamp on.

3. Turn on the power supply to the lamp. Set the voltage to approximately 10 V. **Do not exceed 13 V!** Adjust the distance between the sensor and lamp from 2.5-100 cm and record the sensor reading. **Before the actual experiment think carefully about at what distances you want to take the measurements. Is taking them at constant intervals the optimal approach? At what distances would you expect the sensor reading change more rapidly?**

4. Make a plot of the corrected radiation measured from the lamp versus the inverse square of the distance from the lamp to the sensor ($1/x^2$) and do a linear fit to the data. How good is the fit? Is this data linear over the entire range of distances? Comment on any discrepancies. What is the uncertainty on the slope? What intercept do you expect? Comment on these values and their uncertainties.

5. Does radiation from the lamp follow the inverse square law? Can the lamp be considered a point source? If not, how could this affect your measurements?