Blackbody Radiation

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Abstract-

Black body radiation is a phenomenon that can be observed whenever some object absorbs incident radiation and re-emits that radiation at other wavelengths. Ideally, a “black body” is an object that absorbs all electromagnetic radiation, no matter the frequency or angle of incidence. Additionally, black bodies emit absorbed energy at longer wavelengths as their temperature decreases or at shorter wavelengths as their temperature increases. The subject of this research involved the examination of a black body radiator approximated by a wrapped incandescent light bulb in the laboratory setting. Spectrometric, thermal and visual examinations were made as a function of voltage across the filament. Current readings at each observation step were taken as well.

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Introduction/Theory-

The purpose of this experiment was to compare a real world approximation of a black body radiator to the predictions made by Max Planck' law.

Before the 19th century, light was thought to consist of corpuscles, as propounded by Issac Newton and his contemporaries, baring one man, Christian Huygens. Huygens had proposed a wave nature of light but lacked sufficient evidence to explain Newton's rectilinear propagation and sharp edged shadows objections. Thus, light would remain particulate until a series of experiments from 1800 to 1907 by Thomas Young demonstrated for the first time, the interference and diffraction effects of light. As interference and diffraction had only ever been seen in wave based phenomena, the wave nature of light was back on the table. This apparent contradictory nature would lead to a great debate among physicists on how to reconcile the wave and particle nature of light, until later in the 19th and early 20th century when the wavelength of light would finally be experimentally verified. Another force that strengthened the wave theory of light was the work of Augustin Jean Fresnel, who independently developed the mathematical model of wave based light and established the connection between wavelength and color experimentally. Additionally, by the middle of the 19th century, Michael Faraday and Maxwell had developed a relationship between light and electromagnetism and demonstrated the magnetic polarization of light as well as Maxwell's crowning achievement of discovering the self propagating nature of EM waves and ultimately of light as one such wave.

In spite of such developments, the particle nature of light remained popular and even accrued some additional evidence itself. In 1802 William Wollaston observed dark lines in the solar spectrum, and Joseph Fraunhofer extended that work by expanding and examining the whole solar spectrum. Furthermore, Gustav Kirchoff and Robert Bunsen discovered the element specific emission lines resulting from elements in combustion. Eventually, these spectral lines would lead to the examination of total radiant flux of a blackbody by Josef Stefan. Josef Stefan and Ludwig Boltzmann would eventually develop the Stefan Boltzmann law from Maxwell's thermodynamics, defined below:

$$I = \sigma T^4 \quad .$$

By the late 19th century, some physicists had begun to believe that physics had been solved. Nothing was left to discover or characterize, the world was known and orderly and everything could be described satisfactorily with the theoretical tools of the day. Except one detail, black body radiation; The emission spectra of hot objects that emitted in the visible and ultraviolet spectrum had not been effectively described. Attempts were made, but they had been repeatedly thwarted by the "ultraviolet catastrophe”. A region of the emission spectra where, as temperature increased toward 5000k, the emitted wavelengths approached infinity. Such was the black body problem, that it would stand for nearly a century before it was finally solved by the diligent work of Wilhelm Wien and Max Planck.

In 1893 Wilhelm Wien developed his displacement law, it stated roughly that the adiabatic invariant of energy was always proportional to temperature. This law preempted the development of the more general form by Max Planck later in 1900. Wilhelm Wien and Max Planck developed a description for what is now known as black body radiation, a commonly experienced phenomenon when in the vicinity of hot objects. A cup of hot coffee will not appear any different to a cup of cold coffee until ones hand nears the cup and is warmed by the infrared wavelengths being emitted thus. Likewise, the wavelengths of radiation emitted by any black body as its temperature increases is approximated by Wien’s law below:

$$\lambda=\frac{b}{T} \quad .$$

Wien’s law, while a good approximation does not work as effectively at very short wavelengths or very high temperature. Thus, it becomes necessary to develop a more general law to accurately describe the spectra of black body radiation for objects in higher temperature ranges. Enter Planck, in the year 1900, Max Planck developed his general description of black body radiation that would eventually prove to fit the observed spectra perfectly. Planck’s law of Black Body Radiation is stated below:

$$B_\lambda(\lambda,T)=\frac{2hc^2}{\lambda^5}\frac{1}{e^{\left(\frac{hc}{\lambda k_B T}\right)}-1} \quad .$$

With this much more powerful general description of black body radiation, one can develop a complete model of the spectra emitted by black bodies at temperatures in the failure region of the ultraviolet catastrophe.

A demonstration of black body radiation in a real system is discussed below. Data using a incandescent light bulb, a spectrometer, thermal camera, and voltage control system are provided. Analysis of the data is performed in an informal manner, so as to demonstrate the concepts of black body radiation as it is approximated by the light bulb.

Black body radiation emitted by a object can be described ideally by Planck's Black Body radiation law:

$$B_\lambda(\lambda,T)=\frac{2hc^2}{\lambda^5}\frac{1}{e^{\left(\frac{hc}{\lambda k_B T}\right)}-1}$$

Where h is Planck’s constant, k is Boltzmann's constant, T is the absolute temperature, and λ is the wavelength of the emitted radiation. The wavelength of greatest intensity is calculated as:

$$\lambda_{max}=\frac{0.00289\,m*K}{T}$$

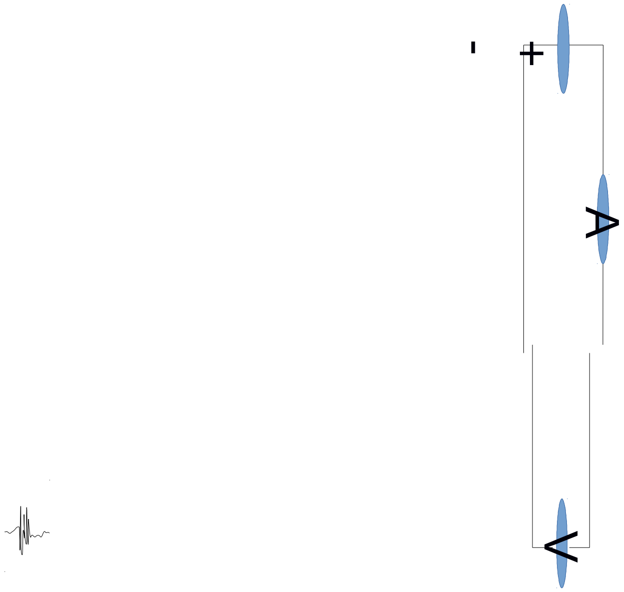
Where T is the absolute temperature of the object, the absolute temperature of the blackbody light filament can be calculated using the resistance of the lit filament. In the calculation of resistance via ohms law :

$$R=\frac{V}{I}$$

V is the voltage applied across the filament, and I the current through the filament, the resistance is going to vary non linearly with temperature. The resistivity for tungsten can be found in the CRC handbook.

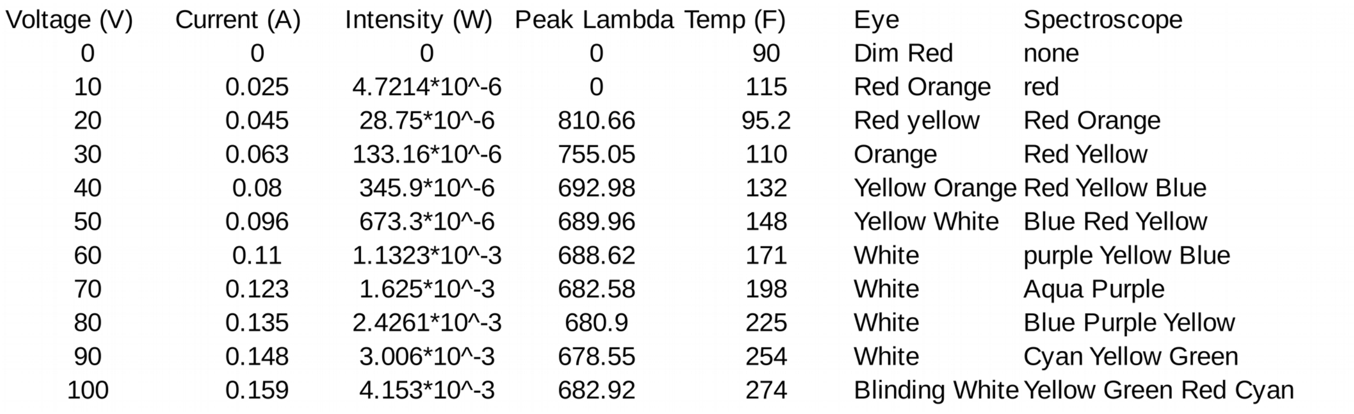
Experimental Procedure-

The bulb, power source, spectroscope and other experimental apparatus components were pre-prepared. The setup included a variable voltage source, a light-bulb, an ammeter, spectroscope, spectrometer, diffraction, and a thermal imaging camera. The experimental circuit was set up as below:

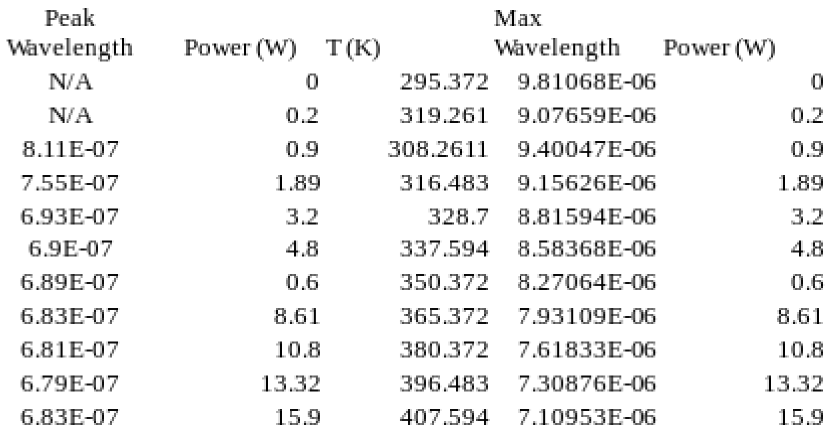


Once familiarization was complete, the voltage on the variac transformer was slowly raised in 10 volt increments. At each increment, observations by eye, thermal imagery, spectroscope and diffractometer were conducted the current and voltage through the lightbulb were recorded at each increment. The power was calculated for each increment and the bulb was allows to dwell at each current and voltage increment until an approximate steady state was achieved. Then the next increment was processed.

Charts and Graphs-

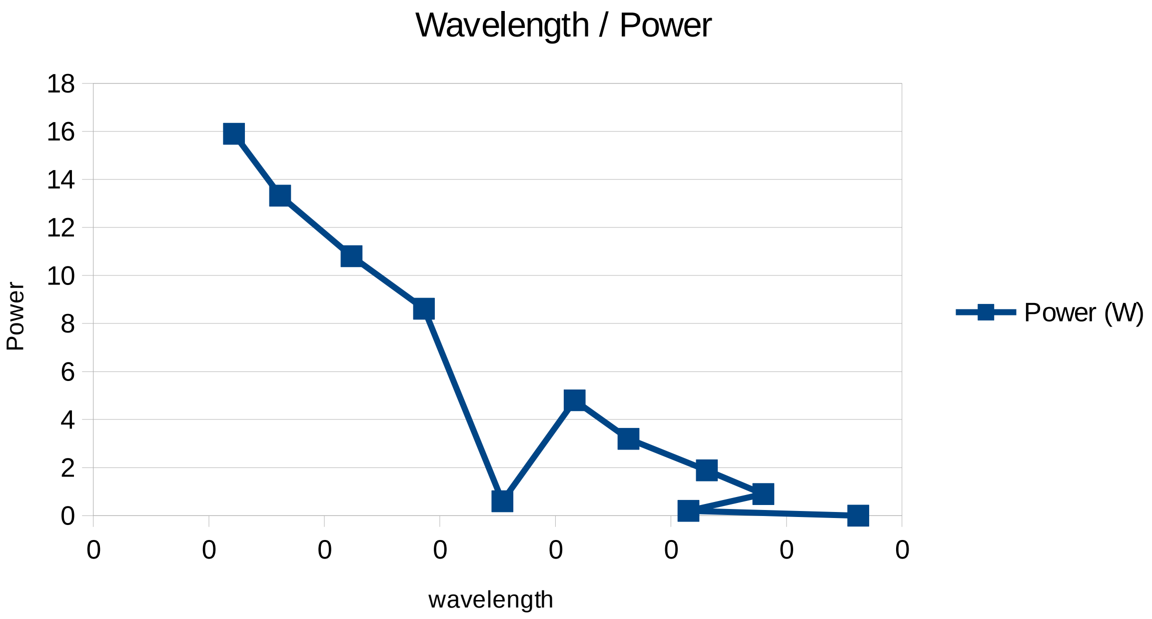


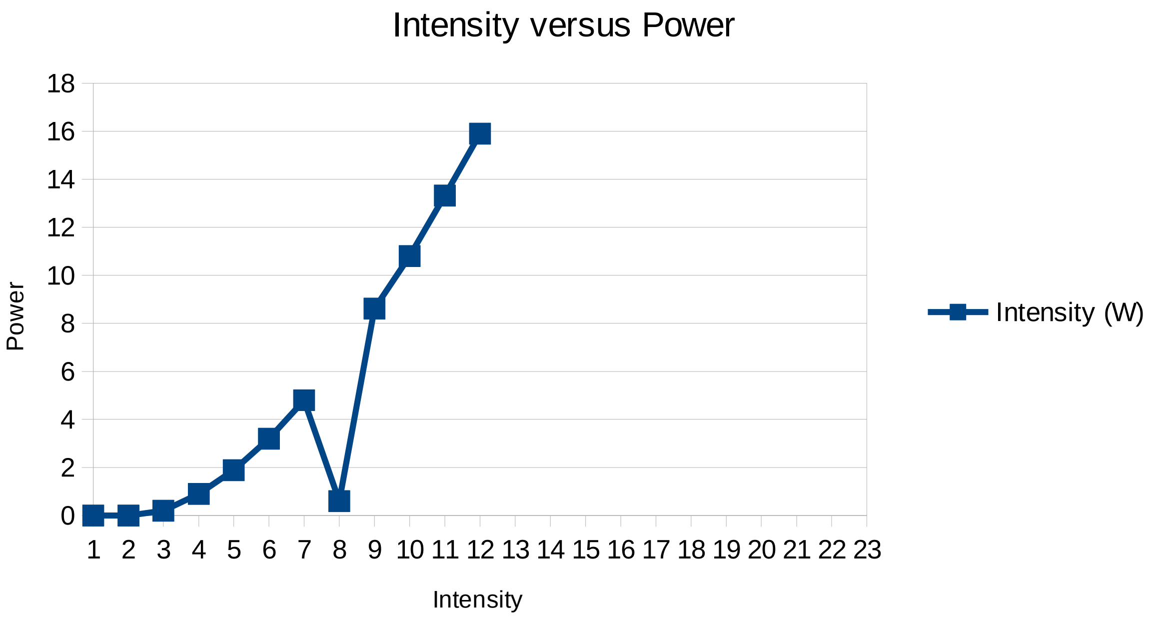
Voltage (V)	Current (A)	Intensity (W)	Peak Lambda	Temp (F)	Eye	Spectroscope
0	0	0	0	90	Dim Red	none
10	0.025	4.7214*10^-6	0	115	Red Orange	red
20	0.045	28.75*10^-6	810.66	95.2	Red yellow	Red Orange
30	0.063	133.16*10^-6	755.05	110	Orange	Red Yellow
40	0.08	345.9*10^-6	692.98	132	Yellow Orange	Red Yellow Blue
50	0.096	673.3*10^-6	689.96	148	Yellow White	Blue Red Yellow
60	0.11	1.1323*10^-3	688.62	171	White	purple Yellow Blue
70	0.123	1.625*10^-3	682.58	198	White	Aqua Purple
80	0.135	2.4261*10^-3	680.9	225	White	Blue Purple Yellow
90	0.148	3.006*10^-3	678.55	254	White	Cyan Yellow Green
100	0.159	4.153*10^-3	682.92	274	Blinding White	Yellow Green Red Cyan



Peak Wavelength	Power (W)	T (K)	Max Wavelength	Power (W)
N/A	0	295.372	9.81068E-06	0
N/A	0.2	319.261	9.07659E-06	0.2
8.11E-07	0.9	308.2611	9.40047E-06	0.9
7.55E-07	1.89	316.483	9.15626E-06	1.89
6.93E-07	3.2	328.7	8.81594E-06	3.2
6.9E-07	4.8	337.594	8.58368E-06	4.8
6.89E-07	0.6	350.372	8.27064E-06	0.6
6.83E-07	8.61	365.372	7.93109E-06	8.61
6.81E-07	10.8	380.372	7.61833E-06	10.8
6.79E-07	13.32	396.483	7.30876E-06	13.32
6.83E-07	15.9	407.594	7.10953E-06	15.9

The instrumentation is not valid for all wavelength ranges, the infrared camera is good for wavelengths between 1 and 15 micrometers, while the spectrometer is good for 200 to 1100 nanometers and the human eye is effective between 390 to 700 nanometers.





The peak intensity shifts toward longer wavelengths as temperature decreases and toward shorter wavelengths as temperature increases.

Analysis and Conclusions-

With the above data, the discussion of how Wiens displacement law and the Stefan Boltzmann law describes the black body radiation curve turns tho the effectiveness of approximations. Wien's displacement Law and the Stefan Boltzmann law are approximations of Planck's law that are valid for low temperatures and low frequencies. The data shown above conform well to the predictions of Stefan Boltzmann and even better to that of Wien, as the temperature of the filament never reaches the region of the ultraviolet catastrophe. However, for temperatures approaching 2000 kelvin and frequencies beyond 2.5 micrometers the approximations of Wien and Stefan and Boltzmann diverge dramatically from Max Planck's black body description. However, in spite of their divergence, the early approximations work well in the case of this laboratory procedure. Additionally, the peak wavelengths shifted toward higher frequencies as temperature increased, and toward lower frequencies as temperature decreased. Furthermore, the intensity of the filament increased proportional to its temperature and a shift in its naked eye observed colors toward bright white occurred as temperature rose toward its maximum. The shape of the curve is rough and not a close approximation of a black body emitter. While it is similar, it lacks the smooth well defined curve of the black body emission spectra. In terms of the observed color of the bulb at high temperatures, It transitions from red at lower temperatures to white at higher temperatures due to the effects of black body radiation. Longer wavelengths appear red to the human eye thus, at lower temperatures where the bulb emits primarily in the longer wavelengths it will appear red. At higher temperatures, more of the spectrum is covered by the bulbs radiation, thus it appears white, due to the human eye's inability to distinguish between all the spectral colors of light. The bulb does not appear blue at higher temperatures, partially because it does not reach temperatures high enough to produce significant amounts of blue light, but also because the human eye is not well adapted to detecting higher frequencies that would appear blue.

Similar to the bulb, the Sun appears whitish yellow due to its peak wavelength that occurs between 483 and 520 nm. These wavelengths are generally yellow, but the sun appears almost white due to its broad spectrum emissivity. It is a large highly energetic system and thus will emit at a variety of frequencies proportional to the range of temperatures found on its surface.

Finally, it was found that the resistance in a system changes with temperature. Ohms law is not in fact a static function, but would be more precisely stated as a relationship of variables that depend on temperature as it in turn varies with current and votlage across a known cross section of a resistive element.