Light Measurements from LED and Incandescent Bulbs

Arjun Sivakumar and Joshua Winterroth

The University of Illinois at Urbana-Champaign

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Abstract

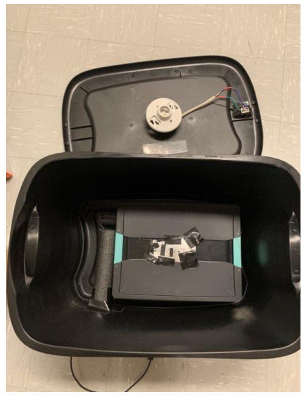
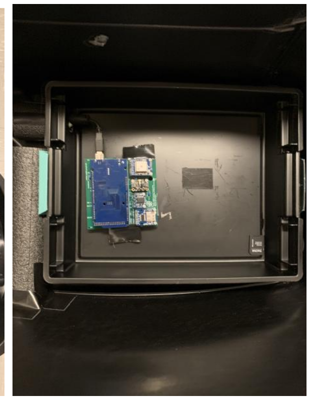
This project is oriented around analyzing the different counts recorded from an Adafruit AS7341 10-Channel Light / Color Sensor Breakout module. A count is a unit that arrives from an Analog to a Digital Converter (ADC) which transforms an input voltage from the sensors registering light into a frequency representative of the voltage's amplitude. These bulbs are often advertised in different black body temperatures, which we find to be an inaccurate evaluation of temperature. We used a Variac Autotransformer to feed different voltages through the lightbulbs that were placed in a black box apparatus to record and interpret data that would guide us through the theoretics and exploration of the project. As such, the nature of the project is largely exploratory as we investigate the varying properties of the bulbs through the voltages to find the true black body fit and equivalent temperatures from the light of the bulbs. The combative nature of the data collection when the rig was constantly being disrupted provided difficulties, but the results were distinctive overall.

Introduction

Humanity relies on lightbulbs to illuminate their homes and appliances every day, so naturally, searching for the most efficient electrical light is often an important concern for the consumer. As such, these companies advertise the many properties of their products, including what they refer to as Black Body temperatures. These are reported temperatures that correlate to the color temperature the bulb produces, yet they can be very inaccurate. Using a programming tool in Arduino, we can measure the counts of color from each bulb and correlate this to a temperature. Additionally, by using a Variac Transformer, we can adjust the power in these bulbs and analyze their change in counts and temperature for supplementary information about the nature of the bulbs. With the tools presented to us, we arranged an apparatus that would allow us to conduct a replicable experiment to analyze the data from our light bulbs and conclude about the nature of the bulbs and the light they produced.

The methodology of our experimentation was conducted in the following manner: A breadboard with an Arduino Mega 2560 is assembled with the DS3231 RTC, microSD breakout, and Adafruit AS7341 10-Channel Light / Color Sensor Breakout components implemented. An SD card is inserted in the reader and then this breadboard is placed and duct-taped in a 12x9.625x3 inches, black plastic box with a removable top and a .25 inch radius hole in the lid to allow light to enter, positioned over the Adafruit Sensor. On the top of this box, a filter with a variety of hole sizes is placed over the .25-inch hole to allow the modification of the amount of light that the sensor receives. This box also has a .5-inch radius hole in its side with a 1-inch, black, cylindrical, twisting foam tunnel, which assists in removing large amounts of external light. This box is then placed and duct-taped in a larger 20x15x13inches plastic box with a removable top that also possesses a small .5-inch radius hole and a same-sized, black, cylindrical foam tunnel that blocks light from escaping into the box.

Wired through the removable top of the box is a light socket that allows either an Incandescent or LED light bulb to be screwed in. The lightbulbs that we used were from two manufacturers: Sylvania for the incandescents and colored LEDs and Felt Electric for the White LEDs. Upon being plugged in, the bulb will illuminate the inside of the larger box as the only light source and the light will filter through the hole in the smaller box to the sensor. A cord connects the Arduino to a laptop through the cylindrical tunnels in both of the boxes. The lightbulb's power cord is plugged into an external Variac Transformer instead of directly into a power source to allow for the modification of voltage provided to the lightbulb. With the physical components of the procedure assembled, a code is written on the Arduino IDE that reads the amount of light received across the ten channels every second and writes this information as a CSV file to the SD card. With a variety of lightbulbs, including Incandescent and LED's of Red, White, and Blue color whose wattage and temperatures also vary, the sensor reads the values of light over time for comparison with each other. Additionally, the Variac is used to alter the voltage provided to the lightbulb every ten seconds, with each experiment starting at one hundred Volts and increasing in increments of five until reaching a voltage of one hundred thirty. The SD card is then removed and placed into the laptop, where the data is then extracted.

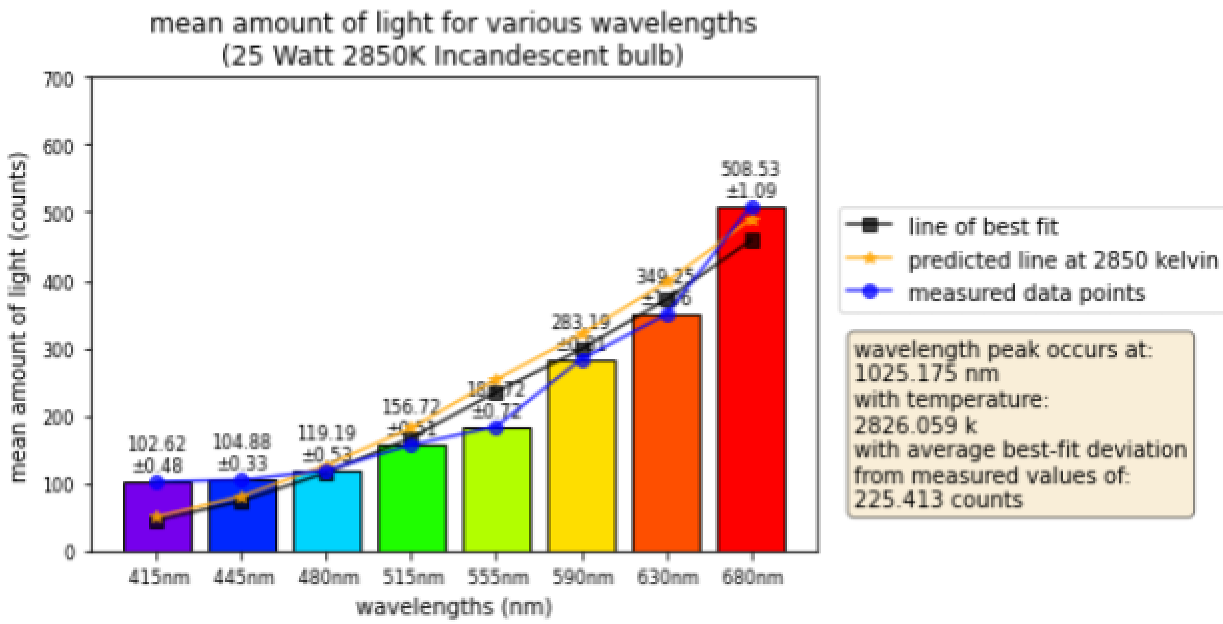
The Arduino

The Arduino platform is made to be utilized in a variety of projects and is intended to provide easily used hardware and software for the programmer to manipulate in accordance with a plethora of motors and sensors. Our project makes use of an Arduino Mega 2560 Microcontroller in tandem with a variety of sensors. The integrated development environment (IDE) is the malleable software that can be used with any of the Arduino boards to create and fine-tune the code used by the Microcontroller. The Arduino communicates with our sensors, primarily the Adafruit AS7341 10-Channel Light / Color Sensor Breakout, which detects light from different wavelengths and communicates it in the form of counts, the DS3231 RTC, which is a Real-Time Clock that records the time of our measurements, and the MicroSD card breakout, which is where the data was recorded to for extraction and analyzation. The most important module is the AS7341 Sensor, which uses the 16-bit ADC to detect light and communicates the information detected with the Arduino via the Inter-Integrated Circuit protocol (I2C). I2C is a serial, 2-wire communication protocol that has multiple 'masters' and 'slaves' to send and receive information. It uses a clock, similar to SPI, and sends a single packet of information at a time. Additionally, it uses an acknowledge/no-acknowledge bit, which is sent back by the receiver to the sender to confirm the information has been received.

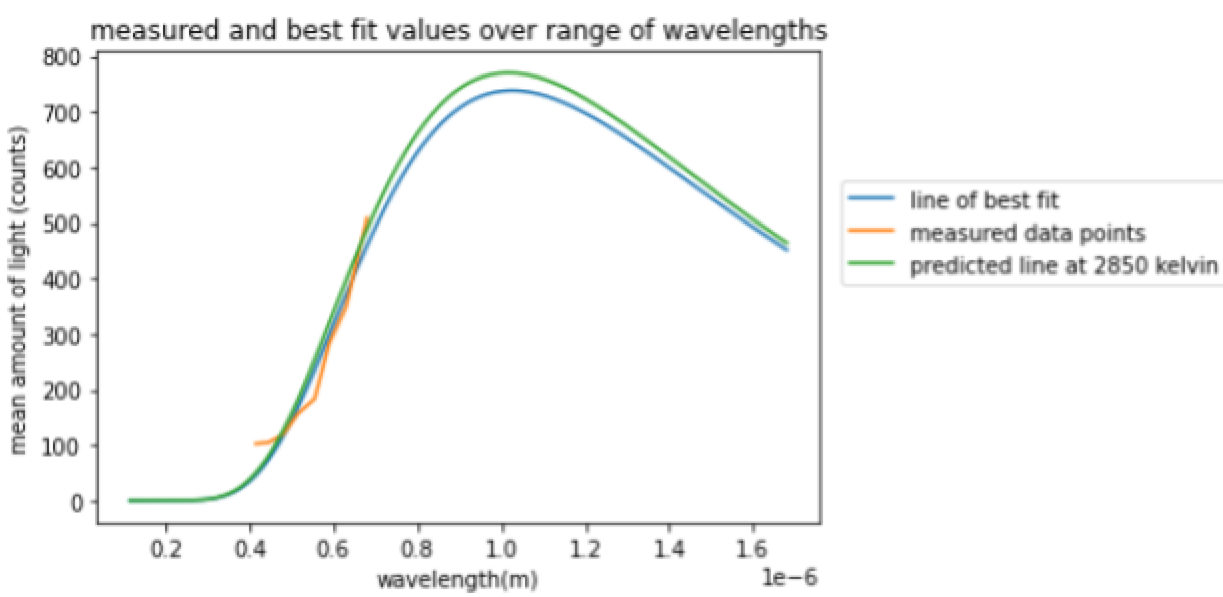
Light Emittance from Bulbs

The two kinds of lightbulbs we are analyzing in this project are Incandescent and LED, as such, a description of their use and why their differences are important to this project is in order. Firstly, an Incandescent bulb is illuminated by running a current through a wire filament, which heats the filament until it glows, producing light. In this manner, the Incandescent bulbs tend to produce a lot of heat, and their light emittance as a consequence is not limited to just the visible spectrum. More specifically, incandescent bulbs produce a fair amount of infrared light. Most of the energy that goes into an incandescent bulb ends up as heat rather than visible light (Barnes 1). These general properties contrast greatly with LED lights. Light-emitting diodes make use of semiconductors and electrons to release photons that produce colored light in accordance with the energy required to cross a specific threshold in the semiconductors (Superior 1). In this capacity, the LED's are capable of producing a specific color of light at a time, rather than simply radiating general light out. In the effort to produce white light, which is a combination of lights, multiple semiconductors are overlapped to create the effect of white light. In the general process of creating visible light, LED usually produce very little to no infrared light. These methods of light production matter to this project because, when measuring the light produced from these bulbs, interesting patterns can be found in the counts of their emittance. Light comes in many colors, and they correlate to certain wavelengths that we can compare to one another. When incandescent bulbs produce their light, they do so in a fashion that greatly resembles a black body spectrum (Shawn-Yu and Yong-Sung 1). This spectrum is controlled by the temperature of the bulb, which marketers of these bulbs give an estimate as an advertising point, the validity of which is often dubious. As we adjust the amount of voltage going into the incandescent bulbs, the temperature also increases and decreases with the voltage, which affects the presented black body spectrum we measure from the counts. Contrastingly, the LEDs do not produce light in the same manner, only providing high counts in the specific color presented, and do not perform well in the same manner of adjusting their voltage. The bulbs contrasting nature can be described by a quality called emissivity, which presents the ratio of thermal radiation to the radiation of an idealized black body. Thus Incandescent bulbs tend to have a higher emissivity than LEDs due to their lack of presenting a black body spectrum. However, there is one notable exception to the lack of a black body spectrum. In the process of creating White LEDs, overlapping bands are combined in a manner that, once measured, produces counts that greatly resemble a black body spectrum. These observations guided much of our project as we examined the relations between light waves and temperature, many graphs are provided to show this journey into the strange field of light.

Analysis of Light Emittance Spectra of Incandescent Bulbs



Graph 1.1. The emission spectra of 25 Watt 2850K Incandescent bulb. 8 of the 10 channels in the spectrometer are used to collect the mean counts measured of specific wavelengths in the visible spectrum. Also a blackbody fit, as well as a predicted fit at manufacturer's color temperature is overlaid on top of the emission spectra. An estimation of peak wavelength and temperature are drawn from the black body fit, as well as a measure of the closeness of the best fit line to the measured values.



Graph 1.2. Displays the trend lines as well as the measured values over a larger range of wavelengths (from 0 to 1600 nm). Provides a clearer visualization of the blackbody trends, and how the measured values match up to the line of best fit and the predicted line at the manufacturer-provided temperature of 2850K.

Discussion of Black Body Fit of Spectra

Black body radiation is the thermal electromagnetic radiation of a black body (an idealized, non-reflective object), which has a spectrum wavelength with an inverse relationship to intensity depending only on the object's temperature. This relationship is characterized by the equation

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

where $B_{\lambda}(T)$ is the spectral radiance, with units of [power / (area * solid angle * wavelength)]. h is the planck's constant, c is the speed of light, k_B is the Boltzman constant, λ is the wavelength, and T is the temperature. As seen in *graph 1.1,* the measurements taken suggest a trend similar to that of a black body, and so a line of best fit can be created using the black-body equation for spectral radiance to match with the measured values and identify if the object behaves like a black body. This line of best fit makes use of the equation for spectral radiance, solving for the temperature at which the intensity vs wavelength graph closely resembles that which was measured. Also, the best fit calculation uses the temperature provided by the manufacturer as a guess of the possible temperature the bulb would have if it were a black body object. Furthermore, the best fit calculation also takes into account the scaling factor as a parameter to further to ensure that an accurate and appropriate line of best fit is creates that communicate clearly communicates the differences in peaks of the light emission spectrum. The resultant trend line is also shown alongside a predicted black-body trend at the color temperature provided by the manufacturers, and this color temperature would be different from the actual temperature at the surface if the object was not a black body.

In the case of the incandescent bulb, the measured values show that the peak of the emission spectra was towards the larger wavelengths, and in fact, the actual peak wavelength was probably too large for the spectrometer to pick up. This can be discerned from the fact that the near-IR value measured by the spectrometer was 3632 counts, which is much larger than the counts measured at other wavelengths. Therefore, the peak of the light emission spectra probably occurs at a larger wavelength as incandescent bulbs produce light by heating up the filament (incandescence) and thus release a lot of near-IR light. This is also why incandescent bulbs are considered inefficient at producing visible light.

Moreover, as seen in *graph 1.1 and graph 1.2,* the line of best fit seems to match up closely with the measured values. *Graph 1.2* demonstrates how the line of best fit and the predicted trend at the manufacturer's color temperature of 2850K follow the measured values closely, while also confirming the suggestion that the peak wavelength was indeed at a larger wavelength, something which could not be measured with the spectrometer.

Color Temperature and Peak Wavelength Variations

Thus, a comparison of the temperature provided by the manufacturer and the temperature calculated for the line of best fit of 2826K gives a difference by 24K or .842% off the provided temperature of 2850K. Also, an accurate peak wavelength for the predicted and best fit lines can be achieved through the Wien's displacement law, which describes the relationship between peak wavelength and temperature as

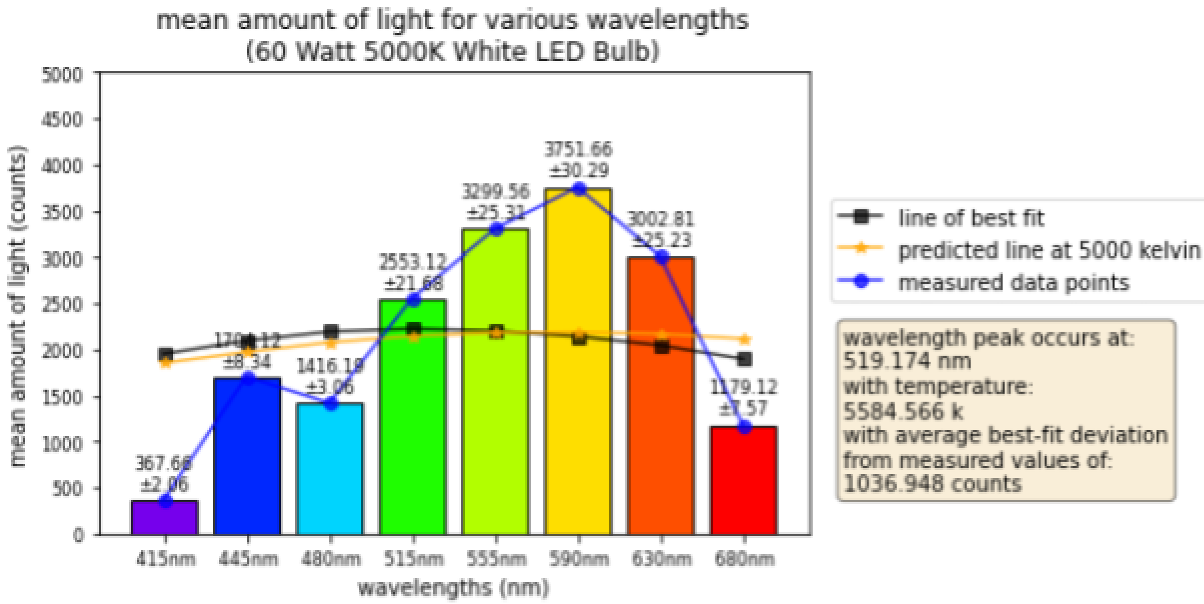
$$\lambda_{max} = \frac{b}{T}$$

where λ_{max} is the peak wavelength, T is the temperature, and b is a constant of proportionality.

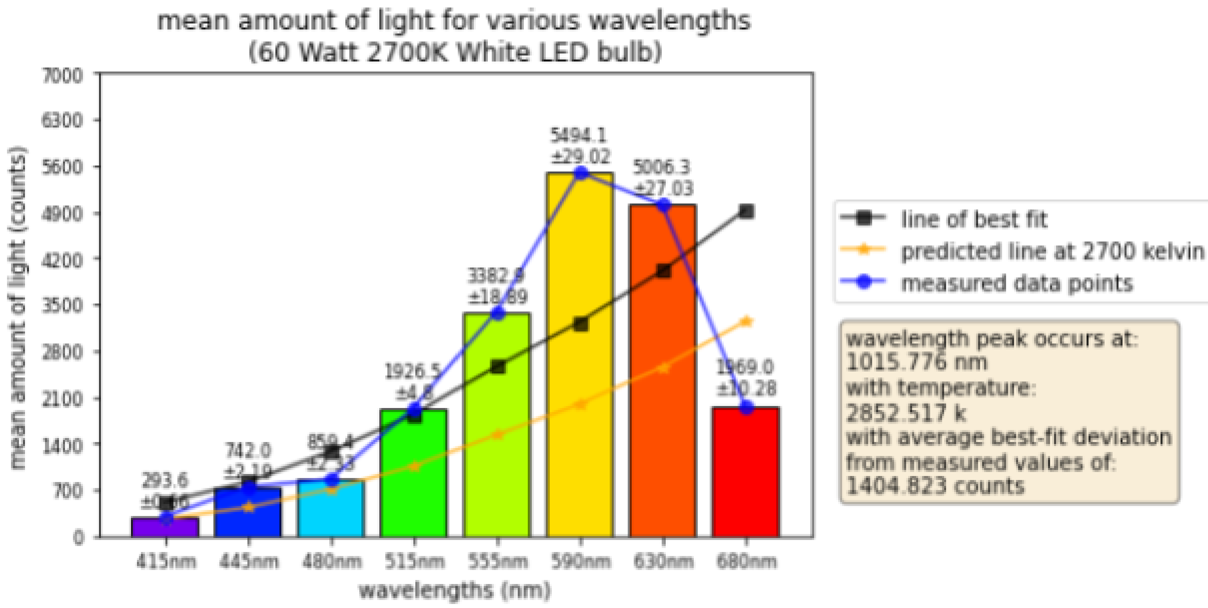
So, the peak wavelength at 2850K is $\lambda_{max} = \frac{b}{2850k} = 1016$ nm, which is very close to peak wavelength found from the line of best fit, which is 1025 nm, and differs by .885% off λ_{max}.

Moreover, the small average best-fit deviation suggests that the line of best fit is a good fit of the measured values. The average best-fit deviation was calculated by taking the sum of the squared differences of the measured and best-fit values, dividing it by the number of bins (in this case 8), and then taking teh square root. This helps identify how much the best-fit values deviated from the measured values in total, which in this case is low enough to indicate that black body best fit line does accurately map the measured values. Thus, this demonstrates that the incandescent bulb indeed has the characteristics of a black body object.

Emission Spectra of LED Bulbs of Varying Color Temperatures



Graph 2.1. The emission spectra of 60 Watt 5000K white LED bulb. 8 of the 10 channels in the spectrometer are used to collect the mean counts measured of specific wavelengths in the visible spectrum. Also a blackbody fit, as well as a predicted fit at manufacturer's color temperature is overlaid on top of the emission spectra. An estimation of peak wavelength and temperature are drawn from the black body fit, as well as a measure of the closeness of the best fit line to the measured values.



Graph 2.2. The emission spectra of 60 Watt 2700K white LED bulb. 8 of the 10 channels in the spectrometer are used to collect the mean counts measured of specific wavelengths in the visible spectrum. Also a blackbody fit, as well as a predicted fit at manufacturer's color temperature is overlaid on top of the emission spectra. An estimation of peak wavelength and temperature are drawn from the black body fit, as well as a measure of the closeness of the best fit line to the measured values.

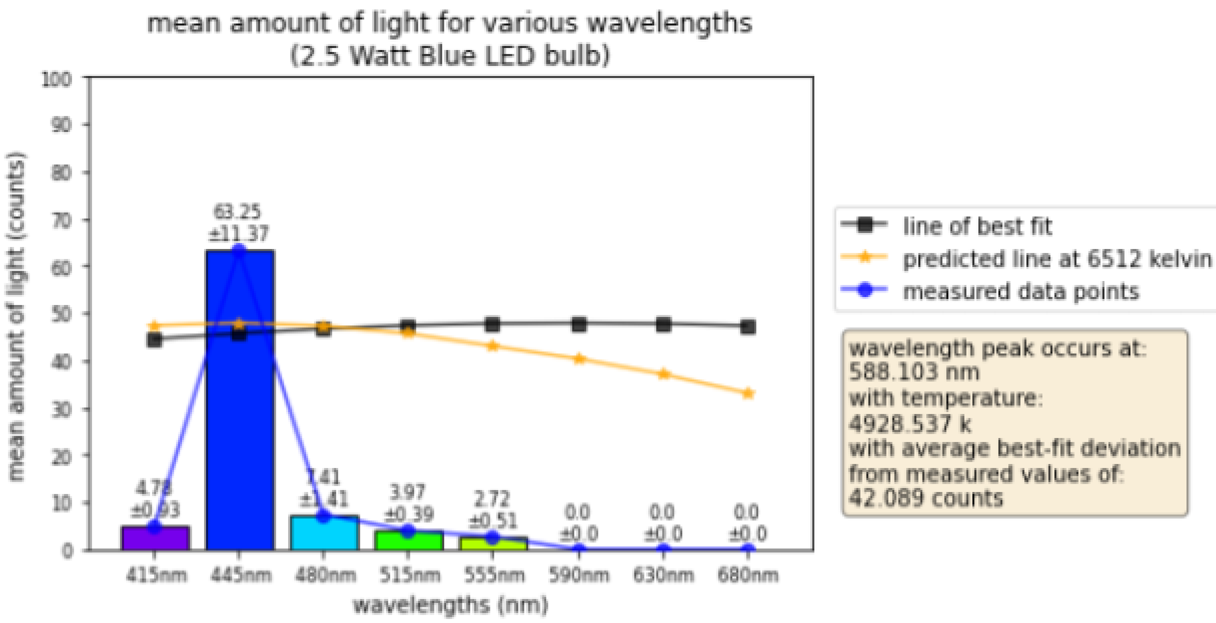
Discussion of Peak Wavelength and Color Temperature

For the 5000K LED bulb, the measured values indicate a peak wavelength (the wavelength at which the count is maximum) of 590 nm, while the line of best fit suggests an earlier peak. On the other hand, when using the temperature provided by the manufacturer, it yields a peak wavelength at 580 nm. Based on Wein's displacement law, the peak wavelength for the predicted black body trend at 5000K would be $\lambda_{max} = \frac{b}{5000k}$ which gives $\lambda_{max} = 580$ nm. A similar calculation can be done for the line of best fit, which with a temperature of 5584K, would have a peak wavelength of $\lambda_{max} = 519$ nm.

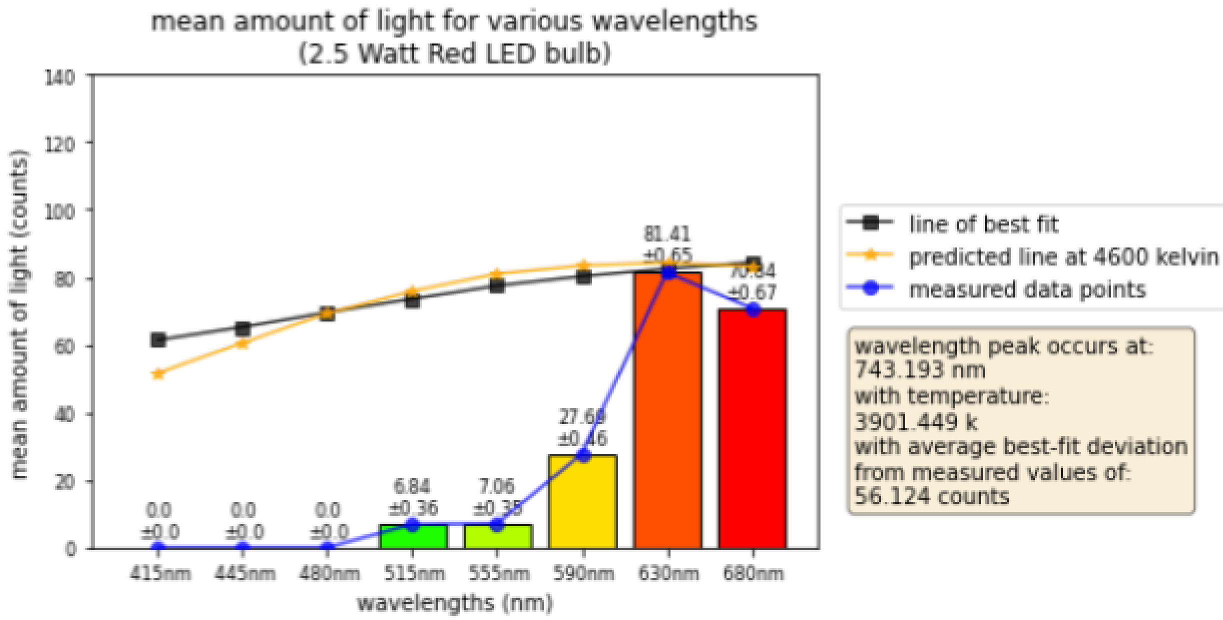
Although the predicted trend line at 5000K has a peak wavelength that matches more closely with the measured values, the line of best fit solved using temperature is a better estimation of the black body radiation trend of the 5000K LED. Therefore, the difference in peak wavelength could then communicate that although sharing characteristics with the intensity-wavelength relationship that a black body has, the LED is not an actual black body, and will therefore not match up exactly with the line of best fit. This can also be further seen with the best fit deviation value seen in *graph 2.1*, which shows that there is a larger amount of differences between the best fit line and the measured values.

Furthermore, when looking at *graph 2.2*, the LED at 2700K also seems to share similarities with a black body radiation trend, but its peak wavelength of 590 nm again differs from the peak wavelength of 1015 nm, with a corresponding temperature of 2852K, a value closer to its manufacturer's provided color temperature. Therefore, it can be more explicitly seen from *graph 2.2* that the black body radiation-based line of best fit does not match the measured values, and in fact, although the manufacturer's provided the temperature is almost half in comparison to 5000K LED, both share the same measured peak wavelength, further indicating that the LED is not a black body object.

Comparisons of Emission Spectra of Colored LED Bulbs



Graph 3.1. The emission spectra of 2.5 Watt Blue LED bulb. 8 of the 10 channels in the spectrometer are used to collect the mean counts measured of specific wavelengths in the visible spectrum. Also a blackbody fit, as well as a predicted fit at manufacturer's color temperature is overlaid on top of the emission spectra. An estimation of peak wavelength and temperature are drawn from the black body fit, as well as a measure of the closeness of the best fit line to the measured values.



Graph 3.2. The emission spectra of 2.5 Watt Red LED bulb. 8 of the 10 channels in the spectrometer are used to collect the mean counts measured of specific wavelengths in the visible spectrum. Also a blackbody fit, as well as a predicted fit at manufacturer's color temperature is overlaid on top of the emission spectra. An estimation of peak wavelength and temperature are drawn from the black body fit, as well as a measure of the closeness of the best fit line to the measured values.

Emission Spectra of Red and Blue LED

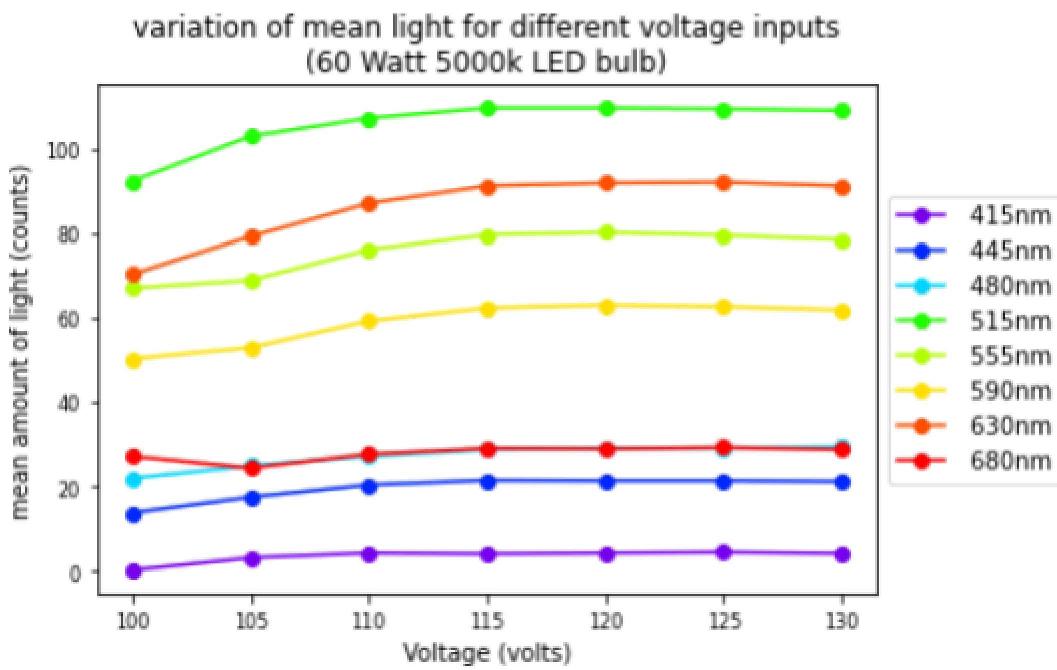
In the case of colored LEDs, it is even more evident that the LEDs are not black body objects, as the measured values indicate a strong response in the wavelength that corresponds to the particular color (at the wavelength of 445nm in *graph 3.1* and wavelengths of 630 nm and 680 nm in *graph 3.2*), while zero or close to zero for everything else. This can be further explored through the analysis of the line of best fit based on the black body radiation relationship between wavelength and intensity. Moreover, the guess for the color temperature to create the best fit line was derived by using Wien's displacement law, taking the peak wavelength from the measured values, and solving for temperature. This was done because the manufacturer did not provide a color temperature, as the LEDs do not produce light through Incandescence (through heating), but rather through electroluminescence and therefore should not have a black body temperature.

The peak wavelength calculated from the line of best fit for the Blue LED is 588 nm as seen in *graph 3.1*, which greatly differs from the measured peak wavelength of 445nm. Also, the corresponding calculated temperature of the best fit line is 4928K, which also differs from the temperature derived from the measured peak wavelength of 6512K. Similarly, in the case of the red LED, as seen in *graph 3.2,* the measured peak wavelength of 630 nm greatly differs from the calculated line of best fit's peak wavelength of 743 nm, along with a lower calculated temperature of 3901K that is again distinct from 4600K temperature found from the measured peak wavelength.

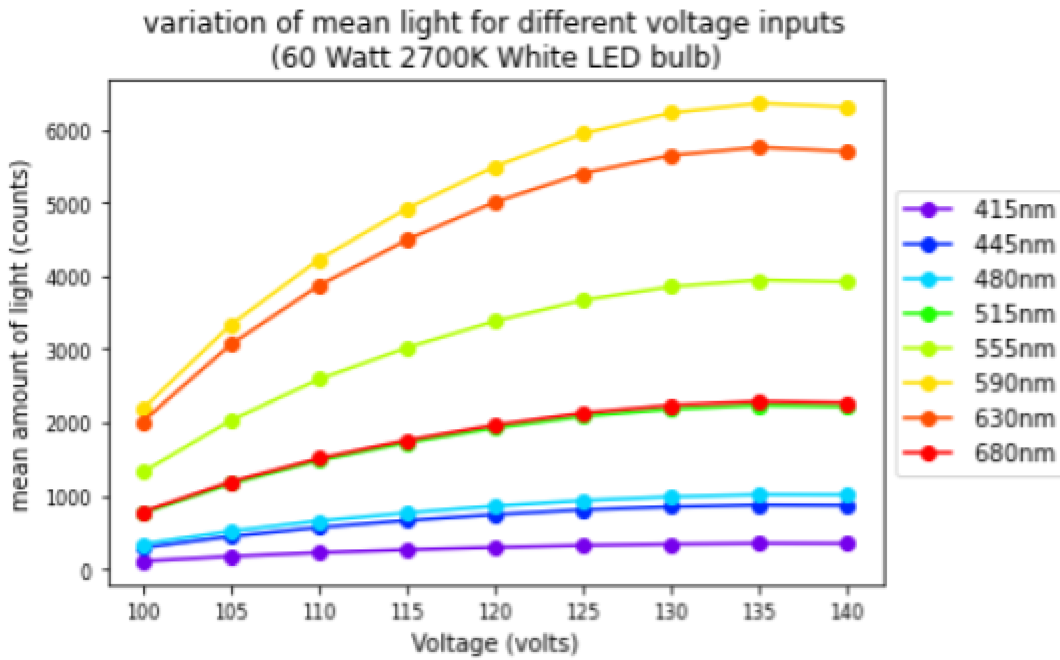
These factors thus indicate that LEDs are indeed not black body objects, as the emission spectra do not correspond to the black body radiation spectra, and the color temperatures provided or found from measurement are not an accurate reflection of how the light is produced. In fact, the black body fit created here can be deemed irrelevant, as it is in now way a line of best fit of the measured values, as the peaks are not produced through black body radiation from a black body like object.

Variation in Emission Spectra of Bulbs Over Changes in Input Voltage

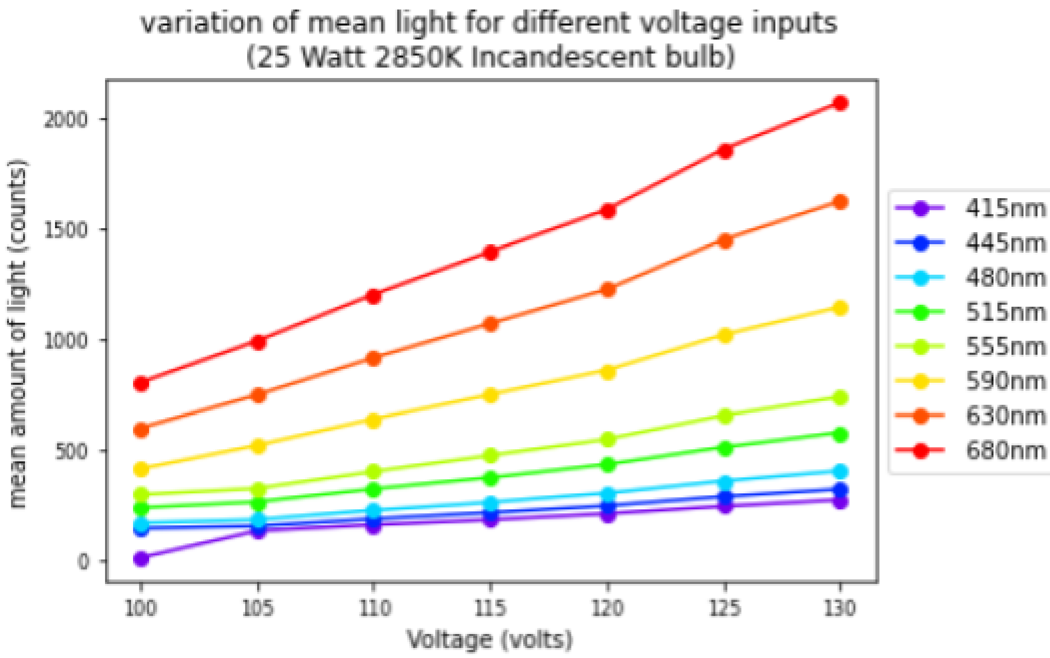
Measurements for LED and Incandescent Bulbs



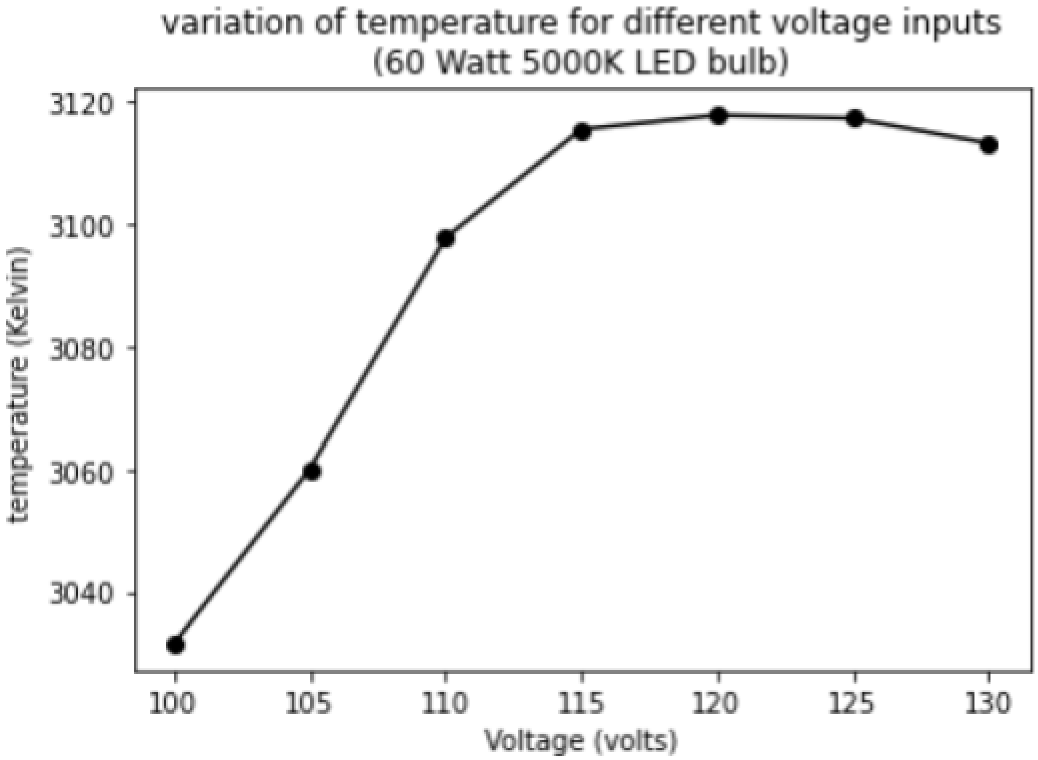
Graph 4.1. Shows the variations in mean amount of light with an increase in voltage 100 to 130 volts for a 60 Watt 5000K LED bulb. The overall trend is similar to that of a radical function, suggesting that with increments in voltage, the rate of increase in intensity falls off. However, the peak wavelength and the relative amount of light for the various wavelengths remains the same, suggesting voltage changes only affects the intensity.



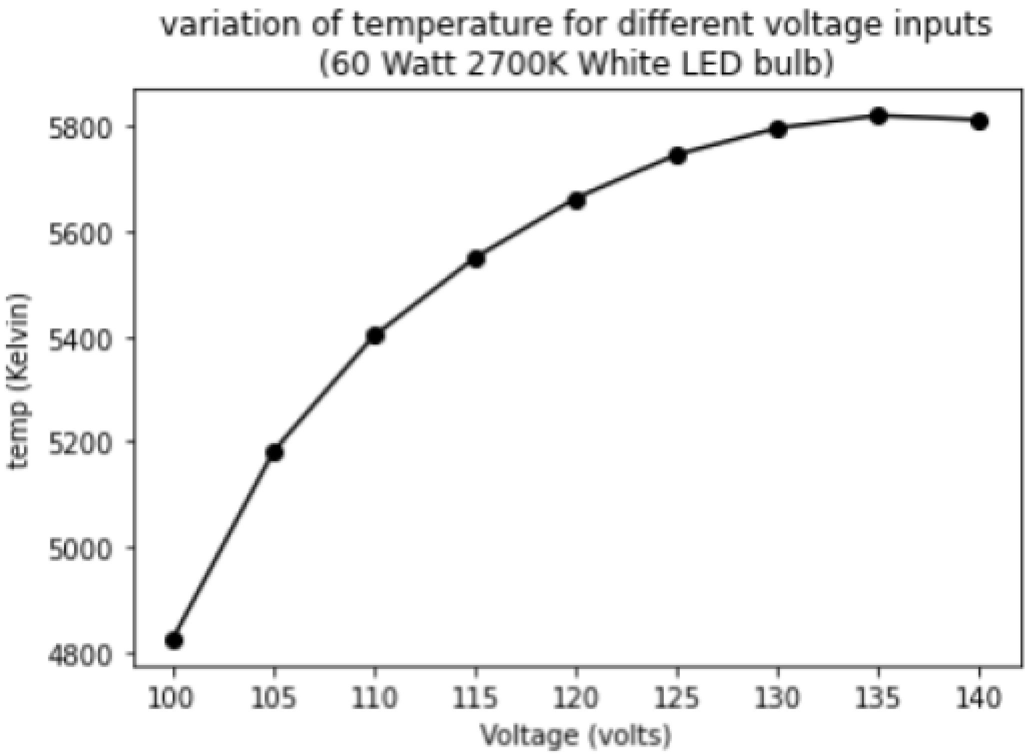
Graph 4.2. Shows the variations in mean amount of light with an increase in voltage 100 to 140 volts for a 60 Watt 2700K LED bulb. The overall trend is similar to that of a radical function, suggesting that with increments in voltage, the rate of increase in intensity falls off. However, the peak wavelength and the relative amount of light for the various wavelengths remains the same, suggesting voltage changes only affects the intensity.



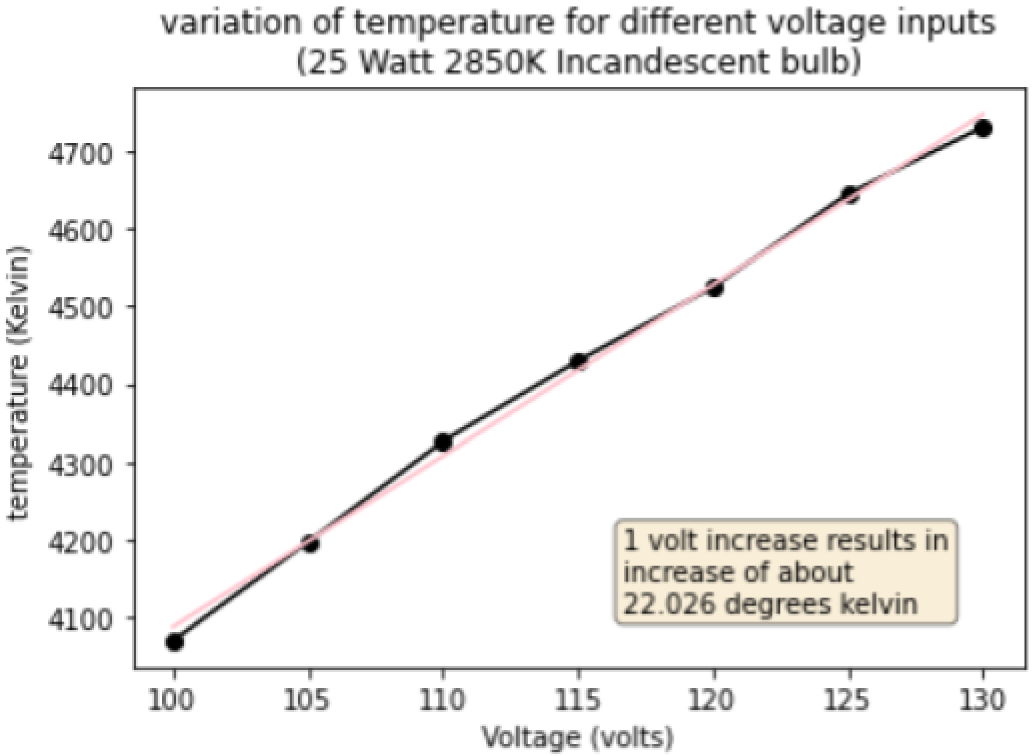
Graph 4.3. Shows the variations in mean amount of light with an increase in voltage 100 to 130 volts for a 25 Watt 2850K Incandescent bulb. The overall trend is similar to that of an exponential function, with the intensity of light increasing at a greater rate with increments in voltage. This differs to the trends seen in *graph 4.2 and graph 4.1,* which could be attributed to incandescent bulbs closely resembling a black body object. Regardless, the increments in voltage continue to only impact the intensity of light and does not shift the wavelengths.



Graph 4.4. Change in temperature based on voltage increments (from 100 to 130 volts) for 60 Watt 5000K LED. The graph shows that the increase in temperature is also like a radical function, which demonstrates a proportional, non exponential relationship between temperature and intensity.



Graph 4.5. Change in temperature based on voltage increments (from 100 to 130 volts) for 60 Watt 2700K LED. The graph shows that the increase in temperature is also like a radical function, which demonstrates a proportional, non exponential relationship between temperature and intensity.



Graph 4.6. Change in temperature based on voltage increments (from 100 to 130 volts) for 25 Watt 2850K LED. Unlike in the case of the LEDs, temperature increases linearly by 22.026K for every 1 volt increment.

Discussion of Intensity and Temperature Relationships

The increments in voltage further demonstrate some of the black body characteristics of the incandescent bulb which differs from the LED bulbs. *Graph 4.3* shows the superlinear increase in the intensity of light for the various wavelengths with changes in voltage, which is in accordance with how incandescent bulbs produce light. Because the incandescent bulb is dimmable, this means that there is an ohmic resistor which allows for a linear relationship between voltage and current while resistance stays constant. A dimmable bulb is one that allows for a change in voltage to alter the intensity of the light emitted by the bulb. This is achieved in two methods, one of which is through directly changing the current going through (less voltage, less current, more dimming), and this is present in incandescent bulbs. Another method which is also sometimes available in LEDs is called the pulse width modulation (PWM) dimming. PWM is a mode of outputting light in which the supply of voltage is turned on and off at a rapid frequency, and dimming is possible by change the amount of time the voltage supply is turend on and off. In the case of the of the incandescent bulb, dimming or brightening is achieved by the voltage change the current. Since temperature is proportional to current, this then results in a linear voltage-temperature relationship, as seen in *graph 4.6*. Furthermore, in the case of a black body object, temperature and power are related by the equation

$$j^* = \sigma T^4$$

where j^* = power emitted per unit area, σ is the stefan-boltzmann constant and T is the temperature. Thus an increase in temperature results in an exponential increase in intensity, which can be seen in *graph 4.3*, explaining the nature of the graph and furthermore demonstrates that the incandescent bulb resembles a black body object.

On the other hand, both the LEDs are non dimmable, therefore to protect from high voltage the resistors in the LED produce a radical curve for the temperature so as to not burn out the diodes in the circuit. This must be a non-ohmic resistor which increases resistance with increments in voltage, thus allowing for the rate of increase in current to diminish and result in a radical temperature-voltage relationship as seen in *graph 4.4* and *graph 4.5.* Consequently, a radical relationship is then established between intensity and voltage, as seen in *graph 4.1* and *graph 4.2*, which would mean that temperature and intensity have a proportional, non exponential relationship, thus showing that LEDs are indeed not black body objects.

Final Discussion and Exploration

Through this experiment, we were able to identify the black body characteristics of the incandescent bulbs, and how they differed in comparison to LED bulbs, demonstrating the LEDs are indeed far from being black body objects. Furthermore, the manufacturer's provided color temperatures, as well as the initially measured values for certain LEDs (such as the 5000K LED seen in *graph 1.1*), can be misleading in that they seem to give the illusion that the LEDs put out black body radiation, which is not true. The line of best fit based on the spectral radiance equation demonstrates that the peak wavelength, as well as calculated temperature, differs in varying lengths from that which was measured or based on the temperature provided by the manufacturer. On the other hand, it was possible to show that there is just about a .8% difference when it comes to calculated temperature and peak wavelength values in comparison to what was measured or provided for the incandescent bulbs, showing that they do resemble a black body object. Furthermore, increments of voltage allowed us to see the impact changes in temperature would have on the intensity, and once more, the incandescent bulb demonstrated an exponential relationship between power and temperature, which is another characteristic of a black body object.

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