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Incandescent Lamp from Black Body Perspective

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ABSTRACT

The incandescent lamp from black body perspective was investigated using commercial lamps of various watts. The major component of the incandescent lamp is the tungsten filament. The resistance of the tungsten filament was measured using a digital multimeter at an initial laboratory temperature. Light produced from lamp was separated into visible colours by an equilateral triangular glass prism. Deduced resistances were used to obtain equivalent temperatures by power-law parameterization. The Wien's displacement law was used to estimate Peak wavelengths at different temperatures. The diameter of the tungsten was measured after dissecting the lamp, and this was used to determine its cross-sectional area. Both Wien's displacement law and Stefan-Boltzmann expressions were applied in determining the filament's spectral emissive power (SEP) in comparison with that of the visible spectrum. Planck's graph of intensity using peak wavelength of tungsten filament as reference was juxtaposed with the intensity of visible spectrum using *OriginPro 2016 SR0 b9.3.226*. The maximum temperature attained was 2852.87 *K* with (SEP) of 1478955.24 Wm^{-2} for the 200W lamp. For the 100W lamp, the (SEP) obtained was 749347.9078 Wm^{-2} at 2489.14 *K*. Both temperatures, and even as low as 1250 *K*, were in agreement with Wien's displacement law. The percentage estimation of visible spectrum in the radiation was about fourteen percent (14 %) while the rest was infra red radiation. This low visible light produced may be as a result of the non-ideal black body nature of the tungsten filament; and so, the incandescent lamp may be considered a quasi-black body.

Keywords:
Tungsten filament,
Peak wavelength,
Spectral emissive power,
Quasi-black body.

INTRODUCTION

This paper aims to appraise the black body attribute of incandescent lamp through the dispersion of light produced by it. The visible spectrum is separated into its colour components, each with its corresponding peak wavelength derivable from Wien's law through the inference of Resistance-Temperature correlation.

A black body is an ideal body that absorbs electromagnetic waves at all wavelengths and angles (Zwinkels , 2015, Li and Zhou, 2016) . Thus, it can be considered a perfect absorber. It absorbs all the electromagnetic energy it receives and emits such radiation so as to be in thermal equilibrium; hence, it is non-reflective (Sharch06). Since no light is reflected, the object appears black thereby justifying the name "black body". A "perfect" black body is not dependent on spectrum of wavelength but on temperature which is a key factor (Sharch06).. Long wavelengths are emitted by cold objects while short wavelengths, visible light and ultraviolet emanate from hot objects. It is an imagined theoretical phenomenon, though it is possible to create an object close to such a body which can capture most radiation falling on it (Meseguer et al., 2012). The above concept of black body may be captured in three sentences below:

i. It is the most emitting surface for a particular temperature and wavelength;
ii. The radiation of black body is independent of direction because its radiation suffers diffusion;
iii. In a vacuum, the total radiation is solely temperature-dependent. This may be a reference point for the radiation properties of other surfaces that are perfect emitters and absorbers (Meseguer et al., 2012).

Plank's empirical formula used to explain experimental energy distribution in the black body spectrum at a given temperature, T is given as:

$$u_\lambda = \frac{8\pi hc}{\lambda^5}\frac{1}{e^{\frac{hc}{k\lambda T}}-1} \quad (1a)$$

where h is Planck's constant = $6.6261\text{x}10^{-34}$ J.s , $c = 2.9979\text{x}10^8 m/s$, λ is the wavelength of radiation, k is the

Boltzmann constant – 1.308x10^{-28} J/K and T is the temperature of radiation.
The equation 1a is a combination of both quantum mechanics and statistical physics for energy density from λ to $\lambda + d\lambda$ for the wavelength, λ and temperature T of the cavity given by (Li and Zhou, 2016) as:

$$u_\lambda = f(\lambda, T) \quad (1b)$$

Equation 1b can answer for both long and short wavelengths; an improvement over Jean-Rayleigh (J-R) that fails at short wavelengths due to "ultraviolet catastrophe". The failure of J-R in black body energy distribution is a failure of classical mechanics that culminated in Quantum mechanics revolution (Nave).

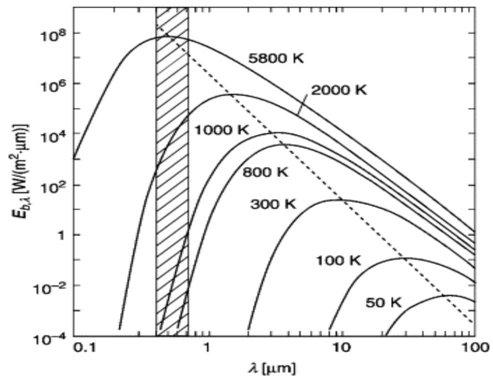


Figure 1: Spectral emissive power of a blackbody, $E_{b,\lambda}$ versus wavelength, λ (Meseguer et al., 2012)

Figure 1 shows different curves of blackbody temperatures, T. The stripped area indicates the visible section of the spectrum which is included in a sun radiation line of almost 5800 K. At 300 K the concentration of radiation is at the Infra-red end. The graph summarizes two important laws (Wien's displacement law and Stefan's law) from experimental findings on black body radiation.
Wien's law stipulates that for every particular wavelength, there is an increase in emitted radiation with temperature (Zwinkels, 2015). The dotted line in figure 1 cuts across wavelengths corresponding to maximum emissive powers for each temperature. The law is given as:

$$\lambda_{max} = \frac{2.898 \times 10^{-3}}{T} \text{ m. K} \quad (2)$$

where λ_{max} is the position of the maximum in the radiation curve i.e the wavelength at which a blackbody radiates most strongly at a given temperature T.

This law signifies that the higher the temperature of an emitting body, the shorter the wavelength of radiation it emits. In addition, as temperature falls, it is not only the maximum that is affected, but there is also a shift towards the region of concentrated radiation approaching longer wavelength.
The Stefan's law involves the total emissive power of black body radiation emitted across the entire spectrum of wavelengths at a given temperature. As the temperature of a black body increases, the total emitted power also increases. The total emissive power of a black body known as Stefan-Boltzmann law is given as:

$$E_b = \sigma T^4 \quad (3)$$

where σ = 5.67x10^{-8} W/m^{2}K^4 and T is in Kelvin. Stefan-Boltzmann law can be used to deduce the energy emitted by a black body in all angles and wavelengths.
A brief summary of the applications of Planck's formula is seen in figure 2:

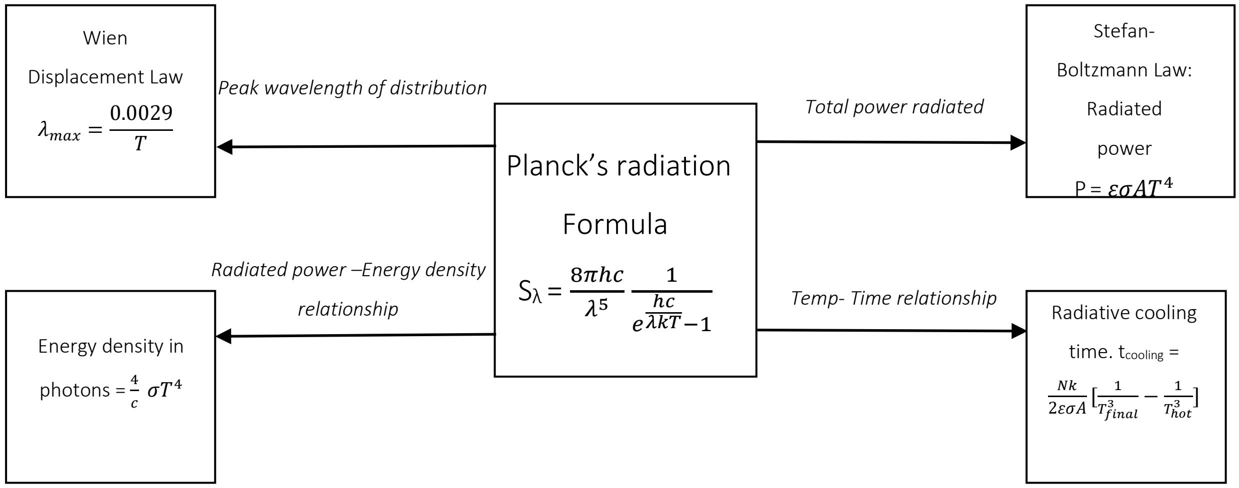


Figure 2: Applications of Planck's formula of black body at a glance (Nave)

Figure 2 is a representation of Planck's radiation formula. In addition to both Wien displacements law and Stefan-Boltzmann law are the Energy density in photons and radiative cooling time representing the cooling rate of a surface.
At high temperature, black body emits spectrum of photon energies spanning the visible range that makes the body to be white while at low temperature it is non-reflective of any light so appears black. An example of the former is the sun. At 5000^0C; surface of the Sun's temperature, radiation is across the visible spectrum band and it is white hot since it has white appearance (Nave). Other examples of black bodies include Black Holes, Cavity with a Hole, Stoves, Stars, Electric heaters, Incandescent lamps, Warm-blooded animals and Burglar alarm.

The Incandescent lamp

Incandescence is the emission of electromagnetic radiation (which includes visible light also) from a hot body as a result of its high temperature or glowing due to heat. Incandescent bodies include light bulbs, electric stoves etc. Incandescent bulbs emit light in a manner closely resembling Planck's law of blackbody radiation. The incandescent lamp acts as a black body radiator since radiation of power off the filament is through visible and invisible light (Zhang et al., 2016).
The tungsten filament is the major constituent of the incandescent lamp. The tungsten filament of a bulb approximates a black body, and by increasing the current through the bulb, its temperature rises (Forsythe and Worthing, 1925). It is close to an ideal black body for a filament because it has a very high melting point and does not evaporate easily. A small quantity of tungsten evaporates and condenses on the glass surface causing the filament to depreciate in thickness and making the frosted glass darker (Roberts, 2005).
Most of the energy consumed by incandescent lamps is radiated in the infrared (Roberts, 2005, Zwinkel, 2015 and Zhang et al., 2016). Only 5% to 10% of the energy used by an incandescent bulb is converted to light; the other 90% is lost as heat (Roberts, 2005). The reason for this is in figure 3 with the visible spectrum region found on the blackbody radiation curves (Roberts, 2005).

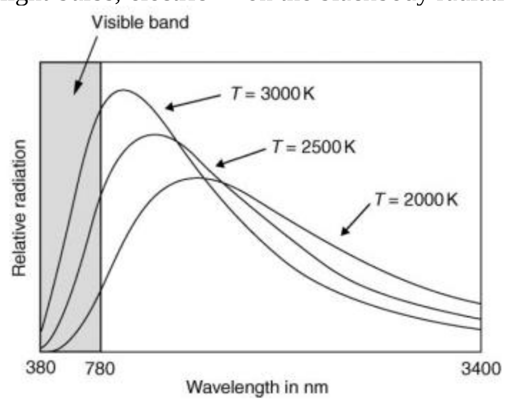


Figure 3: Radiation from blackbody source at various temperatures with visible band (Roberts, 2005)

Some techniques are under investigation to improve the efficiency of the incandescent lamp in producing more visible light. These include:

Efforts to improve the production of visible light from incandescent lamp are:

i. Raising the filament temperature to lower peak wavelength with a consequent rapid tungsten evaporation and shortened lifetime which could be remedied by filling lamp with halogen (Roberts, 2005).
ii. Reflecting some infra red back to the filament resulting in normal temperature with minimal electrical power;
iii. Creating a filament that is a selective radiator for visible light rather than infra red (Roberts, 2005).

The filament geometry is such that the internal part of it experiences serial absorption and reabsorption of radiation leading to temperature spike (Agrawal, 2011, Rajendra, 2020). This is analogous of hole in a cavity- a practical black body

Temperature of the filament deduced from Resistance

The physical properties of the metal constituting the filament are expected to be temperature dependent; the resistance R starts amplifying fast enough according to the power-law parameterization (Leff, 1990) (4);

$$R = R_0 \left(\frac{T}{T_0}\right)^{\beta} \quad (4)$$

where β is 1.214; obtained by making a least-square fit to the available data on the resistivity of tungsten in the range 293–3000 K (Jones and Langmuir,1927).

$$T = T_0 \left(\frac{R}{R_0}\right)^{0.8237} \quad (5)$$

The colour constituents of the visible spectrum are distributed in the wavelength range otherwise known as bandwidth as seen in Table 1:

Table 1: Visible light is between 400 nm and 700 nm (Zimmerman, 2020)

Colour	Lower limit Wavelength (nm)	Upper limit Wavelength (nm)	Band width (nm)
Red	740	625	115
Orange	625	590	35
Yellow	590	565	25
Green	565	520	45
Cyan	520	500	20
Blue	500	435	65
Violet	435	380	55

The combination of the colours above in their right bandwidth gives the white light. The white light in the electromagnetic spectrum is released at the appropriate temperature in the course of the heating effect created by the supply of electrical energy to the tungsten filament. The electromagnetic spectrum has visible light in continuum spectra. At excitation of the atoms of the tungsten filament due to oscillation of bounded electrons, it radiates electromagnetic waves from which the visible spectrum may be separated into its colours. At 2000K, red light shines from the filament since it has a longer wavelength while at 3000K the brightness of the filament is pronounced as it emits shorter wavelength of yellow light (Carla, 2015).

The light output of the filament is estimated from a known steady-state temperature source. Luminous flux Q has the expression:

$$Q\,(\lambda_i \rightarrow \lambda_f) = \int_{\lambda_f}^{\lambda_i} \frac{683V(\lambda).\varepsilon_{visible}.2\pi r_0 L_0.\delta.2\pi hc^2.d\lambda}{\lambda^5[exp^{\frac{hc}{\lambda kT}}-1]} \quad (6)$$

where $\lambda_i = 380nm\ and\ \lambda_f\ = 760nm$ are wavelengths perceptible to the eye, that is the wavelength range of visible spectrum, and best at 555nm; 683 is the lumen for one watt. Upper limit wavelength for violet in visible spectrum is 380nm while 740nm is its lower limit wavelength. $\varepsilon_{visible}$ is emissivity of visible spectrum due to eye perception, r_0 is radius of filament, l_0 is length of filament, δ is a correction factor in the formula of uncoiled surface area of filament (Leff, 1990 and Agrawal, 2017), c is the speed of light, h and k are Planck's constant and Boltzmann's constant, respectively.

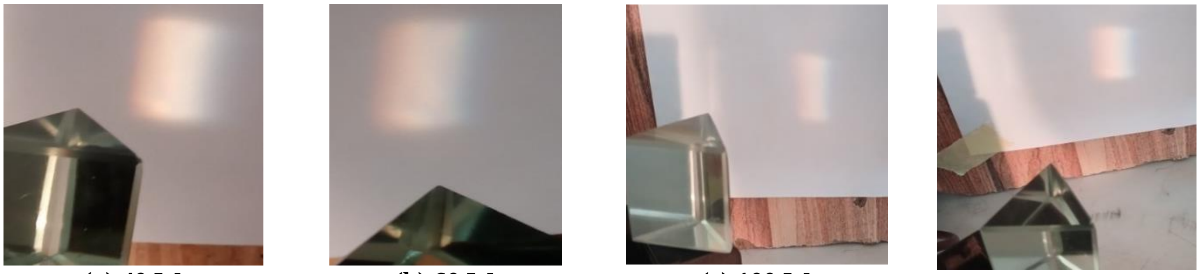
MATERIALS AND METHODS

Commercial frosty incandescent lamps of 40W, 60W, 100W and 200W, line voltage of 220V alternating current (a.c.), voltage stabilizer, equilateral triangular glass prism, digital multimeter, thermometer, micrometer screw gauge, hacksaw blade and screen were used for the experiment.

Tungsten filament resistances were measured using a digital multimeter through the incandescent lamps at the laboratory temperature when they were not in use. The ambient temperature was also recorded before the commencement of the experiment. In view of the expected outcome of the experiment which has its significance on colour separation, the lighting points in the laboratory were switched off in order to acquire sharp colour contrast on the screen. The experiment relied solely on the ambient illumination of the day. Controlled-source rays of light from the powered lamp were made to pass through the triangular glass prism.

Separation of light into various colour components of visible spectrum was accomplished on the screen for the various lamps (Plates 1a, b, c and d). The tungsten filament diameters were measured using the micrometer screw gauge after carefully dissecting the bulbs with a hacksaw blade. The tungsten filament is a series of closely spaced coils when viewed under a magnifying lens.

RESULTS AND DISCUSSION



(a) 40 W **(b) 60 W** **(c) 100 W** **(d) 200 W**

Plates 1a, b, c and d: The separated colours of visible spectrum for the various tungsten filaments of 40 W, 60 W, 100 W and 200 W incandescent lamps respectively by the equilateral glass prism

40 W Incandescent lamp

The resistance of the 40 W Incandescent lamp was 75.0 ohms at 301.0 K. The calculated length of the tungsten filament was 60cm with a measured radius of 12µm and a cross sectional area of 4.52896x10^{-5} m^2. This yielded an intensity of 883204.11 Wm^{-2}.

Table 2: 40 W incandescent lamp

Resistance (Ω)	Temperature (K)	Peak wavelength (μm)	P = $\epsilon\sigma AT^4$ (W)	Intensity (Wm^{-2})	Spec. Emissive Power (Wm^{-2} μm^{-1})
106.88	401.6	7.22	0.03	588.79	81.60
291.23	917.1	3.16	0.73	16008.81	5066.16
535.65	1515.0	1.91	5.41	119216.35	62323.25
796.43	2100.4	1.38	19.99	440464.10	319240.85
982.95	2497.9	1.16	39.99	881070.97	759440.83

From table 2 above, as temperature rises, the peak wavelength falls according to the Wien's law of displacement for blackbody. At a temperature of about 2497.94 K for which the 40 W of tungsten gets fully heated up, its peak wavelength was 1.16 μm with an intensity of 881070.97 Wm^{-2} which is marginally lower than the commercial power rating. Although colour separation of visible spectrum of the 40 W lamp was accomplished, (Plate 1a); the colour contrast across the spectrum is not distinctively attractive.

60 W Incandescent lamp

The resistance of 60 W Incandescent lamp was 60.0 ohms at a room temperature of 301.0 K. The calculated length of the tungsten filament was 75 cm with a measured radius of 15 µm and computed tungsten cross sectional area of 7.07651x10^{-5} m^2. This yielded an intensity of 847875.58Wm^{-2}.

Table 3: 60 W Incandescent lamp

Resistance (Ω)	Temperature (K)	Peak wavelength (μm)	P = $\epsilon\sigma AT^4$ (W)	Intensity (Wm^{-2})	Spec. Emissive Power (Wm^{-2} μm^{-1})
85.50	401.6	7.21	0.04	590.09	81.78
232.98	917.1	3.16	1.14	16044.15	5077.35
428.52	1515.0	1.91	8.45	119479.58	62460.86
637.14	2100.4	1.38	31.23	441436.65	319945.74
774.00	2465.6	1.18	59.31	838106.19	713041.27

The peak wavelength was 1.18μm at 2465.55 K. The total power emitted by the 60 W tungsten filament was 59.31 W producing an intensity of 838106.19 W/m^2. At peak wavelength, the Spectral Emissive Power of 713041.27 Wm^{-2} $\mu m^{-1}$was produced. Though, the colour separation was accomplished but it did not appear brilliant (Plate 1b).

100W Incandescent lamp

The resistance of 100 W Incandescent lamp was 41.0 ohms at a room temperature of 301.0 K. The calculated length of the tungsten filament was 91cm with a measured radius of 20µm and computed tungsten cross sectional area of 1.14622x10^{-4} m^2. This yielded an intensity of 872433.33 Wm^{-2}.

Table 4: 100 W Incandescent lamp

Resistance (Ω)	Temperature (K)	Peak wavelength (μm)	P = $\epsilon\sigma AT^4$ (W)	Intensity (Wm^{-2})	Spec. Emissive Power ($Wm^{-2}\,\mu m^{-1}$)
58.43	401.6	7.22	0.07	590.09	120907.28
159.20	917.1	3.16	1.84	16044.15	276091.03
292.82	1515.0	1.91	13.69	119479.58	456085.78
435.38	2100.4	1.38	50.60	441436.65	632324.78
535.05	2489.1	1.16	99.80	870645.95	749347.91

At a temperature of 2489.14 K, the 100 W lamp had a total emissive power of 99.80 W. Plate 1c shows the quality of colour spectrum captured on the screen with better resolution than in lower wattage lamps.

200 W Incandescent lamp

The resistance of 200 W Incandescent lamp was 44.0 ohms at a room temperature of 301.0 K. The calculated length of the tungsten filament was 103cm with a measured radius of 20.5µm and computed tungsten filament cross sectional area of 1.32467x10^{-4} m^2; yielding an intensity of 1509808.36 Wm^{-2}.

Table 5: 200 W Incandescent lamp

Resistance (Ω)	Temperature (K)	Peak wavelength (μm)	P=$\epsilon\sigma AT^4$ (W)	Intensity (Wm^{-2})	Spec. Emissive Power ($Wm^{-2}\,\mu m^{-1}$)
125.40	710.8	4.08	0.77	5790.96	1420.46
248.91	1250.3	2.32	7.34	55430.53	23915.37
389.40	1807.7	1.60	32.08	242168.00	151055.59
548.11	2395.6	1.21	98.95	746958.29	617463.51
677.60	2852.9	1.02	199.01	1502350.78	1478955.24

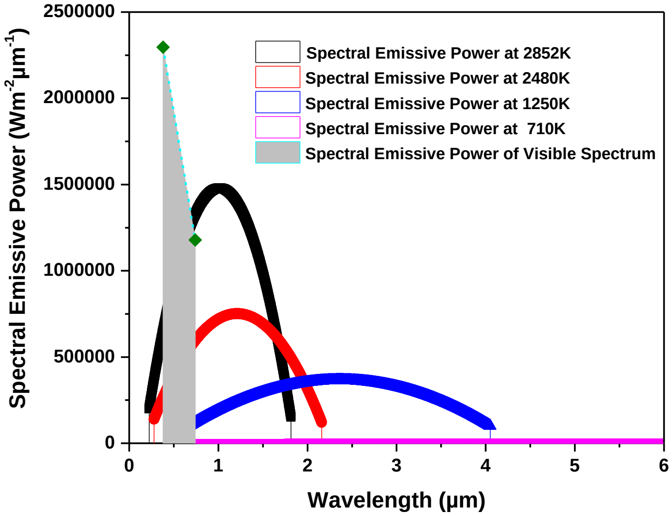


Figure 4: Graph of Spectral emissive powers at various temperatures and visible spectrum

Discussions

The Peak wavelengths of various temperatures were deduced using equation (2). The resistance offered by the filament against the power supply suggests the lamp is close to the definition of a blackbody since heat radiation is both in form of visible light, infra red and probably ultraviolet (Smith and Parmenter, 2016; Chitnis et al., 2016). Intensity of the wire was calculated from the total power dissipated. The surface area of the filament was obtained from the measured radius and calculated length using the expression:

$$l = R\frac{\pi r^2}{\rho} \quad (7)$$

where R is the resistance, r is the radius of wire, ρ is the resistivity from a table (Pawłowski) and l is the wire length.

The filament wattage is given by (Forsythe and Worthing, 1925) as:

$$W = 2\pi r\eta l \quad (8)$$

where η is radiation intensity.

The Spectral Emissive Power arising from Wien's law of displacement which used Pawlowski's temperature-resistance coefficient was juxtaposed with the Spectral Emissive Power of visible wavelength (Smith and Parmenter, 2016; Meseguer, 2012). The comparison of both powers was responsible for deducing the percentage of visible spectrum in a given temperature window for a specific peak wavelength.

The resulting spectral emissive powers of the four tungsten filaments of the incandescent lamps investigated were less than that of the visible spectrum. Although, the colour components of the visible spectrum were successfully separated, they did not appear brilliantly distinct as seen in Plates 1a, b, c and d. However, there was a remarkable improvement in colour contrast and brilliance from plates 1a to 1d. The peak wavelengths of the red and violet colours which are at the upper and lower bounds of the visible spectrum are 0.74 μm and 0.38 μm respectively (Zimmerman, 2020). These values are far higher than the peak wavelengths of radiation of the tungsten filaments. These translate to higher spectral emissive power in view of larger areas covered (Zwinkels, 2015). The commercial power rating of each filament served as a constraint while generating parameters like total power emitted, intensity and spectral emissive power. Both Wien displacement law and Stefan Boltzmann's expressions were deployed in generating peak wavelengths at given temperatures and spectral emissive power respectively.

The 200W tungsten filament has the most brilliantly separated visible colour combinations. The colour contrasts were sharpest and easily distinguishable. This brilliance arose from the intensity of 1502350.76 W/m^2 produced by this lamp at 2852.87 K (Pawłowski; Zanetti,1985) at its peak wavelength which stood at 1.016 μm. This was the closest peak wavelength to the red colour wavelength - the longest in the visible spectrum.

The tungsten filament of an incandescent lamp absorbs the power fed to it but failed to wholesomely emit same. Thermal emission compliments absorption. Internal molecular energy from the heating is transferred to photon radiation process. Photon from heated filament exhibits continuous spectrum. Figure 4 shows that the bulk of the power emitted falls within the infra red portion because a large quantity of the radiation has a longer wavelength than that of the visible light; comparison of their wavelengths shows (Zimmerman, 2020 and Roberts, 2005) . The various curves corresponding to different temperatures grazed the visible spectrum stock as seen on the graph. Curves representing higher temperatures with higher intensities and spectral emissive powers grazed larger areas of the visible spectrum stock. This implies that the larger the area grazed by the temperature curves, the better the resolution of the visible spectrum produced at the reference temperature and vice-versa (Meseguer, 2012) . A little portion of visible spectrum was grazed at the temperatures reached for each filament compared to each curve's occupied area in relation to Planck's curves for black bodies. The failure of the tungsten filament to absorb all the radiation it emits makes it as a non-black body (Chitnis, 2016). Furthermore, the production of visible light arising from the power supplied accounts for some reflection coefficient (Hu and Lucyszyn, 2015). The foregoing reason affirms the inefficacy of the tungsten filament incandescent lamp for use as source of light, though with the possibility of improving on it and deploying it for other uses.

The juxtaposition of the visible spectrum's power and emission plots at various temperatures sheds light on the approximate portion of visible spectrum that may be produced in a working incandescent lamp. The curve at 710 K failed to show any peak wavelength on the plot due to the chosen scale.

CONCLUSION

The power generated by the visible spectrum was approximately fourteen percent (14%) of the total power emitted by the tungsten filament leaving the balance in the form of infra red radiation. This has again confirmed that tungsten filament is not a perfect black body since only a small fraction of the power dissipated in it is in form of visible spectrum. Therefore, a tungsten filament may be considered as a quasi black body.

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