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Colour Temperature measurement of Light Sources using a Silicon Solar Cell

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Abstract

A subject's colour is usually not consistent under different types of lighting. A white subject can appear reddish at sunrise or sunset, and blue-greenish on cloudy days. Colour changes results from different colour temperatures. This paper shows the experimental method of calibration of silicon solar cell and measurement of colour temperature of light sources. A silicon solar cell is calibrated for its spectral efficiency and subsequently it is used for measurement of colour temperatures of incandescent light sources of unknown colour temperature. A light source of known colour temperature and a series of interference filters are made use of for the calibration. Solar cell efficiency was normalised to particular wavelength. The root mean square deviation for all the wave lengths were calculated and plotted against the colour temperature. From the curve between colour temperatures and r.m.s deviation, colour temperature was obtained and it agrees very well with temperature of lamp for the known voltage.

Keywords: Silicon solar cell, Colour temperatures, Interference filters, Solar cell efficiency, Root mean square deviation.

Introduction

It is very important to know the colour temperature of the light source used in photographic, photonic and colour matching applications. For example, in colour photography, the light sources used should have colour temperatures very close to the values (~ 100K) specified for the particular film used for obtaining the best result in photography. In sensitometric exposure to photographic materials or X-ray radiographic materials, it is essential to specify the colour temperature of the source used.

The variety of sources are available on the market for their use in photographic, photonic and colour matching applications. Scientists involved with the practice of visual colour matching should be able to determine which light source is the best to use. The actual decision is rather difficult. So, choosing the light sources is an integral part of establishing the procedure. GTI Graphic Technology, Inc., in 2012 published that viewing system may not conform to specified standards[1] for the commonly available commercial lamps as well as lamps from another standardized light manufacturer. There are several specific conditions to meet when designing light sources as per the ISO 3664:2009 standard. When electricity is passed through a filament of an incandescent tungsten lamp, the filament glows. A quartz halogen lamp is a tungsten incandescent lamp which is very common and is used in colour matching applications. A yellowish to red source is required in colour matching application.3200K Tungsten A-Red/Yellow is used primarily in the photographic film and video industries where a "whitish" source and continuous light output are required. It is not commonly used for colour matching applications. 2865K Illuminant A- Yellowish Red- is a standardized illuminant described in the international standard, CIE Publication and specified for use in colour matching applications. It is the predominant source used for both instrumental and visual colour matching applications.

2300K Horizon-Reddish Source is used for colour matching applications. It is known that Light output and colour temperature of a tungsten lamp vary greatly with the voltage. So colour matching systems using these lamps must employ voltage stabilization circuits for obtaining the stability of colour temperatures. But it is very difficult to maintain the overall stability of light output and colour temperature of tungsten lamps for a reasonable amount of time.

One can define the colour temperature as the temperature of an ideal black-body radiator that radiates light of comparable hue to that of the light source. It describes the quality of light, as far as its spectral distribution is concerned. For tungsten filament lamps, which are by far the largest used in photography and colour matching applications, there can be wide variation of T, from batch to batch and depending on the operating voltage. Thus precise matching of lamps can be done only by calibrating them and maintaining the appropriate voltage to give the same colour temperature.

Normally colour temperature is measured by use of instruments called pyrometers in which the source colour is matched, in a viewing device, with that of a heated filament and voltage applied to the filament at the point of disappearance is calibrated to the colour temperature of the source[2]. This depends on the calibration of the internal filament and is likely to show erroneous readings with the aging of the filament.

The measurements described here make use of the fundamental properties of thermal radiators and so are likely to be more accurate and reliable.

Principle of the technique

In series of experiments using narrow-band interference filters, spectral regions are isolated and the relative energies in the visible spectrum are compared using a silicon solar cell. Once the spectral distribution is found, it is possible to fit this data into a theoretically calculated curve, the assumed temperature of which is the temperature of the source.

The energy radiated per second per unit range of wavelength at wavelength λ from one sq.cm of a full radiator[3] is expressed as

$$E = 2\pi hc^2x^2\lambda^{-5} / (e^{hc/\lambda kT}-1)$$

Or

$$E = C_1\lambda^{-5} / (e^{C2/\lambda T} -1) \qquad (1)$$

Where: C_1 and C_2 are constants respectively equal to $2\pi hc^2$ and hc/k where h is the Planck's constant, c is the velocity of light and k is the Boltzmann's constant. The values of $C_1 = 3.74 \times 10^{-5}$ erg cm^2 sec^{-1} and $C_2 = 1.4380$ cm deg.

For a given values of λ and T, the energy distribution can be calculated from the above formula.

The silicon solar cell is a device to measure light intensities. It is basically a very convenient and inexpensive photodiode optimised for solar radiations. When radiation is incident at the p-n junction of this solar cell, electron–hole pairs are created. The flow of these carriers produces a short circuit current proportional to the incident light intensity. However, the sensitivity of the solar cell differs at different wavelengths and therefore it is necessary to calibrate the cell for its efficiency at different spectral regions. This can be done with a known temperature source and appropriate filters. The short circuit current can be measured by connecting the cell across a micro ammeter.

The normalised value of the cell current multiplied by the efficiency at the appropriate wavelength is then compared with the normalised theoretical values using Equation (1).

The experimental technique

A lamp, condenser lens, interference filter solar cell are arranged in a optical bench. Light from the Lamp (calibrated in case of solar cell efficiency determination) falls on condenser C, which condenses the light on to the solar cell S. Interference filters are introduced in between condenser lens and solar cell making sure that the light beam does not converge sharply through the filter. This is because the wavelength transmission of the interference filters is strongly dependent on the angle of incidence and hence it is to be positioned only in the near-normal incidence. The solar cell, suitably mounted, is positioned, in such a way that it receives only light transmitted by the filters. A micro ammeter (0-100μA) measures the solar cell current. The lamp is operated from A.C. mains through a variac which selects the desired voltage. The voltage output from the variac is continuously monitored with a digital meter so that the output voltage does not vary by more than 0.2 V between any set of measurements.

The lamp used for the calibration of the solar cell was a Philips 115 Volt 500 Watts filament lamp. The lamp has been calibrated in terms of voltage versus colour temperature as given bellow in Table-1.

Table-1
Voltage versus colour temperature

Temp (K)	Voltage (V)
3000	98.5
2850	87.0
2700	76.3
2660	73.5
2360	53.4

The leads of the lamp have been directly soldered on to avoid any drop at the contacts.

The desired wavelength range was selected using a series of interference filters from M/s Schott, German. The peak transmission and the half width of transmission through each filter was independently evaluated in spectrophotometer. Since these two parameters were different for different filters the total area of the curves for each filter was taken as a single parameter for calculating the transmission.

The Solar Cell obtained from local electronic shop was of 25 mm X 25 mm size. The light intensities were adjusted using neutral density filters, so that the maximum current from the cell was measured to be about 93μA. A 0-100 micro ammeter is connected across the solar cell to measure the current directly.

For each setting of the lamp voltage, the current reading was accurately noted for each filter and the average value of several observations was used for the calculation.

Results and Discussion

The energy values for known T and λ were calculated as per equation (1). These energy values were multiplied by the area of the transmission curve for the appropriate filler. Finally these energy values were normalised to λ = 750 nm and taken as 100 as the theoretical relative energy values.

The observed value of the solar cell current was normalised in such a way that the current for 750nm was taken as 100.

For each wavelength λ, the efficiency is given by the formula $\frac{\text{Observed value X 100}}{\text{Theoretical value}}$

The experiments were repeated for several known temperatures and average value of the solar cell efficiency for each λ was obtained.

Table-2 shows the average value of the solar cell efficiency and Figure-1 shows the relative efficiency curve from the actual traces for the various filters. (Even though the silicon solar cell has a max. efficiency at about 850nm, we have normalised the efficiency to 750nm. In our measurements we are limiting to this wavelength which is the limit of the conventional visible spectrum). This curve is traced for silicon solar cell and agrees well with other similar measurements[4].

Table-2
Average value of solar cell efficiency

(λ)	Solar Cell Efficiency
(nm)	**(%)**
400	21.00
425	29.00
450	37.00
475	47.00
500	55.00
525	63.00
550	72.50
575	74.00
600	75.50
625	81.00
650	82.50
675	85.50
700	87.50
725	92.00
750	100.00

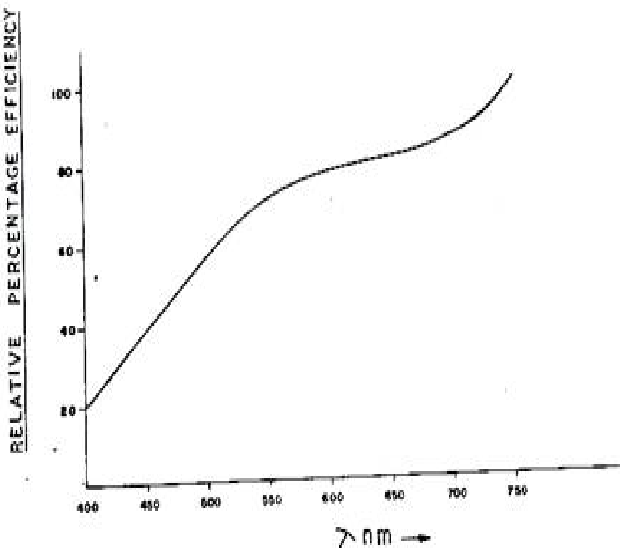

Figure-1
Relative efficiency curve of the solar cell

Finding the Unknown Temperature

The lamp in this case was operated at a voltage corresponding to an unknown temperature and the current readings were taken as usual with the various filters. Using these values and with the previously found out efficiency values, the normalised current readings were calculated.

These values should then be proportional to the energy at the unknown temperature. To find out the temperature at which the best fit is obtained, we proceeded as follows.

The normalised theoretical value for various temperatures at 10^0 K interval was computed and in all cases the parameter (observed value- Theoretical value) was calculated as the deviation.

The root mean square deviation for all the wavelengths were also calculated and plotted against the temperature. The minimum of this curve was taken as the unknown temperature.

Table-3 shows a set of readings. In this case the minimum of the R.M.S value occurs for 2820^0 K as shown in Figure-2(a) and hence this is taken as the temperature of the source. Figure-2(b) shows the calibration of lamp for its colour temperature versus operating voltage.

This method was tested for lamps of known colour temperature and was found to agree well.

Table-3
Deviation (Observed value-Theoretical value)

λ nm / Temp-K	**700**	**650**	**600**	**550**	**500**	**450**	**RMS**
2800	1.36	0.69	9.89	6.79	1.13	2.53	1.74
2810	1.15	0.33	9.46	6.34	0.61	2.23	1.60
2820	0.94	-0.12	9.03	5.88	0.08	1.92	1.54
2830	0.78	-0.58	8.65	5.43	-0.45	1.62	1.57
2840	0.53	-1.03	8.16	4.98	-0.99	1.30	1.68
2850	0.33	-1.48	7.73	4.53	-1.52	0.98	1.86

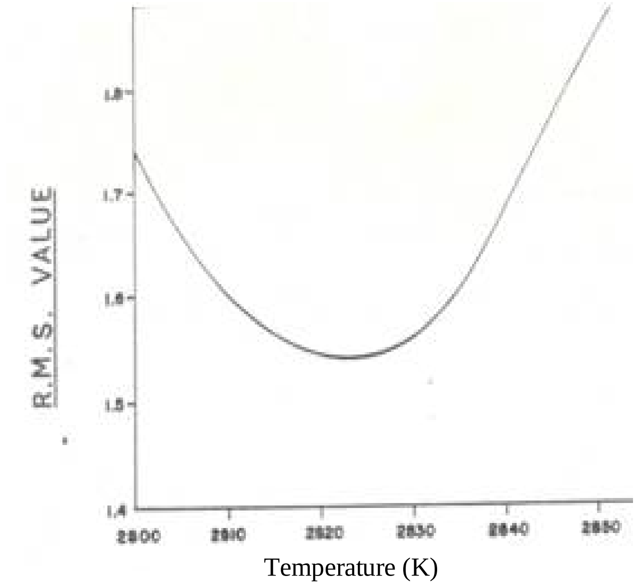

Figure-2(a)
r.m.s deviation versus temperature

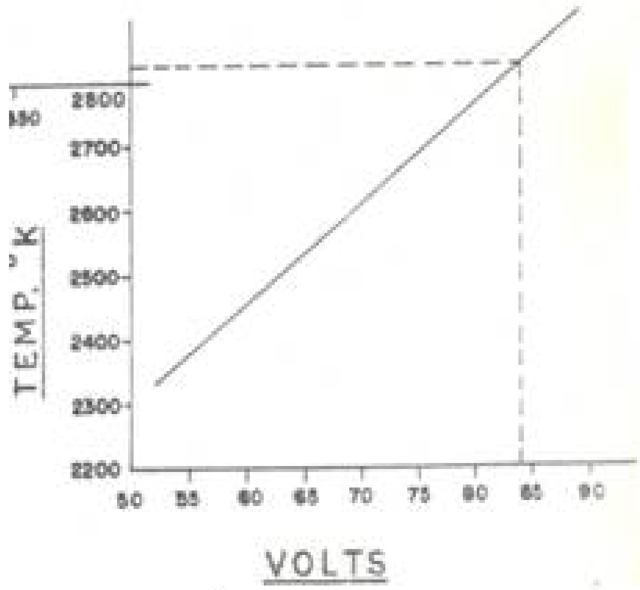

Figure-2(b)
Colour temperature versus operating voltage

Discussion: A laser-based instrument have been developed by Researchers at the National Institute of Standards and Technology (NIST), which generates artificial sunlight to help test solar cell properties. It finds the ways to boost the efficiency of solar cells[5]. This novel NIST system simulates sunlight well across a broad spectrum of visible to infrared light. This simulator is based on a white light laser.

It uses optical-fibre amplifier technology to boost the power and a photonic crystal fibre to broaden the spectrum. NIST researchers used the simulator to measure the efficiency of thin-film solar cells made of gallium-arsenide, crystalline silicon, amorphous silicon and copper-indium-gallium-selenide and the results agreed with independent measurements. Recently Dhonde Mahesh and Jaiswal Rajesh[6] have introduced polymer materials in DSSC (Dye Sensitised Solar Cell) which opens up an interesting research field with a high potential. Polymeric materials are less expensive, lighter and consume less energy for their large scale production, making these cells more environmental friendly.

Conclusion

Colour temperature measurement of light sources has been taken very carefully using the highly efficient solar cells which has been calibrated by us. This attempt has been proved to be a successful method to find the colour temperature of unknown sources. In near future the present experiment can also be tried by finding efficiency of solar cell with the help of laser and improvement can be observed. Experiments with solar cells of DSSC polymeric materials also can be tried in future.

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