SPECTRAL CHARACTERISTICS AND PERFORMANCE ANALYSIS ON BLACKBODY RADIATION FOR GAS LEAKAGE & FIRE DETECTION SYSTEM

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ABSTRACT

In view of importance of "*BLACKBODY*" radiation phenomenon for the purpose of investigation and practical purposes here I presented variation (changes) of some parameters with respect to some other parameters like *wavelength*, spectral radiance, spectral density, emissivity, temperature. In this article I focused mainly on *BLACKBODY* radiation method because of its numerous functions and applications in the field of *Gas leakage &Fire detection system* and other investigations. In addition to this I have presented spectral characteristics like *wavelength vs. spectral density, emissivity vs. radiation energy, wavelength vs. spectral radiance* at different temperatures and different wave lengths i.e. in stage I of the process temperature is kept constant for different wavelengths and measured spectral radiance and in stage II process temperature is changing and kept constant for different wavelengths(by considering low wavelengths in one section and higher wavelengths in other section). This paper also presented the importance of *Rayleigh-Jeans law* for blackbody radiation method. Finally this article presented performance analysis of *BLACKBODY* radiation in terms of tabular forms and graphs.

***Keywords**: Spectral characteristics of Blackbody; Spectral density; Spectral response; radiation energy; Rayleigh-Jeans law.*

Introduction

The term *BLACKBODY* was introduced by Gustav Kirchhoff in 1860. Black-body radiation is also called thermal radiation. Cavity radiation or temperature radiation. Blackbody radiation is the method of radiation in which it radiates electromagnetic waves inside and surrounding the body, the body under thermodynamic equilibrium condition in the environment is one of the crucial things in the analysis of blackbody radiation method [1]. This has a specific, continuous electromagnetic spectrum of various wavelengths, in which some parameters are changing inversely proportional and some parameters are changing directly proportional. In the performance analysis some parameters are kept constant while measuring other parameters, this phenomenon was very clearly described in the tabular forms as well as in the graphical representation.

A *BLACKBODY* was investigated at different temperatures and different wave lengths by keeping one of the parameters is kept constant Emissivity of *BLACKBODY* =1). In the graphical representation ultraviolet region, visible region (with different colors), infrared region was represented very clearly. If the temperature increases above absolute 0k(Kelvin) every object emits electromagnetic radiations. When the temperature of the body changes then distribution of radiated energy also changes, according to Blackbody radiation (plank's law), these relations are clearly explained in[7] section III of this article.

In *BLACKBODY* radiation is emitted according to Plank's law, this law describes the spectral density of electromagnetic radiation emitted by a *BLACKBODY* in thermal equilibrium at a given temperature (T), this was explained clearly in section III, according to the principle of thermal equilibrium, there is no net flow of thermal energy between them (i.e between two ends of object or between two objects) [1] [2].

Under thermal equilibrium condition an Ideal blackbody has two prosperities as mentioned below, i)It acts as An ideal emitter , which emits energy isotropically i.e. energy radiated equally in all the directions. ii) It acts as a diffuse emitter, in which the emitted radiated intensity is independent of direction. So we conclude that a *BLACKBODY* is not only ideal emitter, but also acts as a diffuse emitter [1] [2].

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I. Blackbody radiation methods (BBR) & their Performance Characteristics.

a. Temperature measurement

It is one of the prominent methods for measuring temperature using optical fiber. This “Blackbody radiation method” uses an optical fiber cable with photo detector for realization with low cost. We can design a photo detector with a temperature range of 500 to 1200^{o}C. In case of high temperature range, we use sapphire fiber [3].

A blackbody is having special property of absorbing all wavelengths of light, due to this reason No light is reflected and this is the reason for appearing *black* at low temperatures. A blackbody will emit a spectrum of photon energies that exists in the visible range. For example, the SUN is the high temperature blackbody [3].

“Blackbody” everybody (or) object with non-zero (having some value of temperature except zero value) surface temperature radiating (emitting) certain quantity of energy. Most of the energy is radiated by the so- called “Blackbody radiation” (BBR).The amount of radiated energy and its spectrum depends on the body temperature, mathematically it can be represented by “Planks blackbody emission law” [1] [2] [3] [4].

The radiation from the BLACKBODY is Lambertian. So the total emission into the half of the sphere is given by the product with 2∏

b. Spectral density of radiation intensity measurement

$r(\lambda) = hv^2 / \lambda^2 e^{hv/(KT-1)}$ (1)

$v = C/\lambda$ (2)

Where h=planks constant = 6.626×10^{-34} JS

Boltzmann’s constant (K) = 1.38×10^{-23} J/K

λ = Wavelength

T= Temperature

C = speed of light = 3×10^{10} cm/sec

This radiates signal can easily used for the optical measurement of the body temperature. According to the Stefan- Boltzmann’s constant, the increase of total radiated depends on the absolute temperature with the fourth power [5] [6].

Total radiated energy $E = \sigma T^4$ (3)

Stefan- Boltzmann’s constant $\sigma = 2\pi^5 \cdot K^4 / 15C^2.h^4$

$= 5.670400 \times 10^{-8}$ J/S/m^2/K^4

When the temperature of the body changes the distribution radiation energy also changes, according to Blackbody radiation (Plank’s law), the relation between these parameters is given by[7]

$\lambda_P . T = 289.79$ (4)

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λ_P= Peak sensitivity wavelength (μm)

T = Absolute temperature

c. Spectral radiance of Blackbody Vs Wavelength (λ)

This section presents the variation of Spectral radiance of Blackbody in terms of low wavelength and high wavelength. Radiation energy density can be measured with the help of Rayleigh Jeans law. This section also presents the variation of Spectral radiance of Blackbody with respect to lower wavelength and higher wavelength as shown below.

Rayleigh Jeans law

In case of short-wave spectral region Rayleigh-Jeans law is applicable. According to this law the radiation energy density at the λ interval is given by

$$r(\lambda)\, d\lambda = 8\pi KTd\lambda / \lambda^4 \qquad (5)$$

for example, a blackbody at room temperature (300k) with one-meter square surface area will emit a photon in the range of visibility(390-750nm), at an average rate of one photon for every 41 seconds [14] [15].

Spectral Radiance of Blackbody versus Low Wavelength at different temperatures (300k, 1000k, 1300k), Emissivity remains constant i.e.,

The spectral radiance of blackbody increases with increase in wavelength, here the behavior of spectral curve changes very interestingly at low wavelength by keeping temperature and emissivity constant. A Drastic change in spectral radiance can be observed at 0.390 micrometers at 300k,1000k,1300k similarly at 0.500 micrometers,0.750 micrometers. This can be understood very clearly by observing ***Table 1a 1b,1c & Fig 1a, Fig 1a ,Fig 1c respectively.(attached files of tables and graphs)***

Table 1.a *Wavelength(low) vs. Spectral radiance (Temperature kept constant at 300k and Emissivity=1)*

S.no	Wavelength(um)	Spectral radiance
1	0.390	5.184e-44
2	0.500	8.40423e-33
3	0.750	8.50291e-20

This table shows variation of Spectral radiance with wavelength (Temperature kept constant at 300k and Emissivity remains constant i.e., 1)

Table 1.b *Wavelength(low) vs. Spectral radiance (Temperature kept constant at 1000k and Emissivity=1)*

S. no	Wavelength(um)	Spectral radiance
1	0.390	1.2555e-06
2	0.500	0.00121368
3	0.750	2.34048

This table shows variation of Spectral radiance with wavelength (Temperature kept constant at 1000k and Emissivity remains constant i.e. 1)

Table 1.c *Wavelength(low) vs. Spectral radiance (Temperature kept constant at 1300k and Emissivity=1)*

S. no	Wavelength(um)	Spectral radiance
1	0.390	6.25e-04
2	0.500	92.901
3	0.750	1.96 e +02

This table shows variation of Spectral radiance with wavelength (Temperature kept constant at 1300k and Emissivity remains constant i.e. 1)

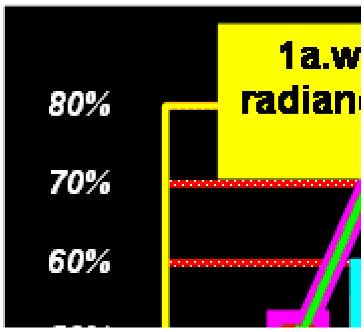

Fig 1a

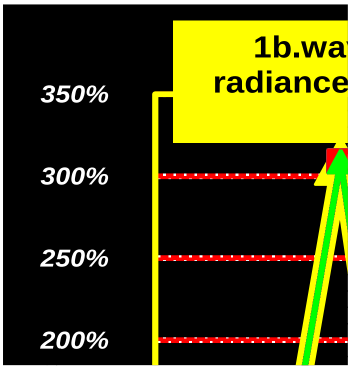

Fig 1b

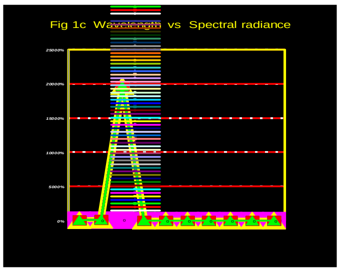

Fig 1c

Fig1a: Spectral radiance of Blackbody vs. Wavelength (low) at temperature T=300k, Emissivity €=1

Fig1b: Spectral radiance of Blackbody vs. Wavelength (low) at temperature T=1000k.Emissivity €=1

Fig1c: Spectral radiance of Blackbody vs. Wavelength (low) at temperature=1300k. Emissivity €=1

Spectral Radiance of Blackbody versus High Wavelength at different temperatures (300k, 1000k, 1300k), Emissivity remains constant i.e. 1(Refer Table 1d -1f & Fig 1d-Fig 1f)

The spectral radiance of blackbody increases with increase in wavelength, here the behavior of spectral curve changes very interestingly at high wavelength by keeping temperature and emissivity constant. A Drastic change in spectral radiance can be observed at 0.1 micrometers at 300k,1000k,1300k similarly at 10 micrometers, 100 micrometers. This can be understood very clearly by observing ***Table 1d, Table 1e, Table 1f & Fig 1d, Fig 1e ,Fig 1f respectively.(attached files of tables and graphs)***

Table 1d. *Wavelength(high) vs. Spectral radiance (Temperature kept constant at 300k and Emissivity=1)*

S. no	Wavelength(um)	Spectral radiance
1	0.1	6.20906e-196
2	10	9.92435
3	100	0.01935

This table shows variation of Spectral radiance with high wavelength (Temperature kept constant at 300k and Emissivity remains constant i.e. 1)

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Table 1e. *Wavelength(high) vs. Spectral radiance (Temperature kept constant at 1000k and Emissivity=1)*

S. no	Wavelength(um)	Spectral radiance
1	0.1	3.8999e-50
2	10	370.407
3	100	0.0769697

This table shows variation of Spectral radiance with high wavelength (Temperature kept constant at 1000k and Emissivity remains constant i.e. 1)

Table 1f. *Wavelength(high) vs. Spectral radiance (Temperature kept constant at 1300k and Emissivity=1)*

S. no	Wavelength(um)	Spectral radiance
1	0.1	1.0248e-35
2	10	588.316
3	100	0.101771

This table shows variation of Spectral radiance with high wavelength (Temperature kept constant at 1300k and Emissivity remains constant i.e. 1)

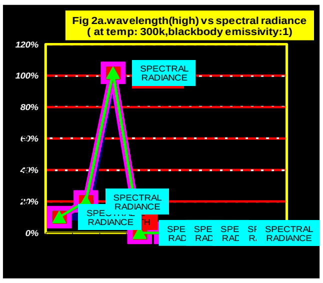

Fig 1d

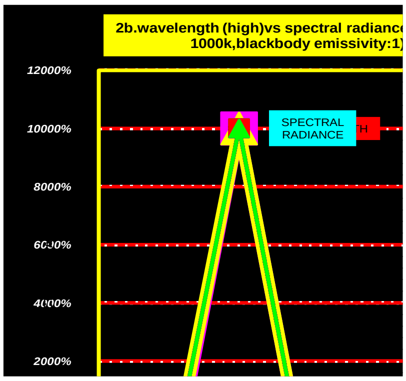

Fig 1e

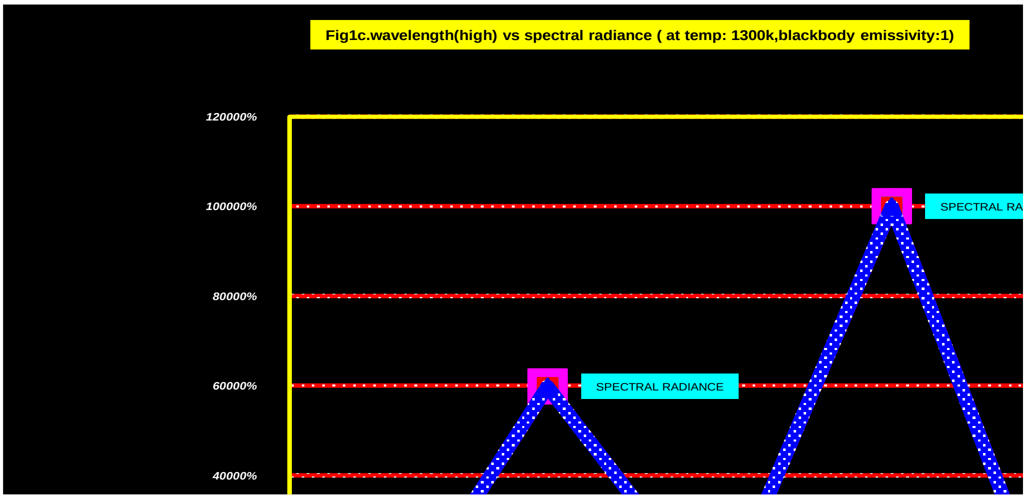

Fig 1f

Fig 1d : Spectral radiance of Blackbody vs. Wavelength (high) at temperature T=300k, Emissivity €=1

Fig 1e: Spectral radiance of Blackbody vs. Wavelength (high) at temperature=1000k.Emissivity €=1

Fig 1f: Spectral radiance of Blackbody vs. Wavelength (high) at temperature=1300k. Emissivity €=1

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As the temperature of a *blackbody* decreases, its intensity also decreases and its peak moves to wider wavelengths. It was shown for comparison is the classical Rayleigh-Jeans law and its catastrophe [14] [15].

From the Spectral characteristics of ***Wavelength vs. Spectral radiance*** we concluded that Spectral radiance increases with increase in Wave length up to some level (peak level), after reaching maximum level/peak level Spectral radiance gets reduced even though we increase the wavelength. This phenomenon observed at different temperatures and different wavelengths. (*Blackbody* taken as reference).

II. Signal detection for Blackbody radiation method & its Performance Characteristics.

a. Introducing Optical fiber for Blackbody radiation method

A better quality and performance Optical fiber cable is capable to transmit or propagate signal to the receiver /detector to a maximum extent/level [5]. It can be achieved through maximum possible (largest) diameter of the core with low cost; here we can use 62.5 µm MM fibers. The FOC is also capable of measuring temperature directly (This phenomenon very much useful in fire detection)

Fiber deformation (change in the dimensions of fiber) takes place at melting point. so at higher temperatures we can use sapphire fibers(combination of sapphire crystal Al_2O_3 and Optical fiber flexibility[6]..

Power density = $PxG/4\pi D^2$ (7)

P= Output power

G= gain

D= Distance

b. Signal detection for Blackbody Radiation Method

At receiver or detector, we use spectrometer to evaluate the measured temperature (or) spectrum. In this process we can measure signal amplitude of the photo diode [5] [6].

Power spectral density is given by

PSD = Power / BW (8)

The analysis between Wave lengths of different regions of the electromagnetic spectrum and their respective Power spectral densities respectively [7] (In this analysis Signal power is assumed to be 40db). The signal detection for BLACKBODY can be understood very clearly by considering the wavelengths of Ultraviolet, Visible range of colours, Infrared and their Power spectral densities (calculated manually). The power spectral densities decrease with increase in wavelengths under different regions of spectrum. We can observe this phenomenon from both pictorial representations [8] and Analytical values from **Fig2a**, **Table 2a respectively (from the attached files of Tables and Figures.)**

Table 2a Ultraviolet, Visible and Infrared regions of spectrum

Spectral region	Range of wavelength in nm	Wavelength average value	Power spectral density	Sub region/colour
Ultraviolet	100-280 280-315 315-380	190 297.5 347.5	0.2105 0.1344 0.1151	UV-C UV-B UV-A
Visible	380-430 430-500 500-520 520-565	405 465 510 542.5	0.0987 0.0860 0.0784 0.0737	Violet Blue Cyan Green

	565-580 580-625 625-740	572.5 602.5 682.5	0.0698 0.06639 0.0586	Yellow Orange Red
Infrared	740-1400 1400-10000	1070 5700	0.03738 0.0070	Near IR Far IR

This table shows the Wavelengths of different regions of electromagnetic spectrum (Ultraviolet, Visible, and Infra-red) vs. Power spectral densities.

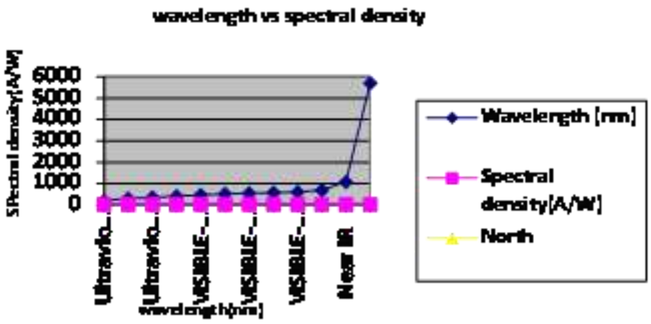

Fig2a: Graph drawn between Wavelengths of different regions of electromagnetic spectrum (Ultraviolet, Visible, infra red) vs. Power spectral densities.

From the graph we concluded that power spectral density gets reduced by increasing wavelength (under different regions of the spectrum i.e. Ultraviolet, Visible, Infrared regions. We can observe this phenomenon from both pictorial representations [8]. (Fig3& tabular form)

III. Dependency of Wavelength, Radiated energy on Emissivity.

a. Emissivity vs. Wavelength

Emissivity

Emissivity is the important factor in radiation thermometry. It is defined as the ratio of the radiance of the object given to that of blackbody at the same temperature and for the same spectral characteristics and directional conditions [9]. Emissivity is the function of wavelength and temperature, there is a correlation between emissivity, temperature, wavelength and radiated energy. So we must consider these factors before analyzing any of these factors.

Thermal sensors measure the emitted temperatures of the objects. The real kinetic temperature values of the objects can be measured/estimated by the radiant temperature if the emissivity of the object is known [10].

For normal incidence, the emissivity €(λ) of a plane-parallel specimen is given by

$$€ (\lambda) = [1-R(\lambda)]\ [1-T(\lambda)]\ /\ [1-R(\lambda)T(\lambda)] \qquad (8)$$

Where R (λ) is true reflectance, λ is the wavelength; T (λ) is the true transmittance. Where true reflectance and transmittance is related to the optometry [10].

Dependency of Wavelength on Emissivity

All objects at temperatures above absolute zero emit thermal radiation. However, for any particular wavelengths and temperatures, the amount of thermal radiation depends on the emissivity of the objects surface [11].

Emissivity measured with the help of spectroscope by determining the ratio of the energies emitted by the surface divided by that emitted energy by a neighboring blackbody [12].

Total radiated energy $W = €\sigma T^4$ (9)

Where W = radiated energy

Total radiated energy $E = \sigma T^4$ (10)

Ϭ (Stefan- Boltzmann's constant) = $2\pi^5 \cdot K^4 / 15C^2.h^4$

$= 5.670400 \times 10^{-8}$ J/S/m^2/K^4

€ =0 to 1(1 for blackbody, 0 for reflecting body, <1 for gray bodies) our concentration on blackbody.

Emissivity normally varies with wavelength. The emissivity of polished metals tends to reduce as wavelength increases [12][13].

b. Emissivity vs. Radiated energy

Radiated energy depends on the type of material[12] [13]we used because different types of materials having different emissivity's. Radiate energy is 0 incase of Perfect reflector and very high value in case of BLACKBODY i.e 371608.78 at 1600 degrees, this was proved analytically and graphically. Similarly, the radiated energy increases with increase in Emissivity of different materials (increasing order of Emissivity) like polished copper, polished gold, polished aluminum, silicon, Black paint. Radiated energy values with respect to Emissivity. These emissivity values are clearly described in **Table 3a, Fig3a(from the attached files of Tables and Graphs.**

Table 3a *Emissivity vs. Radiated energy*

Type of material	Emissivity (€)	Radiated energy (at 800º	Radiated energy (at 1200º	Radiated energy (at 1600º	Radiated energy (at 2000º
Polished aluminum	0.04	929.02	4703.17	14864.35	36289.92
Polished copper	0.025	580.63	2939.48	9290.21	22681.2
Polished gold	0.03	696.766	3527.38	11148.26	27217.44
Black paint	0.9-0.95	20902.98	105821.46	334447.9	816523.2
silicon	0.71	16490.13	83481.33	263842.23	644146.08
Blackbody	**1**	23225.54	117579.34	371608.78	907248
Perfect reflector	**0**	0	0	0	0

This table gives the clear explanation of how radiated energy changes for different materials with different emissivity's at different temperatures.

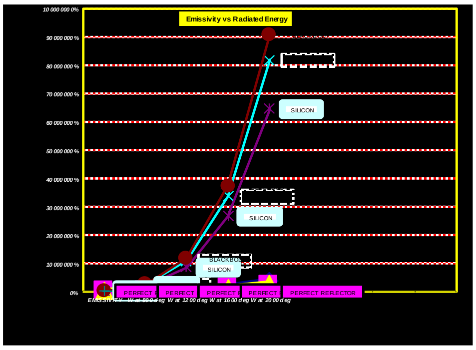

Fig3a: Spectral characteristics between Emissivity *vs. Radiated energy* at different emissivity with different temperatures T=800k,1200k, 1600k, 2000k (keeping temperature constant at any one said and measure Radiated energy)

At constant emissivity radiated energy increase with increase in temperature where emissivity is lessthan1, here it shows maximum emissivity takes place in the case of blackbody i.e. €= 1,W = 907248 and minimum emissivity takes place in the case of perfect reflector i.e €= 0,W = 0

Results and Discussions

1) From the Spectral characteristics of Wavelength vs. Spectral radiance we concluded that Spectral radiance increases with increase in Wave length up to some level (peak level), after reaching maximum level/peak level Spectral radiance gets reduced even though we increase the wavelength. This phenomenon observed at different temperatures and different wavelengths. BLACKBODY taken as reference.
2) From the Spectral characteristics of Wavelength vs. Spectral density we concluded that power spectral density gets reduced by increasing wavelength (under different regions of the spectrum i.e. Ultraviolet, Visible, Infrared regions. We can observe this phenomenon from both pictorial representation (Fig3& tabular form)
3) At constant emissivity radiated energy increase with increase in temperature where emissivity is lessthan1, here it shows maximum emissivity takes place in the case of blackbody i.e. €= 1,W = 907248 and minimum emissivity takes place in the case of perfect reflector i.e. €= 0,W = 0
4) From the Spectral characteristics between Emissivity vs. Radiated energy at different emissivity with different temperatures T=800k,1200k, 1600k, 2000k (keeping temperature constant at any one said and measure Radiated energy). Here we concluded that radiated energy increases with increase in emissivity as well as temperature, Blackbody having highest emissivity and reflecting surfaces having zero emissivity and zero radiated energy.

Conclusion

Here my intension is to build up perfect FGS(Fire and Gas safety System).For this purpose these Spectral characteristics and performance analysis on Wavelength, Emissivity, Spectral Radiance, Spectral density, Irradiative energy, Blackbody radiation methods are very useful. These characteristics provide us better platform for better understanding and better analyzing capabilities for designing new systems not only for Fire and Gas safety system.

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