Pisco Med Publishing

Insight - Energy Science, 2018, 1(1) doi: 10.18282/i-es.v1i1.115

Original Research Article

Research and Verification of Blackbody Radiation Law

Xiaoming Lu*, Qishan Tang, Wendong Kang

School of Physics and Information Technology, Dongying Teachers College, Shandong, China
**Correspondence: xiaoming12sl@gmail.com*

ABSTRACT

Blackbody radiation theory is one of the important origins of light quantum theory in the twentieth century. It is not only an important basis for quantum mechanics and photonics theory, but also an important conclusion of blackbody radiation, and an important foundation of modern measurement. In the early nineteenth century, the study of thermal radiation was supported by thermodynamics and spectroscopy, and the rapid development of electromagnetism and optics was used. By the end of the 19th century, it was recognized that both the thermal radiation and the optical radiation were electromagnetic waves, and began to study the distribution of radiant energy in different frequency ranges, especially the study of blackbody radiation in theory and practice. Blackbody radiation experiment is one of the contents of modern physics experiment in colleges and universities. This paper mainly studies and validates the law of blackbody radiation by the WGH-10 blackbody experimental device. There is already a calibrated bromine tungsten lamp energy curve at 2940k. At the beginning of the experiment, we should scan at 2940k color temperature to get the baseline, and then calculate the transfer function. Again, the energy curve obtained by scanning at different color temperatures is divided by the transfer function to obtain the correct energy radiation curve. The experimental study of blackbody radiation by computer scanning grating spectrometer and bromine tungsten lamp was carried out. By means of scrolling grating and sine mechanism, the data were recorded by computer scanning to verify the three laws of blackbody radiation directly, and the radiation, transmission and reception of blackbody were analyzed Error correction.

KEYWORDS: blackbody radiation; radiation source; transfer function; receiver

Received: 8th Apr. 2018 **Accepted**: 4th Aug. 2018 **Published Online**: 31st Aug. 2018

1. Introduction

1.1. Introduction to Blackbody Radiation Theory

In 1900, the famous physicist Kelvin reviewing the history of the development of physics, he made a speech on the future development of physics. He pointed out that the physics of the building has been completed and the future of the physicists needs to do some tinkering work. But there are two dark clouds in the clear physics sky, one of which is convenient for blackbody radiation. And then around the black body of radiation, human understanding of the natural into the quantum stage. The process of knowing the blackbody radiation is twists and turns. In 1894 the German physicist Planck began to study the blackbody radiation. In 1899, from the thermodynamics, Planck derived the law of Wien. But the same year the German physicist Ruth found in the high-frequency region Wien's law and experimental results are biased. Finally in 1900, Planck through unremitting efforts to get our well-known Planck blackbody radiation formula. But this is only based on experimental data derived from the semi-empirical formula, and did not get a reasonable theoretical explanation. After a few months of work, Planck finally found that for the rational interpretation of the formula, the only feasible assumption is that the object in the emission and absorption of energy, the energy is not continuous change, but a certain number of values of the integer Times jumping. In other words, in the process of radiation emission and absorption, the energy is not infinitely separable, but there is a minimum unit, the smallest unit, Planck called energy quantum or quantum, it is bold. The hypothesis knocked the door of the new era. Black body radiation as the 20th century, the scientific community has epoch-making significance of the research content, opened a new era.

1.2. The Background and Significance of Papers

In our living world, any object has the ability to continuously radiate, absorb, and emit electromagnetic waves. The emitted electromagnetic waves in the various bands are not the same, and have a certain spectral distribution [4]. This spectral distribution is related to the nature of the object itself and its temperature, and is therefore referred to as heat radiation. In order to study the thermal radiation laws of objects, physicists define an ideal object, the black body, as a standard object for thermal radiation research.

The general object of the external radiation, both the role of reflection and absorption. If an object on the external wavelength of all the radiation, neither the role of reflection nor no absorption, the object is called absolute black body, referred to as bold. The blackbody is a special kind of radiator which absorbs all the wavelengths of electromagnetic radiation. Blackbody does not exist under natural conditions, it is just an idealized model, but many objects are better blackbody approximations (in some bands). Kirchhoff's law of radiation, the ratio of the energy radiated to the absorbed energy in the heat-balanced state is independent of the physical properties of the object, only in relation to wavelength and temperature. According to Kirchhoff's law of radiation, at a certain temperature, the blackbody must be the largest object of radiation, can be called a complete radiator.

In a sense, because we live in a radiant energy environment, we are surrounded by natural electromagnetic energy. It produced a measurement and control of radiation energy requirements. With the development of science and technology, the measurement of radiation measurement is becoming more and more important for the development of high-tech sectors such as aviation, aerospace, nuclear energy, materials, energy sanitation and metallurgy. The black body radiation source as a standard radiation source, widely used as an absolute standard for infrared equipment, it can be used as a standard to correct other radiation sources or infrared machine. In addition, the basic radiation law of the blackbody can be used to find the radiation law of the entity and calculate the radiation quantity. The law of blackbody radiation provides the basis for the theory of thermal radiation, and this law has a wide range of applications in many fields of modern natural sciences. In real life, the black pigment has a black body characteristics, can absorb different wavelengths of visible light, almost no outward reflection. Winter wear black clothes more warm, is the truth. Solar water heaters also use this principle. In the field of science, the use of black body radiation principle, made to absorb radar waves of black paint can be used to coat the surface of the coating of stealth aircraft; laser inventions also use this principle. In addition, the blackbody radiation technology in industrial smelting metal, environmental pollution and other aspects has also been widely used. It can be seen that the black body in the field of radiation research, has a very wide range of applications, with absolute research significance.

1.3. The main content of the paper

The equipment used in this paper is the WGH-10 type blackbody experiment device. The equipment uses the bromine tungsten lamp as the blackbody radiation source, and uses the computer to scan the recorded data by means of the blazed grating and the sinusoidal mechanism to verify the black body radiation law directly. The paper reads as follows:

1. The introduction part introduces the blackbody radiation theory, and summarizes the research background and significance of the subject.
2. The theoretical part summarizes the basic theory of blackbody, and introduces three basic laws of blackbody radiation. This part has laid a good foundation for the next job.

The experimental law and theoretical basis of the blackbody radiation experiment are validated and studied on the law of blackbody radiation.

2. The basic theory of bold

2.1. Blackbody radiation

Any object, as long as its temperature is above absolute zero, like the surrounding radiation, is called temperature radiation. The blackbody is a complete temperature radiator, that is, the radiation flux emitted by any non-blackbody is less than the radiation flux emitted by the blackbody at the same temperature; and the non-blackbody's radiation is not only related to temperature but also to the surface material nature related. While the blackbody's radiation capacity is only related to temperature, the blackbody's radiance is the same in all directions, i.e. the bold is a complete cosine radiator.

2.2. Radiation and Kirchhoff's Law

Kirchhoff's law is the most basic law of the performance of heat radiators. Any object, as long as it is temperature in the absolute zero 0K or more to the surrounding radiation, the molecules are subject to thermal excitation and the phenomenon of electromagnetic waves called heat radiation [5]. As long as the temperature above the absolute zero, but also from the outside world to absorb the energy of radiation. The physical quantity describing the radiation law of the object is the radiation emissivity and the emission intensity of the monochromatic radiation. The relationship between them is:

$$M(\lambda,T)=\int_0^{\infty}M(T)d\lambda$$

Experiments show that the thermal radiation has a continuous radiation spectrum, the wavelength extends from far infrared region to the ultraviolet region, and the distribution of the radiation energy according to the wavelength mainly depends on the temperature of the object. Objects in different temperatures and environments emit energy in the form of electromagnetic radiation. The so-called black body refers to the incident electromagnetic waves are all absorbed, neither reflection nor transmission (of course, the black body still have to radiate). Obviously there is no real blackbody in nature, but many objects are better blackbody approximations (in some bands). The blackbody is a complete temperature radiator, that is, the radiation flux emitted by any non-blackbody is less than the radiation flux of the blackbody at the same temperature; and the radiant ability of the non-blackbody is not only related to the temperature but also to the surface material of the nature of the radiation, and the black body of the radiation is only related to temperature. In the blackbody radiation, there are electromagnetic waves of various wavelengths, whose energy is related to the temperature of the blackbody according to the wavelength distribution.

As early as 1859, the German physicist Kirchhoff, on the basis of summing up the experimental findings at that time, obtained the general law of the heat radiation of all objects in theory: the energy and energy absorbed by the objects in the heat balance state. The ratio is independent of the physical properties of the object, only with wavelength and temperature. That is, at the same temperature, the ratio of the monochromatic radiation (radiation ability) M_i (λ,T) of each radiation source to the monochromatic absorption rate (absorption capacity) α (λ,T) is independent of the nature of the object. The ratio is the same for all radiation sources (α=1, 2...), and is a universal function that depends only on wavelength and temperature. M_i (λ,T) and each of the monochromatic absorption rates α (λ,T) varies greatly depending on the object.

Kirchhoff's law can be expressed as:

$$\frac{M_1(\lambda,T)}{\alpha_1(\lambda,T)}=\frac{M_2(\lambda,T)}{\alpha_2(\lambda,T)}=\ldots=f(\lambda,T)$$

For all wavelengths, this object becomes an absolute blackbody, resulting in:

$$\frac{M_1(\lambda,T)}{\alpha_1(\lambda,T)}=\frac{M_2(\lambda,T)}{\alpha_2(\lambda,T)}=\ldots=M_{\lambda b}(T)$$

Where the mass $M_{\lambda b}$ (T) of the monochromatic radiation of the blackbody at the same wavelength is the temperature.

Thus α (λ,T) = 1, Kirchhoff' s universal function is the absolute blackbody's spectral radiance. The radiator is absolutely black, referred to as bold. The blackbody's radiance is the same in all directions, i.e. the bold is a complete cosine radiator. Radiation capacity is less than the blackbody, if α (λ,T) < 1, and for all wavelengths, the various temperatures are constant, called the gray body. The distribution of the radiation spectrum of the gray body is similar to that of the blackbody at the same temperature. Nature does not exist in an object whose inherent characteristics are not inferior to the gray body, but for a limited wavelength region, the object can be approximated to the gray body. All is not a black body is not a gray body of the actual object, we call it selective radiator. Its absorption capacity, and with the wavelength and temperature changes, but also with the light polarization and the incident angle of light and change in the spectral distribution of these objects and the Planck curve of nature, there are few strict senses of the black body, the general heat radiators are selective radiators.

2.3. Blackbody radiation law

The law of blackbody radiation is used to describe the relationship between the emissivity of electromagnetic radiation emitted from a blackbody and the frequency of electromagnetic radiation at any temperature. There are various wavelengths of electromagnetic waves in the blackbody radiation, and the monochromatic radiation varies with the color temperature according to the wavelength distribution.

2.3.1 Background of the law of blackbody radiation

At the end of the 19th century and the beginning of the 20th century, scientists began to pay attention to the relationship between the monochromatic emittance and the radiation frequency (or wavelength) of the blackbody, in order to explain the experimental blackbody radiation distribution from the theory. In 1879, the Stirvs experimentally observed that the rotation of the blackbody (the total radiated power of the various frequencies emitted by the blackbody's surface area) was proportional to the fourth power of the color temperature, that is, the Staples-Boltzmann's law The The law only gives the radiation of the blackbody radiation, but does not involve the specific function of the monochromatic radiation. In 1893, Wien calculated the expression of the blackbody monochromatic radiation, that is, the Wien formula [8]:

$$E_{\lambda T}=\frac{c_1}{\lambda^5 e^{\frac{c_2}{\lambda T}}}$$

Where: for the black body monochrome radiation (w/m^3);

$c_1=2\pi hc^2=3.745\times10^{-16}\ (w\cdot m^2)$; $c_2=hc/k_B=0.1439m\cdot k$; λ for radiation wavelength; T the color temperature.

The Wynne formula is in good agreement with the experimental data in the short band. In 1900, Rayleigh was deduced from classical statistical mechanics; Kings modified a numerical error in the Rayleigh derivation formula. Thus got the Rayleigh - Kings Formula [8]:

$$E_{ăT} = c_3 ë^{-4} T$$

The Rayleigh-Kings formula is in good agreement with the experimental data in the long band, but in the short wavelength (such as the ultraviolet region), with the decrease of the wavelength, the monochromatic radiation tends to infinity, contrary to the experimental data. This is the history of physics, 'two clouds' in one of them, that is, UV disaster events.

The above two classical formulas cannot separately explain the behavior of blackbody radiation over the entire wavelength range. Later, Planck used the interpolation method to deal with the above two formulas, and got the Planck formula. The Planck formula is in good agreement with the experimental data, and on this basis, the energy quantum hypothesis is proposed.

2.3.2 Black body radiation three laws

1. Spectral distribution of blackbody radiation - Planck's law of radiation [9]

In 1900, the long-term study of thermodynamics of the German physicist Planck integrated Wien formula and Rayleigh - Kings formula, the use of interpolation method to introduce their own a constant, the results obtained a formula, and this formula and The experimental results are precisely consistent, it is the Planck formula, that is, Planck's law of radiation [6]. This law is expressed in terms of spectral radii, in the form of [7]:

$$E_{ăT} = \frac{C_1}{ë^5 \left(e^{\frac{C_2}{ăT}} - 1\right)} \quad (W / m\,3)$$

Where:

the first radiation constant C1 = 3.74 × 10^{-16} (watts/m^2) Second radiation constant C2 = 1.439810^{-2} (m × Kelvin)

The brightness of the blackbody spectrum is given by:

$$L_{ăT} = \frac{E_{ăT}}{ð} \quad \text{(Watts / m3 - Spherical Corner)}$$

Integral Radiation of Blackbody - Stefan-Boltzmann's Law This law is expressed as radii [7],

$$E_T = \int_0^{\infty} E_{ăT}\, dë = ăT^4 \quad (W / m\,2)$$

Where:

T is the absolute temperature of the blackbody,
Stefan-Boltzmann constant is 5.670 × 10^{-8} (w / m^2. Kelvin [4])
k is the Boltzmann constant, h is the Planck constant, and c is the speed of light.

As the black body radiation is the direction of the passage, the radiation brightness and the relationship between radiation:

$$L = \frac{E_T}{ð}$$

Thus, the Stefan-Boltzmann's law can also be expressed as radiant brightness:

$$L = \frac{ä}{ð} T^4 \quad \text{(W / m 2. Sphere)}$$

2. Wien's Law of Displacement [7]

The wavelength of the maximum spectral luminance is inversely proportional to λ_{max} and its absolute temperature T,

A is a constant, A = 2.89610^{-3} (m × Kelvin), L_{max} =4.1015 ×10^{-6} (Watt / m. Spherical angle Kelvin [5]).

As the temperature increases, the maximum wavelength of the absolute blackbody spectrum fluctuates toward the shortwave.

3. Blackbody Radiation Experiment

3.1. Experimental principle of blackbody radiation

The blackbody radiation law validation experiment is to get the blackbody monochromatic radiation with varying wavelengths at different color temperatures to verify the three laws of blackbody radiation. The physical equipment used in modern physics experiments is the WGH-10 blackbody radiation experimental device, which uses a bromine tungsten lamp as a blackbody radiation source [6], by means of a blazed grating and a sinusoidal mechanism, using computer scanning to record data directly to the blackbody Law to verify. In this experiment, the use of regulated bromine tungsten lamp as light source, the choice of lead sulfide as optical signal receiver. The radiation energy curve (called the baseline) of the bromine tungsten lamp obtained from the lead sulfide receiver is deviated from the energy curve corrected by the calibration of the tungsten lamp, mainly due to the absorption of the water vapor, carbon dioxide and other spectral structures in the air, In order to eliminate the baseline deviation from the bromine tungsten lamp calibration energy curve, the introduction of transfer function. There is already a calibrated bromine tungsten lamp in the 2940k energy curve in the WGH-10 companion software. At the beginning of the experiment, we should scan at 2940k color temperature to get the baseline, and then calculate the transfer function. Again, the energy curve obtained by scanning at different color temperatures is divided by the transfer function to obtain the correct radiation energy curve.

3.1.1 The basic composition of the instrument

WGH-10 row of black body experimental device, by the grating monochromator, receiving unit, scanning system, electronic magnifying glass, A / D acquisition unit, adjustable voltage regulator tungsten lamp light source, computer and printer components [5].

3.1.2 Host structure

The host part has the following component as shown in **Figure 1.**

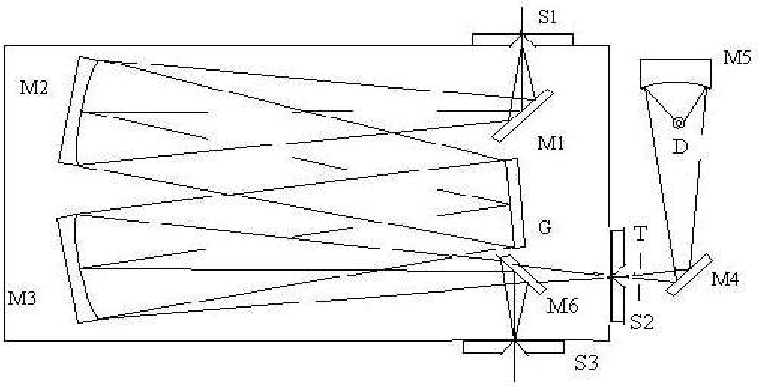

Figure 1. Optical schematic structure. M1 - reflector, M2 - collimator, M3 - objective, M4 - reflector, M5 - deep ellipsoid, M6 - mirror, G - plane diffraction grating, S1 - incident slit, S2 & S3 - exit slit, T - modulator.

The entrance slit, the exit slit are straight slits, the width of the range of 0-2.5 mm continuously adjustable, the light emitted by the light beam into the entrance slit S1, S1 is located on the focal plane of the reflective beam mirror M2, through the S1 injection Of the beam is reflected by the M2 into a parallel beam onto the planar grating G, and the diffracted parallel beam is imaged on the S2 by the objective lens M3. M4, M5 converge on the photoelectric receiver D.

M2 & M3 focal length = 302.5 mm

Grating G per minute mark 300 shine wavelength 1400 nm

Filter work range: First piece of 800-1000 nm, Second piece 1000-1600 nm, Third piece 1600-2500 nm

3.1.3 Bromine tungsten light source

Standard blackbody should be the main setting of the blackbody experiment, but the purchase price of a standard blackbody is too high. Therefore, the experimental device adopts the stabilized bromine tungsten lamp as the light source, the filament of the bromine tungsten lamp is made of tungsten filament, and the tungsten is the refractory metal, its melting point of 3665 K.

The tungsten filament is a selective radiator, and the resulting spectrum is continuous. Its total radiation speculation can be found by the following equation.

$$R_T = \varepsilon_T \sigma T^4$$

Where R_T is the total radiation coefficient at the temperature T, which is the ratio of the radiation intensity of the given tungsten wire to the radiation intensity of the absolute blackbody:

$$\varepsilon_T = \frac{R_T}{E_T} \quad \text{Or} \quad \varepsilon_T = (1 - e^{-BT})$$

Where $B = 1.47 \times 10^{-4}$ (a constant)

The distribution of the radiation spectrum of the tungsten filament is $R_{\lambda T}$

$$R_{\lambda T} = \frac{C_1 \varepsilon_T}{\lambda^5 \left(e^{\frac{c_2}{\lambda T}} - 1\right)}$$

Above mentioned the black and tungsten filament radiation intensity of the relationship between the factories will be used to match the tungsten light source, a set of standard working current and color temperature corresponding to the relationship between the information.

Table 1. working temperature of bromine tungsten lamp - color temperature correspondence table

Current (A)	Color Temperature (k)
2.5	2940
2.3	2860
2.2	2770
2.1	2680
2.0	2600
1.9	2550
1.8	2500
1.7	2450
1.6	2400
1.5	2330
1.4	2250

3.1.4 Receiver

The working range of the experimental device is 800-2500 nm, so the use of lead sulfide as the optical signal receiver, from the monochromator out of the monochromatic light signal emitted by the modulator, modulation of the 50 Hz frequency signal received by the lead sulfide, the choice of Lead Sulfide is a transistor housing structure that encapsulates lead sulfide components in a transistor shell, filled with dry nitrogen or other inert gases, and is melted or welded to ensure full sealing. The device can work in high temperature, humid conditions and stable and reliable performance.

3.1.5 Electric control box

The electronic control box controls the spectrometer to work and sends the collected data and feedback signals to the computer.

3.2. Experimental content and steps

1. Open the black body radiation test system power control box power supply and bromine tungsten lamp power switch.
2. Turn on the computer.
3. Double-click the 'bold' icon to enter the blackbody radiation system software main interface, set: Working mode - mode: energy, interval: 2 nm
   Working range - starting wavelength: 800nm, termination wavelength: 2500 nm.
   Maximum: 4000.0; Minimum: 0.0
   ('maximum' and the width of the slit, the greater the width, the greater the amount)
4. Adjust the working current of bromine tungsten lamp is 2.5 A, that is, the color temperature is 2940 k, click 'one way' to calculate the transfer function.
5. Create a transfer function and fix it as a bold.
6. Record the full spectrum of the bromine tungsten light source in register-1.
7. Change the working current of bromine tungsten lamp, draw the blackbody radiation energy curve at different color temperature, and store the whole spectrum in 5 register.
8. Normalize the data in each register.
9. Validate Planck's Law of Radiation.
10. Verification of Staples - Boltzmann's Law.
11. Validate for Wien's Law.

4. Conclusion

This paper introduces the law of blackbody radiation and its verification experiment combined with the modern physics experiment practice. Firstly, by calculating the transfer function, the energy curve obtained by scanning at different color temperature is divided into the transfer function, and the blackbody radiation energy curve at different color temperature is drawn. Secondly, the experimental data are used to validate the Planck's radiation law. The Stokes-Boltzmann's law can be verified by the integral method, and the Werner's displacement law is verified by the experimental data. The Boltzmann constant, Wien constant, and the error with the theoretical value are calculated. which demonstrates the feasibility of the experimental method.

References

1. Zhao Kaihua. Quantum Mechanics [M]. Beijing: Higher Education Press, 2001.1-13.
2. Yao Qijun. Optical tutorial [M]. Beijing: Higher Education Press, 2002: 414-425.
3. Li Zhengping. Microscope scanning blackbody radiation experiment [J]. Physical Experiment, 2004,32 (04); 44-49.
4. Wu Tieshan, Li Daoyin. University physics experiment [M]. Wuhan: Hubei Science and Technology Press, 2005.
5. He R, Xin M, Liu F. Abandon the black body concept of thermal equilibrium radiation theory. Journal of Dalian Nationalities University, 2009,18 (05); 3-5.
6. Chen Xiaoming. Blackbody radiation law and related teaching problems [J]. Physical Experiment and Exploration, 2009,28 (5); 27-29.
7. Kang Yongqiang, Yang Chengquan, Jiang Xiaoyun. Black body radiation law research and verification [J]. University Physics Experiment, 2010,23 (04); 18-39.
8. Huang Yongyi. Planck black body radiation law of the establishment process [J]. Guangxi Physics, 2011,32 (03); 6-10.
9. Kong Xiangsheng, Qian Yonggang, Zhang Anding. Black body radiation law remote sensing teaching reform design and practice [J]. Science of Surveying .2012,37 (06); 1-5.
10. Wang Dexin. Quantum Mechanics [M]. Science Press, 2008.5-12