Unveiling The Theory and Application of Radiation Thermometry

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Abstract. This paper mainly explores the basic principle of radiation thermometry, the related temperature measurement methods, and their applications in various fields. The radiation temperature measurement method uses the relationship between the heat emitted by an object in a thermal equilibrium state and its surface temperature to measure. The basic principle is based on the blackbody radiation law, which means that the surface temperature of an object can be calculated by the relationship between the total energy of infrared radiation emitted by the object and the surface temperature of the object. The results of radiation temperature measurement may be influenced by various factors such as object emissivity, environment and conditions, measurement distance, etc. Therefore, suitable radiation temperature measurement methods and equipment should be selected based on specific situations. The paper introduces the relevant temperature measurement methods of radiation temperature measurement. The basic theories include thermal radiation law, Planck radiation law, and Stefan Boltzmann law, providing a theoretical basis for subsequent research.

Keywords: Blackbody radiation; Radiation thermometry; The law of thermal radiation; Stefan-Boltzmann law.

1. Introduction

Blackbody radiation refers to the electromagnetic radiation emitted by an idealized object that can completely absorb external electromagnetic radiation without reflection or transmission. This concept was first proposed by German physicist Kirchhoff in the 19th century. The spectral distribution of blackbody radiation is continuous and closely related to the temperature of the object. However, within the framework of classical physics, there is a significant deviation between the theoretical predictions and experimental results of blackbody radiation, especially in the high-frequency region, which is known as "ultraviolet catastrophe" [1]. To explain this phenomenon, physicist Max Planck proposed the quantum hypothesis in the early 20th century, which states that light also has particle properties, known as photons, whose energy is discrete rather than continuous. This theory, known as energy quantization theory, provides a new analytical method for blackbody radiation problems.

By using molecular dynamics and quantum mechanics methods in statistical physics, scientists can accurately calculate the spectral distribution of blackbody radiation, and the results are very close to experimental data. This method not only provides a more accurate means of predicting blackbody radiation, but also reflects the physical properties of the radiator more accurately [2]. The development of quantum mechanics has had a profound impact on understanding blackbody radiation and even the entire physical world. The particle wave theory in quantum mechanics plays a crucial role in handling the physical properties of atoms and molecules. The discovery of atoms benefited from the understanding of quantum mechanics, where atoms were described as "finely modulated pulse generators" with electrons only present at specified energy levels. This theory can explain the spectra of atoms and molecules, and this spectral information is also widely used to measure the properties and composition of stars and galaxies far from Earth.

The significance of radiation thermometry lies in its provision of a non-contact temperature measurement method, which has the advantages of being fast, accurate, and does not require probes or sensors to contact the surface of the measured object. Therefore, it is particularly suitable for temperature measurement in harsh environments such as high temperature, high pressure, and strong corrosion. In addition, radiation thermometry can also be used for temperature measurement of

remote targets, such as monitoring the surface temperature of spacecraft or observing the temperature distribution of distant celestial bodies. In terms of application, radiation thermometry is widely used in industrial production, scientific research, medical diagnosis, and other fields. For example, in the process of steel smelting, the radiation temperature measurement method can be used to monitor the temperature inside the furnace in real time to ensure product quality and production safety. In the medical field, radiation thermometry can be used to monitor the temperature changes of patients, providing important basis for diagnosis and treatment [3]. In addition, with the continuous progress of technology, the application fields of radiation thermometry will continue to expand.

The layout of the remaining parts of the paper is as follows. The Section 2 currently explains the basic principle and derivation process of radiation temperature measurement. Section 3 explains the applications of radiation thermometers, including brightness temperature measurement, colorimetric temperature measurement, laser-induced fluorescence, interferometric temperature measurement, and infrared temperature measurement. Finally, Section 4 provides a summary of radiation temperature measurement.

2. Basic Principles

A blackbody is an ideal physical model that completely absorbs all incoming radiation without any reflection or transmission. Blackbody radiation refers to the electromagnetic radiation emitted by a blackbody in a thermal equilibrium state, and its spectrum and intensity are only related to temperature. Experimental observations indicate a close relationship between the intensity of blackbody radiation and temperature. As the temperature increases, the intensity of blackbody radiation also increases. German physicist Max Planck proposed the Planck radiation law to describe blackbody radiation in 1900 [4]. This law provides the energy distribution of blackbody radiation at different wavelengths and temperatures. The basic formula for radiation temperature measurement is the Stefan-Boltzmann law, which describes the relationship between the total energy radiated by a blackbody at all wavelengths and its surface area and temperature. Namely [5],

$$E = \Delta I(\lambda, T)d\lambda = \sigma T^4. \tag{1}$$

Among them, E is the energy radiated per unit surface area of an object per unit time, i.e. the radiance, measured in watts per square meter ($\mathrm{W/m^2}$). σ is the Stefan Boltzmann constant, with a value of approximately $5.670373 \times 10^{-8}\mathrm{W/(m^2 \cdot K^4)}$. T is the thermodynamic temperature of an object, measured in Kelvin (K). This formula indicates that the radiation power of an object (i.e. the energy radiated per unit time) is directly proportional to the fourth power of its temperature. That is to say, the higher the temperature of an object, the more energy it radiates.

Radiation temperature measurement is based on this principle, by measuring the thermal radiation emitted by an object to determine its surface temperature. In practical applications, infrared radiation thermometers are usually used to measure the infrared radiation emitted by objects and convert it into corresponding temperature values. This method does not require contact with the surface of the object, making it particularly suitable for high temperature, moving, or non-contact objects. Planck's law provides the energy distribution of monochromatic radiation emitted by a blackbody at a certain temperature. Its expression is [6]

$$E(\lambda, T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kT} - 1}. \tag{2}$$

Among them, $E\ (\lambda, T)$ is the energy density of λ-monochromatic radiation with a wavelength at temperature T, h is the Planck constant, c is the speed of light, and k is the Boltzmann constant. Boltzmann's law describes the total energy distribution of black body radiation at a certain temperature, and it is expressed as

$$u(T) = \int_0^\infty E\ (\lambda, T)d\lambda. \tag{3}$$

In order to derive Boltzmann's law from Planck's law, one needs to integrate Planck's law over the entire wavelength range. Firstly, by rewriting Planck's law in the form of frequency, as the relationship between frequency and wavelength is $\nu = c/\lambda$, it is found that

$$E(\nu, T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1}. \tag{4}$$

Then, integrate this expression over the entire frequency range to obtain the total energy density

$$u(T) = \int_0^\infty E\,(v, T)dv = \int_0^\infty \frac{2h\nu^3}{c^2}\frac{dv^3}{e^{h\nu/kT}}. \tag{5}$$

To simplify this integration, a variable replacement can be performed such that $x = h\nu/kT$, so $d\nu = kT/hdx$, and the upper and lower bounds of the integration remain unchanged (because ν goes from 0 to ∞, and x also goes from 0 to ∞). After replacement, the integral becomes

$$u(T) = \frac{2k^4T^4}{h^3c^2}\int_0^\infty \frac{x^3}{e^x - 1}dx. \tag{6}$$

Clearly, there is an integral appearing here $\int_0^\infty \frac{x^3}{e^x-1}dx$. This integral is a mathematical constant called Riemann ζ function in $s = 4$ is recorded as $\zeta(4)$, or it can also be expressed as $\pi^4/15$. Therefore, the expression for Boltzmann's law can be obtained [7]

$$u(T) = \frac{2\pi^5k^4T^4}{15h^3c^2}. \tag{7}$$

This formula provides the total energy density $u(T)$ of a black body at temperature T.

3. Application of Radiation Thermometry

3.1. Radiance Thermometry

The brightness temperature of an object is represented by the temperature of a blackbody with the same radiation power within a narrow spectral range near a given wavelength. The brightness temperature measurement method is based on the different radiation energy emitted by objects at different temperatures to achieve temperature measurement. According to Planck's radiation law, the radiation energy emitted by an object is related to temperature and wavelength. By measuring the radiation energy or brightness of an object at different wavelengths, the temperature of the object can be inferred [8]. The implementation of the brightness temperature measurement method mainly includes two parts: hardware and software. The hardware mainly includes infrared detectors, optical systems, signal processing circuits, etc. Infrared detectors are responsible for receiving infrared radiation emitted by objects and converting it into electrical signals; The optical system is responsible for focusing and filtering infrared radiation to improve the receiving efficiency of the detector; The signal processing circuit amplifies, filters, and analog-to-digital converts the electrical signal output by the detector to obtain a digital signal for software processing. In practical applications, infrared radiation is generally used as the measurement band, because most objects have a higher emissivity in the infrared band and are not visible to the human eye, making them less susceptible to environmental light interference.

3.2. Colorimetric Thermometry

The colorimetric temperature measurement method uses the ratio of radiation intensity within two adjacent narrow bands to measure temperature. The colorimetric temperature measurement method uses wavelength narrowband comparison technology. According to Venn's shift law, the maximum monochromatic absolute blackbody is measured when the temperature increases. From the perspective of detection methods, the total radiation temperature measurement method measures the

temperature by measuring the radiation energy of the entire wavelength band. The radiation of the surrounding background, changes in the absorption rate of the medium, and prediction of the emissivity all pose difficulties in measurement, making it difficult to achieve high accuracy. The single radiation temperature measurement method requires a narrower band to be selected, but if the bandwidth is too narrow, the energy received by the detector will become too small, thereby affecting its measurement accuracy [9]. The multi wavelength radiation temperature measurement method is a very accurate measurement method, but the process is relatively complex, and the cost is high, making it difficult to promote and apply. The colorimetric temperature measurement method adopts wavelength narrowband comparison technology, which overcomes many shortcomings of the above methods. Even under extremely harsh conditions, such as environments with smoke, dust, steam, and particles, as well as changes in the emissivity of the target surface, high accuracy can still be achieved. The radiation intensity moves in the direction of decreasing wavelength, causing the brightness ratio of two fixed wavelengths to change with temperature. Therefore, measuring their brightness ratio indicates the corresponding temperature. Especially in situations where the absorption of intermediate media is large and in small point or local applications, the attenuation of radiation energy is almost the same at two wavelengths, so it will not affect the ratio between them.

3.3. Laser Temperature Measurement

Laser temperature measurement technology is based on the blackbody radiation law, which means that an object radiates energy outward in the form of electromagnetic waves, and its radiation energy density is proportional to the fourth power of the object's temperature. When a laser is irradiated on an object, some of the light is reflected, absorbed, and scattered, and the absorbed light energy is converted into heat energy, causing the temperature of the object to rise. The principle of laser temperature measurement is to utilize the high consistency of the laser beam and the monochromaticity of light. The frequency and wavelength of light are related to its energy and temperature, so when light is absorbed or reflected, its energy also changes. By measuring the energy changes of reflected or scattered light, the temperature of an object can be calculated [10].

3.3.1 Laser induced fluorescence temperature measurement

Laser induced fluorescence technology is a technology that utilizes the characteristic of specific substances emitting specific fluorescence under laser irradiation for flow display and measurement. It usually involves adding a certain fluorescent substance (usually a fluorescent molecule dissolved in the fluid) as a tracer to the test fluid. When the laser is irradiated on these fluorescent substances, they will absorb light energy and transition to the excited state. Subsequently, these substances will release fluorescence of different wavelengths than the excitation light, and this fluorescence process is laser-induced fluorescence. Due to the direct relationship between the concentration of fluorescent substances and their flow conditions, the flow conditions, concentration field, temperature field, pressure field, and velocity field of fluids can be calculated by measuring information such as fluorescence intensity and wavelength. In addition, due to the strong directionality and monochromaticity of the excitation light used in laser induced fluorescence technology, its detection sensitivity is higher compared to other laser spectroscopic methods. For example, there have been reports that this technology can detect atomic concentrations below 100 per cm^2. For most molecules, it is easy to detect up to $10^6/cm^2$ of the concentration. Overall, laser induced fluorescence technology has advantages such as high sensitivity, high resolution, and high measurement accuracy, making it widely applicable in fields such as fluid dynamics, chemical reaction kinetics, environmental monitoring, and medical diagnosis.

3.3.2 Interferometric Temperature Measurement

When the incident laser beam is irradiated on a transparent plate with two parallel planes, interference caused by multiple reflections in the transparent plate will occur, and light fringes can be observed. By measuring the changes in fringes at a specified wavelength, the thickness (thermal expansion) and refractive index changes can be calculated, and further temperature changes can be

inferred. The accuracy of interferometric temperature measurement method mainly depends on the quality of optical components, the stability of optical path, and the design of interferometer. Common sources of error include air disturbances in the optical path, small displacements of optical components, and refractive index changes caused by temperature changes. In order to reduce errors, a series of measures need to be taken, such as stabilizing the optical path, isolating environmental interference, and real-time correction.

3.4. Infrared Thermometry

The infrared thermometer mainly consists of a display output circuit, an optical system, a photodetector, a signal amplification and processing amplifier, and other parts. The infrared energy radiated by the measured object is received by the infrared thermometer through a certain distance of transmission. Many gas molecules in the atmosphere have a certain absorption effect on infrared radiation, and in the short range of normal body temperature measurement. The influence of gases within the specified range of the instrument can be ignored. Its foundation is the law of infrared radiation, among which the Stefan Boltzmann law and the Planck radiation law are particularly important [11]. The Stefan-Boltzmann law states that the total energy of blackbody radiation is proportional to the fourth power of its surface area and temperature. The Planck radiation law describes the distribution of radiation intensity emitted by a blackbody at different temperatures. These laws provide a theoretical basis for infrared temperature measurement. The infrared thermometer obtains temperature information by measuring the infrared radiation emitted by the target object. When measuring, factors such as the emissivity, surface area, and measurement distance of the target object need to be considered. Emissivity reflects the ability of an object's surface to radiate infrared energy, and different objects or materials have different emissivities. Based on the measured infrared radiation signal and the emissivity of the target object, the temperature of the target object can be calculated using a temperature inversion algorithm. Temperature inversion algorithms are typically modeled based on the law of infrared radiation and detector response characteristics to achieve the conversion from infrared radiation signals to temperature. Infrared thermometers may experience errors during long-term use or under different environmental conditions. In order to improve the accuracy of temperature measurement, it is necessary to perform error correction on the system. Common error correction methods include regular calibration, temperature drift compensation, and linearization correction.

4. Conclusion

The optical temperature measurement method is based on the relationship between the thermal radiation of an object and its temperature and calculates its temperature by measuring the thermal radiation emitted by the object. This method is widely used in industries, healthcare, scientific research, and other fields, especially in difficult to contact or high-temperature environments, where its non-contact temperature measurement characteristics are particularly prominent. The advantage of the optical temperature measurement method lies in its fast, accurate, non-contact nature, and the ability to achieve remote and real-time temperature measurement. In addition, with the advancement of technology, modern optical measurement equipment is becoming increasingly miniaturized, intelligent, easy to operate, and highly reliable. This article comprehensively compares and analyzes four temperature measurement methods: brightness temperature measurement, colorimetric temperature measurement, laser temperature measurement, and infrared temperature measurement. The results indicate that each temperature measurement method has its unique advantages and applicable scenarios. In practical applications, appropriate temperature measurement methods should be selected according to specific needs to obtain accurate and reliable temperature measurement results. However, the optical temperature measurement method also faces some technical challenges, such as light source stability, temperature measurement error correction, environmental interference, etc. These issues require continuous research and improvement to improve temperature measurement

accuracy and stability. Looking ahead to the future, with the continuous development of technologies such as optics and electronics, optical temperature measurement is expected to be applied in more fields, such as biomedical and aerospace. Meanwhile, technological innovation will further enhance the accuracy and reliability of optical temperature measurement methods, promoting their important role in more scenarios.

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