Principles and Applications of Optical Temperature Measurement Methods

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Abstract: Temperature measurement plays a vital role in industrial production, scientific research, and daily life. Traditional contact temperature measurement methods face limitations such as restricted measurement range and probe aging in extreme environments. Contact temperature measurement techniques offer high accuracy, fast response, and strong adaptability, but still encounter challenges such as the uncertain emissivity of high-temperature objects and interference from environmental reflections. This paper systematically reviews the fundamental principles of optical temperature measurement, categorizes its methods, and elaborates on the principles, characteristics, and applications of radiation thermometry and fiber-optic temperature measurement. Case studies, including molten steel casting temperature monitoring, gas turbine blade temperature measurement, and natural gas tank inspection, are analyzed to explore the applicable scenarios, advantages, and disadvantages of different optical methods. Optical temperature measurement enables non-contact, real-time, and long-distance temperature sensing, making it highly promising for applications in industrial high-temperature monitoring and energy pipeline inspection. Research shows that combining optical techniques with traditional methods, optimizing optical system design, and introducing advanced signal processing technologies can enhance measurement accuracy and expand their applicability in complex environments.

1 INTRODUCTION

The measurement of surface temperature and its distribution is crucial and has a wide range of applications in various fields. Traditional temperature measurement methods mainly include pressure type, RTD, thermocouple, liquid thermometer, etc., mostly contact temperature measurement. Despite its high accuracy and practicality, it is limited by temperature range, linearity, probe aging, and response time in extreme environments, with a long response time, and cannot be used to measure very high temperatures and the temperature of moving objects, and is gradually being replaced by non-contact temperature measurement methods.

The non-contact temperature measurement method can measure the temperature of objects with rapid temperature change without affecting their status by simply aligning the optical receiving system to the object to be measured, which can realize non-destructive, real-time monitoring of temperature. By optimizing the design of the thermometer's optical system, it is also possible to measure the temperature distribution in three-dimensional space (Xu & Yang, 2012). The method has the advantages of high accuracy, high response, and adaptability. For example, the infrared imager response speed, response time up to microseconds, suitable for measuring panoramic fast temperature field measurement range of -30 ~ 2000 ° C, sensitivity up to 0.05 ° C, and error of ± 0. 5% of the full scale. Temperature measurement of small areas up to a few microns can be simultaneously performed on the point temperature, line temperature, and surface temperature measurement, measurement results are visualized in an image (Xie, 2017). Therefore, non-contact temperature measurement has gradually become an important method of modern industrial temperature measurement.

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Among them, photothermometry is a typical non-contact temperature measurement method, which mainly includes infrared radiation thermometry, fiber optic thermometry, Raman spectroscopy, phosphorescence thermometry, laser induced fluorescence thermometry, and chromatic aberration thermometry, etc. The purpose of this study is to review in depth the research and progress of radiation thermometry and fiber optic thermometry, as well as their applications in various fields. The purpose of this study is to review and summarize the research and progress of radiation and fiber optic thermometry, as well as their applications in various fields, and to look forward to the future trends from the current development, to contribute new insights and ideas to theory and practice, and to make positive contributions to the progress of related fields.

2 RADIOMETRIC THERMOMETRY

2.1 Principle of Radiometric Thermometry

The basic principle underlying radiometric thermometry is the blackbody radiation law, which states that the radiation spectrum of a blackbody is determined by the thermodynamic temperature of the blackbody. This usually includes Planck's blackbody radiation law, Wien's displacement law, and the Stefan-Boltzmann law. On this basis, the total radiation law, the peak Wien displacement law, and the brightness thermometry law can be derived (Xu & Yang, 2012).

2.1.1 Venn's Method of Peak Displacement

Wien's displacement law, which can be derived from Planck's formula, describes the relationship between the wavelength and frequency corresponding to the maximum brightness in blackbody radiation. i.e.

$$\lambda_m T = b \quad (1)$$

where λ_m is the value of the wavelength corresponding to the maximum radiance at that temperature in m.

For a blackbody the relation between monochromatic radiance and temperature and wavelength is given by Planck's equation:

$$M_{\lambda T}^{0} = \frac{C_1}{\lambda^5 e^{\frac{C_2}{\lambda T}} - 1} \quad (2)$$

where $M_{\lambda T}^{0}$ is the irradiance of the blackbody; λ is the wavelength; $C_1 = \ = 3.7418 \times 10^{-16} W \cdot m$ is the absolute temperature; $C_2 = 1.4388 \times 10^{-2} m \cdot K$ is the first Planck coefficient and m is the second Planck coefficient. Figures 1 and 2 are the images drawn according to Planck's formula.

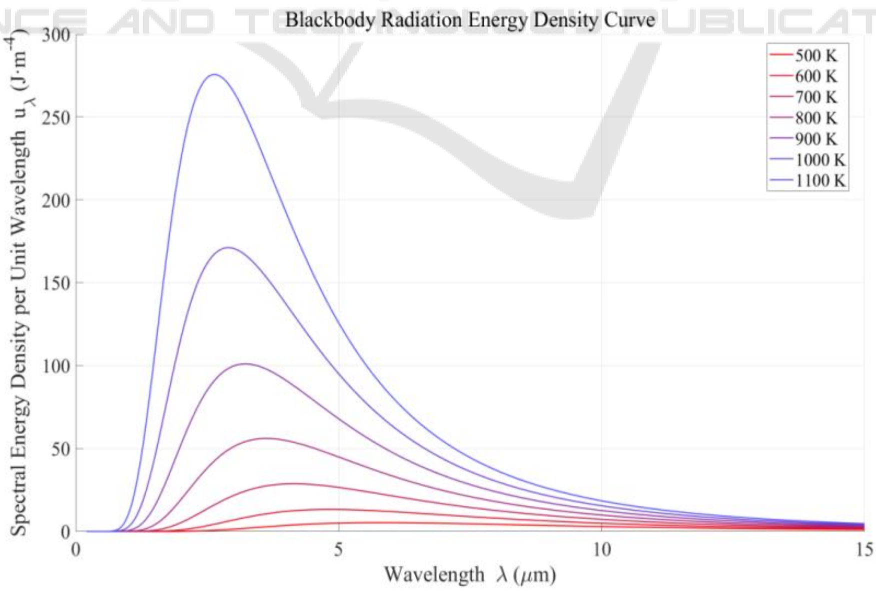

Figure 1: Spectral energy density curves of blackbody radiation at different temperatures (Original).

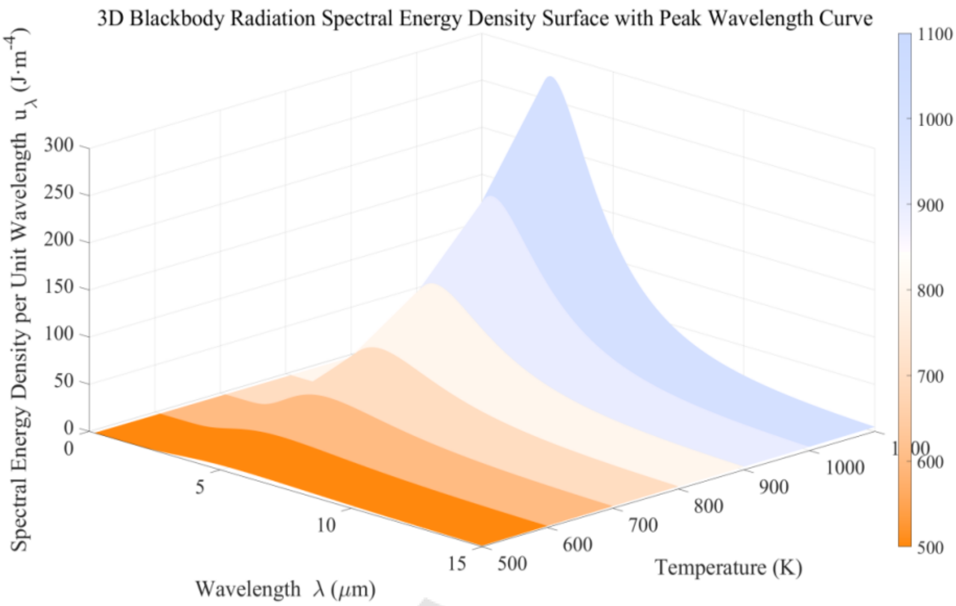

Figure 2: 3D surface of blackbody radiation spectral energy density as a function of wavelength and temperature (Original).

According to the Figures. 1, 2, it can be seen that the monochromatic radiance has a unique extreme value, and the product of its corresponding peak wavelength and temperature is a definite constant μm · K. That is, the temperature of the radiating body can be determined simply by determining this value.

2.1.2 Total Radiometric Thermometry and Luminance Thermometry

The total radiation method is based on the Stefan-Boltzmann law, which integrates the spectral radiance over the entire wavelength to obtain the full-wave radiant energy flux per unit area. This means that the temperature of the radiating body is determined by measuring the total radiation:

$$M^0 = \sigma T^4 \tag{3}$$

Where M^0 is the total amount of radiation radiated per unit time from a unit area of a blackbody at a temperature of T, called the total radiance; $\sigma = 5.67032 \times 10^5\ \mathrm{W \cdot m^{-2} \cdot K^{-4}}$ is the Stefan-Boltzmann constant, and T is the temperature of the object. The temperature of the radiating body can be determined as long as M^0 is measured.

If Planck's formula is written in the form of luminosity, i.e (Fan, 2016).

$$L_{\lambda T}^{0} = \frac{C_1}{\pi^5 e^{\frac{C\lambda}{\lambda T}-1}} \tag{4}$$

where $L_{\lambda T}^{0}$ is the monochromatic radiance measure of the spectrum. That is, the temperature of the radiator is determined by measuring the radiant luminance$L_{\lambda T}^{0}$of the radiator.

2.1.3 Multispectral Pyrometry

Multispectral thermometry, in contrast to total radiometric thermometry, which collects the total radiant energy in the infrared band (where the object to be measured is approximated as an ideal blackbody, i.e., the surface emissivity ε(λ) is approximated to be 1), collects the intensity of radiation at multiple wavelengths to derive the temperature based on a mathematical model.

Consider general object surface emissivity

$$L_m(\lambda) = \varepsilon(\lambda)L(\lambda, T) + \big(1 - \varepsilon(\lambda)\big)L_{env}(\lambda) \tag{5}$$

A system of equations can be constructed for the intensity of radiation $L_m(\lambda_i)$ measured at multiple wavelengths $\lambda_1, \lambda_2, \ldots, \lambda_n$:

$$L_m(\lambda_i) = \varepsilon(\lambda_i)\frac{C_1}{\lambda_i^5} \cdot \frac{1}{exp\left(\frac{C_2}{\lambda_i T}\right)-1} + \big(1 - \varepsilon(\lambda_i)\big)L_{env}(\lambda_i) \tag{6}$$

The temperature T and the unknown emissivity ε(λ) can be solved for using numerical fitting.

2.2 Radiation Thermometry Characteristics

As shown in Table 1, a comparison of the advantages and disadvantages of the different methods is demonstrated.

Table 1: Comparison of different methods.

Temperature measurement method	Main principle	Vantage	Drawbacks
Venn's method of peak displacement	Calculation of temperature by determining the peak wavelength of radiation	The method is intuitive and simple to calculate	Susceptible to background noise and large measurement errors
Luminance thermometry	Measuring the brightness of monochromatic radiation to derive temperature	Simple equipment, fast measurement	Limited measurement accuracy by relying only on single-wavelength information
Total radiometric thermometry	Measurement of the total radiant energy of the target in all wavelength ranges	Wide coverage and high temperature measurement accuracy	Need to consider the spectral response characteristics of the detector, interference from background radiation
Multispectral pyrometry	Detects infrared radiation in multiple wavelength ranges to obtain spectral information.	Reduces emissivity variations and environmental interference errors, making it suitable for high-precision measurements.	Complexity of equipment and calculations

2.3 Radiometric Thermometry Applications

The radiation method of temperature measurement is applicable to the temperature measurement of solid surfaces such as blast furnace walls, workpiece surfaces, cooling walls, etc.; the spectral line broadening method and the molecular spectral line rotation light intensity distribution method are applicable to the measurement of the temperature and its distribution in the furnace chamber. In the industrial field, the application of optical temperature measurement technology to the real-time monitoring of blast furnace temperature is of great significance to extend the life of the furnace, improve product quality, and reduce energy consumption (Xu & Yang, 2012).

When smelting new steel grades, the first steelmaking plant of Tianjin Tiangang Group Co., Ltd. needs to accurately determine the casting temperature of steel when it is cast into ingot molds. Due to the interference of smoke on site, the measurement result of a conventional infrared thermometer or optical pyrometer is more than 300 degrees lower than the actual value. If a thermocouple thermometer is used for the measurement, the thermocouple will be lost.

In order to solve this problem, the plant uses fiber optic infrared thermometer, on-site temperature measurement, the probe and fiber optic cable installed in a metal protective tube with insulation, manipulate the protective tube to the probe end of the steel close to the steel (from the steel only 300mm) for measurement. When the steel was ready to be discharged, the fiber optic infrared thermometer was calibrated alternatively with a consumable tungsten-molybdenum thermocouple thermometer (the consumable thermocouple thermometer was calibrated at 1663°C and the fiber optic infrared thermometer was calibrated at 1637°C, and the fiber optic infrared thermometer was adjusted from 1637°C to 1663°C). In the casting site, each ladle can be cast eight groups of ingot molds, each group of about 8min minutes. At the initial trial, eight casting temperatures were measured, in chronological order: 1574°C, 1602°C, 1651°C, 1643°C, 1631°C, 1617°C, 1596°C, 1568°C. The measurement results correctly reflect the law of casting temperature change with time, which provides a reference for the development of the smelting process for new varieties of steel. After a number of casting temperature measurements, the reproducibility of the program is good (Cao, 1998).

This composite scheme combines radiation thermometry with traditional thermocouple thermometry, and calibrates the fiber-optic infrared thermometer with a consumable thermocouple of higher accuracy to compensate for the initial deviation of the instrument. According to the measurement data, the scheme has better repeatability and higher stability, and the loss is much lower than the traditional thermocouple temperature measurement scheme, and the accuracy is higher than that of the scheme using only infrared temperature measurement.

In addition, Zhan Chunlian et al. from the No. 205 Research Institute of China's weapon industry proposed a high-speed multispectral real-time temperature measurement technology program for gas turbine blades, which solves the technical problem that the high-speed and high-temperature blades of domestic gas turbines cannot be monitored in real time. By constructing a comprehensive system integrating high-speed multispectral detection, optical decomposition, signal processing, and software monitoring, Chunlian Zhan effectively solved the limitations of traditional temperature measurement methods in high temperature and high-speed environments, and realized the goal of online real-time temperature measurement and fault warning for turbine blades (Zhang et al., 2018).

3 OPTICAL FIBER THERMOMETRY

3.1 Principle of Distributed Fiber Optic Thermometry

A distributed fiber optic temperature sensor obtains spatial temperature distribution information by using the principle of using light transmission in the optical fiber can produce backward scattering. Injected into the fiber with a certain energy and width of the laser pulse, it is transmitted in the fiber at the same time constantly produce backward scattering light waves, the state of these light waves by the fiber where the temperature of the scattering point and change the scattering back to the light waves by wavelength division multiplexing, detection and demodulation, sent to the signal processing system can be real-time display of temperature signals and by the optical fiber light wave transmission speed and the backward light return time can be on the These information can be localized. The principle and structure of the block diagram are shown in Figures 3 and 4 (Bo, 2024).

Rayleigh scattering, Raman scattering, and Brillouin scattering are mainly involved in distributed fiber optic temperature sensors.

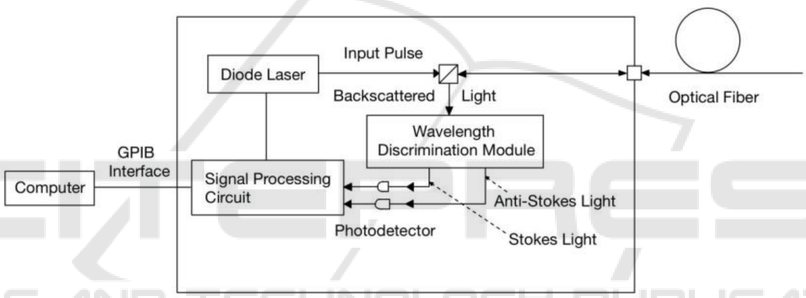

Figure 3: This diagram illustrates the basic working principle and signal processing flow of a fiber-optic distributed temperature sensing system based on Raman scattering (Original).

3.1.1 Rayleigh Scattering

Rayleigh scattering refers to the elastic scattering phenomenon that occurs when an incident electromagnetic wave (e.g., visible light) encounters a tiny particle that is much smaller than its wavelength, due to the excitation of the particle by an external electric field that exhibits an electric dipole radiation effect. Rayleigh scattering occurs when light is incident into an optical fiber, where the backscattered light can be used to monitor the temperature distribution.

The backscattered optical power per unit length is:

$$P(t) = \left(C_g/2\right)E_0{\sim}S(t)\alpha(t)exp\left[-\alpha(t)C_g t\right] \quad (7)$$

Here, it is assumed that the fiber is homogeneous and absorption is neglected. Where $t = 2L/C_g$, i.e., the time experienced by the optical pulse front from injection to return to the injection end from the L point on the optical fiber, different t corresponds to different positions of the sensing fiber; C_g is the speed of light in the optical fiber; E_0 is the injected optical pulse energy; $S(t)$ is the backward scattering factor; $\alpha(t)$ is the Rayleigh scattering coefficient (proportional to the temperature), the change of the temperature causes the change of the numerical aperture of the optical fiber and the Rayleigh scattering coefficient, thus affecting the backward intensity of the scattered light. Based on this property, the temperature distribution along the fiber can be deduced by analyzing the intensity of the backscattered signal returned at different times during the transmission of light pulses in the fiber.

Rayleigh scattering temperature measurement usually uses a pulsed laser light source and a beam splitter between the laser and the fiber. When the backscattered light returns to the injection end of the optical pulse, the beam splitter reflects it back into the detection optical path. The light signal is then detected by an optical receiver system consisting of an avalanche photo diode (APD) and a mutual impedance amplifier, and transmitted to a computer for display after signal processing (Shi et al., 1997). The structure of the device is shown in Figure 4.

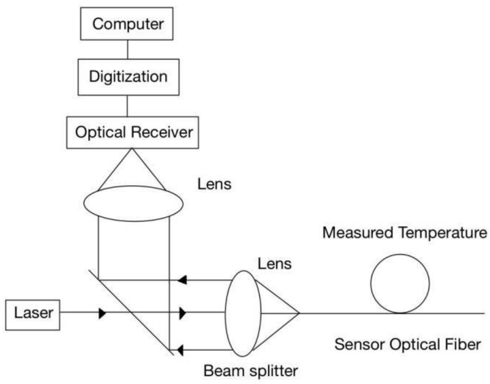

Figure 4: This diagram shows a fiber-optic temperature sensing system using a laser source, beam splitter, lenses, and an optical receiver for temperature measurement and digitization. (Original).

In distributed fiber optic temperature measurement systems that use Rayleigh scattering, the insensitivity of Rayleigh scattered light to physical quantities of temperature leads to a lower temperature resolution in systems that use this scheme. Therefore, the technology of the distributed fiber optic temperature measurement system based on Rayleigh scattered light is gradually being eliminated. When Brillouin scattering is used in the distributed fiber-optic temperature measurement system, the distributed temperature measurement system using Brillouin scattering is not considered for the time being because the corresponding variable physical quantities in the Brillouin-scattered signals and the changes in the temperature are sensitive to the changes in the temperature, which are prone to cross-influence. While in the distributed fiber optic temperature measurement system based on Raman scattering, its Raman scattering signal is only sensitive to the temperature change around the fiber, not easy to be interfered by other signals, and the theoretical knowledge is relatively rich and perfect, there is no special requirement for the type of optical fiber, which is easier to realize and more practical value compared to the above two techniques (Xia et al., 2019).

3.1.2 Raman Scattering

Raman scattering is an inelastic light scattering phenomenon, i.e., after the incident photon interacts with matter, the frequency of the scattered photon changes due to molecular vibration or lattice vibration, resulting in Stokes and anti-Stokes scattering, and its intensity is much lower than that of Rayleigh scattering, which is about as much as that of Rayleigh scattering as shown in Figure 5.

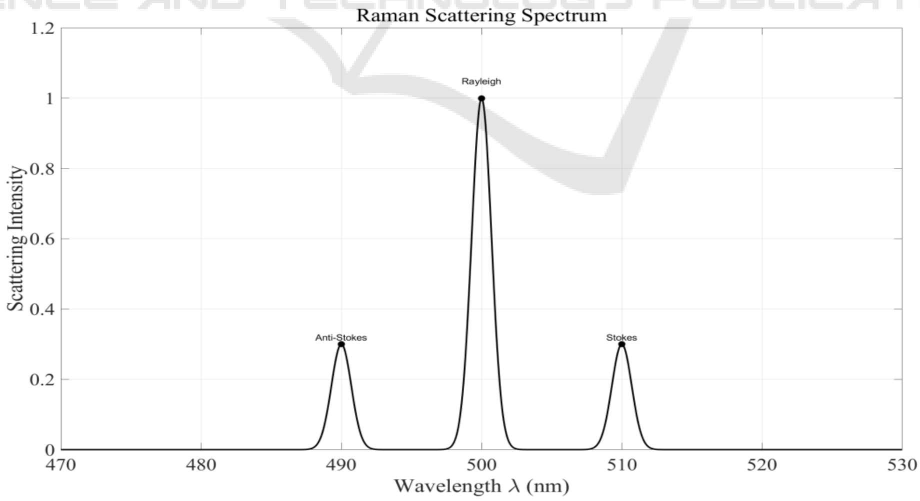

Figure 5: This graph shows the Raman scattering spectrum with Rayleigh, Anti-Stokes, and Stokes peaks used for temperature sensing (Original).

The following is the ratio (R) of anti-Stokes light to Stokes light intensity for Raman scattering as a function of temperature.

$$R = P_{as}/P_{s} = (\lambda_{s}/\lambda_{as})^{4} exp(-hc\gamma/kT) \quad (8)$$

Where, P_{as}, P_{s} are the anti-Stokes and Stokes light intensities of Raman scattering, respectively; λ_{as}, λ_{s} are the anti-Stokes and Stokes light wavelengths of Raman scattering, respectively, which are only related to the fiber material: h is Planck's constant; c is the speed of light;γis the Raman frequency-shift wave number, which is only related to the fiber material; k is Boltzmann's constant; and T is the absolute temperature.

It can be seen that the optical intensity ratio R is not affected by the incident laser power, injection conditions and stress, and thus has good temperature response characteristics. Therefore, the temperature distribution along the fiber can be accurately determined by analyzing the backward Raman scattering intensity ratio of light pulses returned at different times when they are transmitted in the fiber (Hu, 2014).

3.2 Fiber Optic Thermometry in Industry

Due to the distributed Raman temperature measurement technology has the advantages of intrinsic safety, easy to use, low maintenance cost, strong anti-interference ability, large measurement range, in the long-distance application scenarios can be achieved Continuous and uninterrupted temperature detection, can be quickly demodulated in real time temperature, and can be arranged in the environment of the complex and harsh environments, and therefore is often used in oil and gas transmission pipelines, large warehouses, large machinery, Therefore, it is often used in oil and gas pipelines, large warehouses, large machinery, power supply and other scenarios.

In the field of liquefied natural gas (LNG) storage tanks, the distributed fiber optic temperature measurement and warning system is of great significance in the safety management of the tank area. Through the reasonable deployment of distributed fiber optic temperature measurement can be accurate measurement of the tank temperature, can detect the temperature of the tank is too low point, in order to achieve the LNG storage tank perlite filling layer settlement of real-time online monitoring. Distributed fiber optic temperature monitoring system for LNG storage tank temperature monitoring and early warning provides nearly perfect detection performance (Bo, 2024). Table 2 shows the evaluation results in three stages after application. With the continuous improvement of the system, its temperature measurement accuracy is significantly improved, and the percentage of samples with error within 5% is increased from 61.58% in stage 1 to 93.93% in stage 3. Meanwhile, the most negative error and the most positive error are also reduced significantly, indicating that the system error tends to converge and the temperature measurement results are more stable and reliable.

Table 2: Assessment results in the three phases (Xu, 2024).

Phase	Total number of samples taken	Conformity (M ≤ 5%)	minuscule error	logarithmic error
Phase 1	151	61.58%	-51.68%	75.58%
Phase 2	143	85.31%	-21.54%	17.50%
Phase 3	33	93.93%	-6.02%	1

4 CONCLUSION

Compared with the traditional contact temperature measurement method, the optical temperature measurement technology has the advantages of fast response speed, good dynamic performance, and will not destroy the surface temperature field of the measured medium. Due to the uncertainty of the emissivity of the surface of the object, photothermometry may produce errors in the temperature determination process. Therefore, the relevant fields by combining the traditional thermocouple calibration measurement, the introduction of signal processing systems (including APD and mutual impedance amplifier, etc.) to achieve real-time display of temperature signals and distribution of localization, combined with the confocal measurement technology, but also to obtain the temperature distribution of the three-dimensional space, the computer automated control and other programs. Thus, the optical temperature measurement technology without interference, fast response, wide measurement range of features to a greater extent to benefit human production and life and scientific research. In summary, the development trend of optical temperature measurement technology is toward higher accuracy, intelligence and automation, multi-functional integration, better performance and stronger environmental adaptability, the future will bring more innovation and convenience for industrial production and scientific research fields.

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