# Research on On-Line Measurements of Radiation Parameters for High-Temperature Particles Based on Radiation Spectroscopy

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**Abstract** For the radiation heat transfer of particles in high-temperature combustion environment, radiation spectroscopy was presented to on-line measure radiation heat transfer parameters based on Planck's law. According to the changes of radiation spectrums with wavelength in visible range, the temperature and radiation intensity of radiation heat transfer were obtained directly based on parameter fitting method. In order to verify the measurement accuracy, the measurement system of high-temperature blackbody furnace was built. The results of measurements showed that the relative deviation of temperature measurements and setting value was less than 3%, and the relative deviation of radiation intensity measurements and theoretical calculation value was less than 5%. On this basis, the water-cooled probe for radiation heat transfer parameters measurement of particles in high-temperature combustion environment was designed and applied to measure 200～1 100 nm radiation spectrums of gas-solid two phase flow in high-temperature combustion environment. The across section distribution of temperature and radiation intensity of high-temperature particles were obtained directly by using this method. It can eliminate influence of gas convective heat transfer effectively, and provide data support for research on radiation heat transfer of high-temperature particles.

**Keywords** Radiation spectroscopy; High-temperature particles; Radiation heat transfer; On-line measurements

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## Introduction

As one of the main heat transfer modes of combustion equipment such as pulverized coal furnace, radiation heat transfer is of great significance to the optimization of heat transfer process and the improvement of energy utilization rate[1]. In the gas-solid two-phase flow of combustion equipment such as boilers, radiation heat transfer is made up of gas and solid radiation[2-3]. At present, the researches on the influence of radiation parameters on the heat transfer of combustion equipment mainly rely on numerical simulation to establish the complex gas-solid two-phase radiation heat transfer model. In order to obtain the effect of radiation parameters on the heat transfer of combustion equipment[4-6].

However, with the complex absorbing, emitting and scattering of radiation, it is difficult to establish an accurate radiation heat transfer model for high-temperature combustion

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environment. Therefore, it is necessary to carry out radiation heat transfer measurement in high-temperature combustion environment. The methods of radiation heat transfer measurement in high-temperature combustion environment can be divided into indirect measurement and direct measurement[7]. The indirect measurement methods such as heat flow meter areused to calculate the radiation energy based on heat analysis of the energy conservation law and temperature measurement. Rendesigned the film radiation heat sensor based on temperature different measurement, and analyzed the influences of the materialproperties on the measurement results[8]. Chen et al. measured radiative heat transfer parameters by using a transient bolometer under the conditions of stable natural convection heat transfer and weakened heat conduction[9]. But the influence of convection heat transfer on the radiation heat transfer measurement cannot be eliminated in the case that radiation heat transfer and convection heat transfer coexist. The detection device needs complex protection structure in high-temperature environment. And the flow field will be disturbed by the measuring equipment. The direct measurement methods are used to obtained radiation energy directly to analyze the temperature and radiation intensity, including radiation thermometry, radiation spectroscopy and radiation imaging method. Yang et al. used the radiation spectroscopy to carry out experimental research on radiation spectrum of pulverized coal combustion flame, and obtained flame temperature and emissivity parameters based on radiation spectroscopy[10]. Cheng et al proposed the DRESOR method to solve radiation transfer equations and calculated the distribution of radiation intensity in space based on radiation imagingmethod[11]. Garces et al. proposed the improvedradiation temperature measurement algorithm of the radiation signals of combustion flame in industrial furnaces[12]. These direct measurement methods can eliminate influence of other heat transferin the combustion environment on radiation heat transfer measurements effectively and have more measurement accuracy for high-temperature by using parameter fitting method. In particular, more abundant spectrums and space distribution information can be obtained.

Owing to many influence factors such as spectral response, range and resolution on the measurement accuracy of radiation spectroscopy, the measurement system of high-temperature blackbody furnace was built, and experimental research was carried out to verify the measurement accuracy in this paper. Furthermore, the water-cooled probe was designed and applied to measure temperature and radiation intensity of radiation heat transfer parameters of particles in the high-temperature combustion environment.

# 1 Principle of Radiation Spectroscopy

A spectrometer was used to obtain high-temperature particle. The high-temperature particles were treated as a gray body. According to the Planck's law, the radiation intensity received by the spectrometer can be expressed as follows:

$$E_{\lambda_i} = k\varepsilon\lambda_i^{-5}\left(\exp\left(\frac{-C_2}{\lambda_1 T}\right)-1\right) \tag{1}$$

Where $E_{\lambda_i}$ is the spectral emissive power distribution for a given wavelength, is the average emissivity of the high-temperature particles in detected waveband, $T$ is temperature, $k$ is the response coefficient of the spectrometer, $C_1=3.741\,9\times10^{-16}$ W · m$^2$ and $C_2=1.438\,8\times10^{-2}$ m · K are called Planck's firstand second radiation constant, respectively.

When $\lambda T\leqslant 2\,000$ μm · K, Planck's Law can be simplified to Wien's relation

$$E_{\lambda_i} = k\varepsilon\lambda_i^{-5}\exp\left(\frac{-C_2}{\lambda_i T}\right) \tag{2}$$

Thus, the establishment of the objective function is expressed according to the nonlinear least squares method

$$f(\varepsilon',t) = \sum_{i=1}^{n}(\ln E_{\lambda_i}-y_i)^2 = \sum_{i=1}^{n}\left(\ln k+\varepsilon'-5\ln\lambda_i-\frac{C_2}{\lambda_i}t-y_i\right)^2 \tag{3}$$

Where $\varepsilon'=\ln\varepsilon$, $t=1/T$, $y_i$ is the logarithm of the radiation intensity corresponding to the wavelength measured during the experiment.

$\varepsilon'$ and $t$ are the only unknown parameters in the expression. When the minimum of objective function $f(\varepsilon',t)$ is achieved, the corresponding value $\varepsilon'$ and $t$ can becalculated by the nonlinear least square method. Therefore, $\varepsilon$ and $T$, the average temperature and emissivity along the line-of-sight can be obtained. Combined with the Stefan-Boltzman's Law, the $E$, radiation intensity of high-temperature particles can be calculated as follows

$$E = \varepsilon C_0\left(\frac{T}{100}\right)^4 \tag{4}$$

Where $C_0=5.67$ W · (m$^2$ · K$^4$)$^{-1}$ is the black body radiation coefficient.

# 2 Experimental study on measurement accuracy

## 2.1 Experimental system

In order to verify the measurement accuracy of the radiation spectroscopy, a blackbody furnace measurement system is builtto carry out high-temperature blackbody radiation measurement. The set temperature ranges from 1 073 to 1 373 K. The temperature and radiation intensity are obtained by radiation spectroscopy. The measurement result is compared with the set temperature in blackbody furnace and the corresponding theoretical blackbody radiation intensity.

The experimental system is shown in Figure 1. The collimator probe is used to converge the parallel light along the line-of-sight of the high-temperature black body in the blackbody furnace. And the light signal is transmitted to the spectrometer (Ocean optics, HR4000, 200～1 100 nm) by optical fiber. The spectrometer is connected to the computer through the USB data cable. And the signal is transferred to the computer for analysis after the photoelectric conversion in spectrometer.

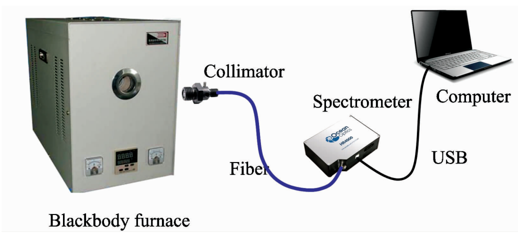


**Fig. 1 Experimental system of radiation parameter measurement**

### 2.2 Results and analysis

The spectrum with a wavelength ranging from 200 to 1 100 nm is obtained by spectrometer in blackbody furnace with a temperature ranging from 1 073 to 1 373 K, as shown in Figure 2. The radiation intensity increases with the increasing temperature. The spectrums in 700～900 nm wavelength range are selected for data analysis due to high signal-to-noise ratio, and the spectral response coefficient is relatively flat with the wavelength distribution, the error caused by the data analysis is small[13].

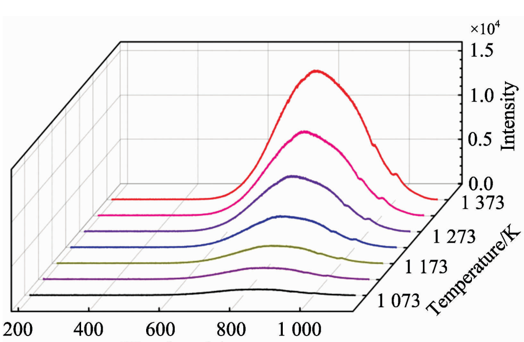


**Fig. 2 Response spectrums of spectrometer in 200～1 100 nm wavelength rangeat different temperatures in blackbody furnace**

The original spectrums ranging from 700 to 900 nm are calibrated according to the spectrometer response coefficient, and the actual radiation spectrums of the blackbody furnace at different temperatures are shown in Figure 3.

The nonlinear least squares method is used to analyzed actual radiation spectrum to obtain temperature $T_m$ and emissivity $\varepsilon$, and the radiation intensity $E_m$ can be calcumated by Stefan-Boltzman's Law. The result is compared with the set temperature in blackbody furnace and the corresponding theoretical blackbody radiation intensity $E_b$, as shown in Table 1, which shows that relative deviation between the temperature measured by Radiation Spectroscopyand theset temperature is less than 3%, and the relative deviation between the measured radiation intensity and theoretical blackbody radiation intensity is less than 5%. The calculated radiation intensity and temperature are generally higher than the set value and the theoretical value. Because the measured radiation signal is the accumulative value along the measurement direction in the blackbody furnace. However, it has little influence at the temperature ranging from 1 073 to 1 373 K during the measurement. This verifies the measurement accuracy of radiation parameters in high-temperature environment based on Radiation Spectroscopy.

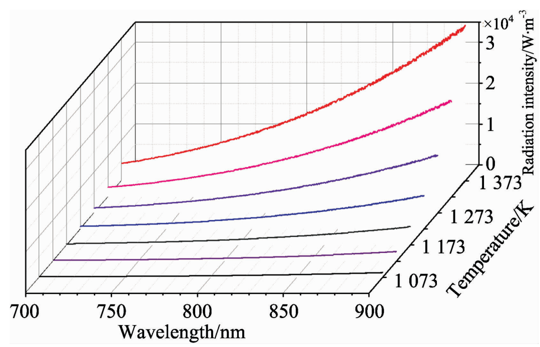


**Fig. 3 Radiation spectrums in 700～900 nm wavelength range after calibration by response coefficient**

**Table 1 Verification of measurement accuracy**

| $T_b$ /K | $E_b$ /(W · m$^{-2}$) | Measurement result | | | |
|---|---|---|---|---|---|
| | | $T_m$ /K | Dewiation /% | $E_m$ /K | Deviation /% |
| 1 073 | 75 159 | 1 076 | 0.28 | 77 171 | 2.54 |
| 1 123 | 90 178 | 1 131 | 0.71 | 92 071 | 2.10 |
| 1 173 | 107 343 | 1 185 | 1.04 | 111 551 | 3.92 |
| 1 223 | 126 849 | 1 251 | 2.23 | 130 388 | 2.79 |
| 1 273 | 148 901 | 1 290 | 1.31 | 156 271 | 4.95 |
| 1 323 | 173 709 | 1 349 | 1.97 | 181 421 | 4.44 |
| 1 373 | 201 495 | 1 412 | 2.87 | 211 046 | 4.74 |

## 3 Measurement in high-temperature environment

### 3.1 Measurement system

The high-temperature particle multi-parameters measurement system includes measurement probe, water cooling system, optical fiber, spectrometer and data processing system. During the measurement, the radiation signal of high-temperature particle is collected by measurement probe and the signal is transmitted to the spectrometer by optical fiber. The spectral characteristics of the high-temperature particle can be analyzed when the radiation spectrum signal is input into data processing system for processing.

The measurement probe is used to measure the radiation parameter of high-temperature particles in a coal-fired boiler. The measurement point is positionedon boiler wall, as shown in Figure 4. The depth of measurement points ranges from 0 to 6 m and the distance between each measurement point is 1 m.

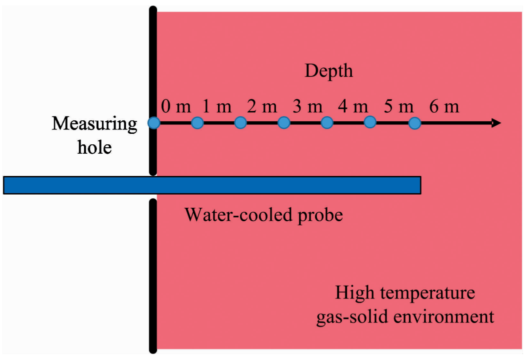


**Fig. 4　Location of measurement points**

### 3.2　Results and analysis

The radiation spectrumis obtained at different measurement points, as shown in Figure 5. The high-temperature gas-solid combustion environment is mainly composed of triatomic gases ($CO_2$, $H_2O$, etc.) and suspended solid particles (coal, ash, soot). The radiation and absorption characteristics of the gas and particle are completely different. The triatomic gas radiation concentrats in the infrared wavelength range, and the spectrum is banded due to the molecular absorption characteristics. The solid particle radiation spectrum is consisted of continuous spectrum and the strong atomic emission lines caused by excitation of metal atoms under certain conditions[14]. Therefore, it can be considered that the radiation spectrum in the 200～1 100 nm wavelength range is mainly a continuous radiation spectrum generated by a gray body such as a solid particle. With the increase of the measurement point depth, the radiation intensity of high-temperature particles gradually grows, and the radiation signal from 0 to 4 m increases rapidly. And radiation intensity tends to be lower within the depth ranging from 4 to 6 m, as shown in figure 5. The spectrum signal is weak in the 200～500 nm band of radiation spectrum due toits low intensity in the high-temperature environment of power station boilers, and that's why the growth trend with temperature is not obvious.

The high-temperature particles spectrum shows alkali metal emission peaks at 767 and 769 nm. According to the NIST's (National Institute of Standards and Technology) atomic spectra database, the atomic emission peaks are generated by the alkali metal element Na and K. The radiation spectrum of the combustion medium in high-temperature environment always appears as strong atomic emission lines caused by alkali metal elements at specific wavelengths, and these characteristic lines will interfere with the measurement results. Besides, the high-temperature particle radiation spectrum is not exactly consistent with the radiation characteristics of the grey body. These factors cause analysis errors for the radiation parameter measurements. Therefore, a gray property judgment method for high-temperature particle based on spectral analysis and the two-color method is used to select the appropriate wavelength range[15]. The emissivity with the wavelength distributionat different measurement points in the 500～1 000 nm wavelength range is obtainedby using the two-color method, as shown in figure 6.

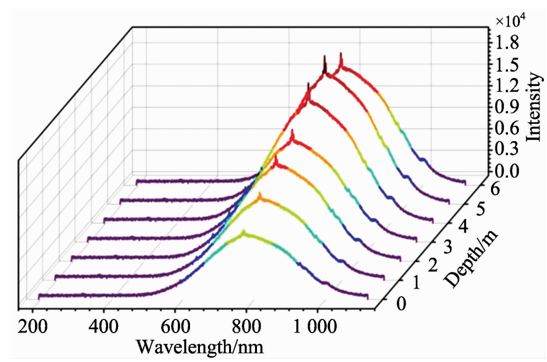


**Fig. 5　Radiation spectrum of high-temperature particles at different measurement points**

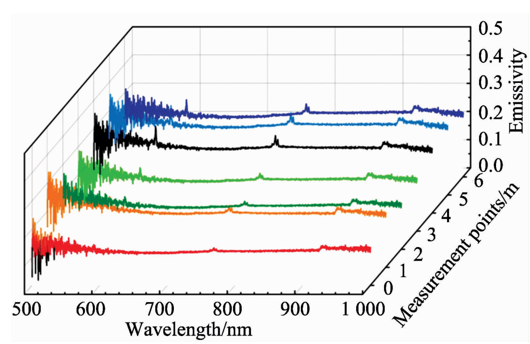


**Fig. 6　Wavelength-dependent emissivity distribution of high-temperature particles in 500～1 000 nm wavelength range at different measurement points**

A spectrometer has different response characteristics at different wavelength bands. The emissivity profiles of high-temperature particles fluctuate widely in the 500～700 nm wavelength range due to small signal-to-noise ratio of the spectrometer. The fluctuation of the emissivity in the 900～1 000 nm wavelength of the radiation spectrum due to high-temperature particles in this range cannot be assumed as a gray body. The discontinuous spectra near the 769 nm represents the emission peak caused by the alkali metal element. These factors will cause analysis errors in the measurement of radiation parameters. Therefore, the spectrum ranging from 700 to 900 nm wavelengthis intercepted and the discontinuous emission peak caused by the alkali metal element is separated. The emissivity profile in 700～900 nm wavelength rangeis shown in figure 7, describing how high-temperature particles can be assumed to be a gray body.

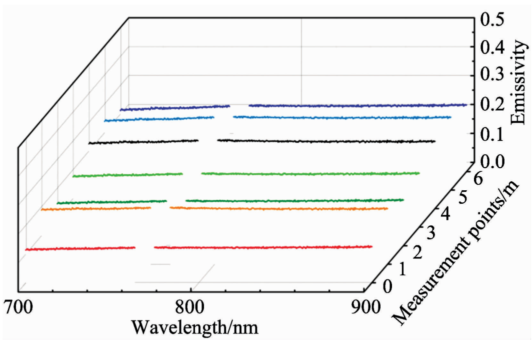


**Fig. 7 Wavelength-dependent emissivity distribution of high-temperature particles in 700 ～ 900 nm wavelength rangeat different measurement points**

The measurement results of high-temperature particle radiation parameters are shown in Figure 8. The temperature and emissivity are obtained by the parameter fitting method,

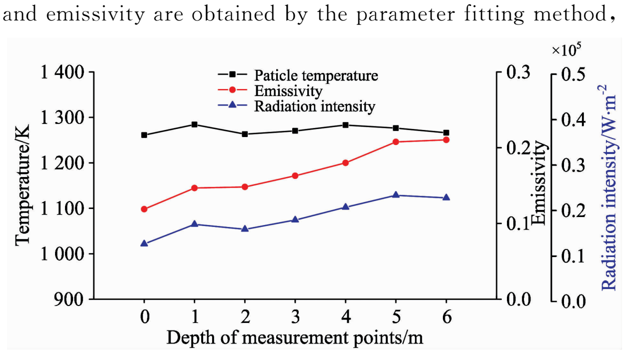


**Fig. 8 Parameters distribution of high-temperature particles in high-temperature gas-solid environment**

and the radiation intensity of high-temperature calculated using Stefan-Boltzman's Law. The high-temperature particles is particle's temperature fluctuates less in their own environment. However, their emissivity and radiation intensity increase as the depth of the measurement points grows. The combustion process of high-temperatureparticles is approximately similar in the same section in the combustion environment. Therefore, their emissivity can also be used to characterize their concentration and a higher emissivity is caused by a higher concentration. When the particles concentration is greater and the radiation heat transfer conditions are better in the deeper position of the measurement point.

## 4 Conclusion

(1) For the radiation heat transfer of particles in high-temperature combustion environment, radiation spectroscopy was presented to on-line measure radiation heat transfer parameters based on Planck's law. According to the changes of radiation spectrums with wavelength in visible range, the temperature and radiation intensity of radiation heat transfer were obtained directly based on parameter fitting method.

(2) The measurements accuracy experimental results showed that the relative deviation of temperature measurements and setting value is less than 3%, and the relative deviation of radiation intensity measurements and theoretical calculation value is less than 5%.

(3) The water-cooled probe for radiation heat transfer parameters measurement of particles in high-temperature combustion environment was designed and applied to measure 200～1 100 nm radiation spectrums of gas-solid two phase flow in high-temperature combustion environment. The across section distribution of temperature and radiation intensity of high-temperature particles were obtained directly by using this method. It can eliminate influence of gas convective heat transfer effectively, and provide data support for research on radiation heat transfer of high-temperature particles.

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# 基于辐射光谱法的高温颗粒辐射传热参数在线测量方法研究

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**摘　要**　针对在高温燃烧环境中的颗粒辐射传热问题，基于普朗克辐射定律，提出了用于高温颗粒辐射传热参数在线测量的辐射光谱法，根据高温颗粒可见波段辐射光谱随波长变化情况，通过参数拟合方法直接获得颗粒温度及辐射强度等辐射传热参数。为验证该方法测量准确性，搭建了高温黑体炉辐射测量系统，实验测量结果显示：温度测量值与设定温度相对偏差小于 3%；辐射强度测量值与理论计算值相对偏差小于 5%。以此为基础，设计了应用于高温燃烧环境下的颗粒辐射传热参数测量的水冷结构探针，并利用该探针开展了高温燃烧环境气固两相流 200～1 100 nm 波段辐射光谱测量，基于上述方法，直接获得了高温颗粒温度、辐射强度等辐射传热参数沿截面分布情况，有效剥离了高温气体对流传热的影响，为高温颗粒辐射传热研究提供数据支撑。

**关键词**　辐射光谱法；高温颗粒；辐射传热；在线测量

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