Application of a Temperature Measurement System Based on CCD Sensor in Blast Furnace Tuyere Raceway

Xiaoman Cheng, Shusen Cheng, Dongdong Zhou, and Ruixuan Zhang

Abstract According to the principle of spectral radiation, a color charge-coupled-device (CCD)-based pyrometer system has been established for the detection of combustion in the blast furnace tuyere raceway. The two-color method is applied to calculate the two-dimensional projection temperature distribution, as it has great advantages in the harsh measurement environment. In this chapter, the radiation images of the flame in the raceway are photographed using a color CCD camera and its two-dimensional projection temperature distribution is obtained by the two-color method and image processing technology. The results show that the average projection temperature of 320 and 5500 m^3 blast furnace are about 2260.5 K and 2266.8 K, respectively. The measured results are basically agreed with the theoretical combustion temperature. It is indicated that the temperature measurement system developed in this chapter can accurately evaluate the combustion situation in the raceway and it contributes to the stable operation of the blast furnace.

Keywords CCD sensor · Raceway · Radiation images · Two-dimensional projection temperature · Image processing

1 Introduction

The temperature field of the blast furnace raceway directly reflects the combustion behavior of the injected pulverized coal and descending coke. Observation through tuyere is the only way to monitor the inner situation of blast furnace [1]. Thermocouple is one kind of common temperature element. However, it needs to be sent into the raceway [2]. This method is difficult to implement on the blast furnace raceway. The non-contact temperature measurement method is suitable for measuring the

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E. T. Quinto et al. (eds.), *The Proceedings of the International Conference on Sensing and Imaging, 2018*, Lecture Notes in Electrical Engineering 606,
https://doi.org/10.1007/978-3-030-30825-4_17

temperature of the raceway because of short temperature response time and non-contact [3]. Therefore, the high-temperature measurement method based on CCD image sensor has become a research hotspot in recent years.

The temperature field distribution of the flame by the area CCD is not strictly representative of a true temperature distribution, and is called the "projection temperature field" [4]. But it does not mean that measurement is not practical. F. Meriaudeau proposed a multispectral imaging system based on two CCD cameras and it should be used in the laser cladding process [5]. Huang Y et al. reported experimental investigations on temperature distributions in a 500-kW model furnace [6]. Jiang Z et al. presented a method to derive the temperature by a color CCD image for coal-fired combustion processes [7]. Temperature measurement methods based on digital imaging technology were widely used in industrial industries.

In this chapter, a pyrometer that is based on a CCD camera is used to measure the temperature distribution in blast furnace raceway. During the calibration and measurement of the blackbody furnace, it is found that the exposure time should be fixed to reduce the error, and different calibration parameters were used according to the exposure time. Finally, the experiment was carried out in two different blast furnaces. The projection temperature distribution is obtained through image processing and the two-color method.

2 Experiments

Temperature Measurement System Based on Digital Imaging

The system used in this work is shown in Fig. 1. The most important device in this system is a color CCD camera (MER-125-30UC). The sensor is Sony ICX445 CCD. The CCD sensor has Global Shutter, 1/3 in. chip, 1292 (H) × 964 (V) pixel resolution, 3.75 μm × 3.75 μm cell size. For 8 bit output, the range of gray level is from 0 to 255. The sensitivity curves of the three channels are provided by the manufacturer, as shown in Fig. 2. The focal length of lens is determined by the distance from the measured object.

Experiments are conducted on 320 and 5500 m^3 blast furnaces by this system to detect the temperature of the blast furnace raceway. The specific steps are as follows. Firstly, the lens in the peephole is checked for brightness and cleanness to avoid blocking light. Secondly, the CCD camera is installed in the front of the tuyere peephole of blast furnace to receive the light beam emitted from the raceway. Then fine-tune the camera position so that the image is as centered as possible on the screen. Finally, the camera parameters are adjusted to avoid saturation or excessively small data values for the high-temperature measurements.

The image processing procedures are shown in Fig. 3. Median filtering is a typical pre-processing step which can eliminate noise and preserve edges at the same time. The region of interest (ROI) is found by image thresholding algorithm.

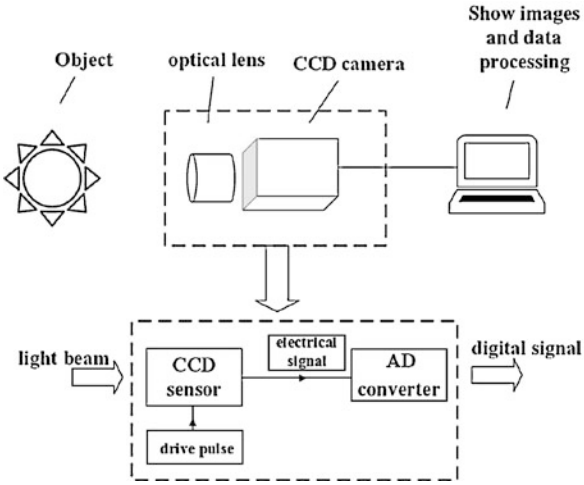

Fig. 1 Schematic diagram of the measuring system

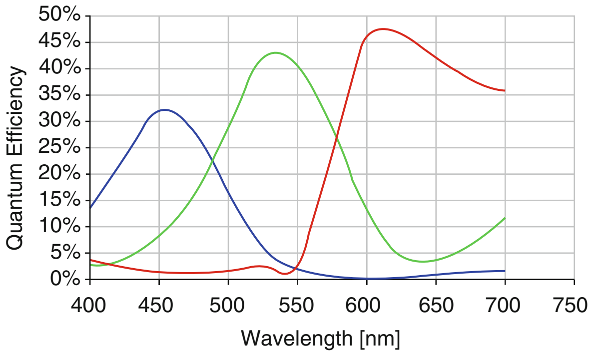

Fig. 2 Spectral response curve of CCD camera

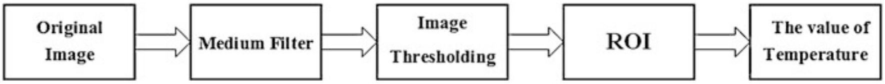

Fig. 3 Image processing routines

In this chapter, the ROI is the flame of blast furnace raceway in visible range. Then temperature can be calculated by two-color method finally.

Imaging Principle and Calculation Method

Figure 1 details the signal processing procedure. The high-temperature object emits light due to thermal radiation, and the light beam is irradiated to the CCD sensor through the optical lens. Photoelectric conversion is performed on the photosensitive pixels of the CCD sensor to form a signal charge. The signals are sequentially shifted out under the action of the drive pulse, eventually forming an electrical signal. It is converted into a digital signal via an A/D converter, and the digital signal forms a digital image stored in a memory [8]. The relationship between the gray value of the image pixel output and the spectral radiation of the measured object is given by:

$$H = \frac{\eta \mu t \omega}{F^2} \int_{\lambda_2}^{\lambda_1} \varepsilon\left(\lambda, T\right) E\left(\lambda, T\right) V\left(\lambda\right) d\lambda \tag{1}$$

where η is the modulus conversion coefficient, μ is the photoelectric conversion coefficient, ω is the influence coefficient of the optical system, t is the exposure time, F is the aperture value, and $\varepsilon(\lambda, T)$ is the emissivity of the object, $E(\lambda, T)$ is the monochromatic radiation power and $V(\lambda)$ is the spectral response function of the CCD camera.

Due to the spectral response function of the color CCD camera is complicated, the response curves of the red, green, and blue channels are approximated ideal, so that Eq. (1) is simplified. According to the International Commission on Illumination (CIE), the three-channel wavelengths are selected to be 700.0 nm (R), 546.1 nm (G), and 435.8 nm (B), respectively.

Defining $N_i = {}^{\eta \mu t \omega}\Big/_{F^2}\ V\left(\lambda\right)$:

$$H_i = N_i \varepsilon\left(\lambda, T\right) E\left(\lambda, T\right), i = \mathrm{R, G, B} \tag{2}$$

The two wavelengths in the two-color method can be selected, but the spectral sensitivities of the R and G channels are higher in the temperature measurement system. Moreover, it can be approximately regarded as a gray body, because when the two wavelengths are close, the flame emissivity hardly changes. The expression can be written as:

$$\frac{H_\mathrm{R}}{H_\mathrm{G}} = \frac{N_\mathrm{R}}{N_\mathrm{G}} \frac{E\left(\lambda_\mathrm{R}, T\right)}{E\left(\lambda_\mathrm{G}, T\right)} \tag{3}$$

where $N_\mathrm{R}/N_\mathrm{G}$ contains conversion coefficients and device parameters. It is necessary to be calibrated to get accurate values. Blackbody furnace as a standard reference was used to calibrate the pyrometer. The temperature range of blackbody furnace was 1773–2273 K. Images were captured at the interval of 100 K. Images with exposure times of 10, 30, 50, 70, 90, and 110 μs at the same temperature were taken.

3 Results and Discussion

Calibration in Blackbody Furnace

For images of blackbody furnace, the gray level of the two wavelengths can be obtained by using image processing technology. However, it is worth noting that when the temperature of blackbody furnace is the same, the gray value of each channel increases at different speeds with the exposure time changes, so the ratio is

Fig. 4 The value of H_R/H_G at different exposure times

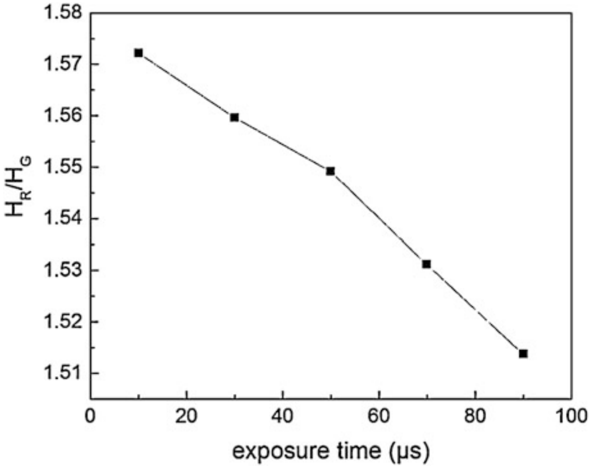

Table 1 Calculated temperature using different calibration results

The temperature of the black furnace/K	Calculated temperature/K	
	Calibration results of 10 μs	Calibration results of 70 μs
2073.0	2075.2	2034.5
2073.0	2074.1	2034.3
2073.0	2075.3	2034.8
2073.0	2074.1	2034.1
2073.0	2075.8	2035.3

different. The value of H_R/H_G at different exposure times in 2073 K are shown in Fig. 4. It can be obviously found that the ratio decreased from 1.57 to about 1.51. Theoretically, the exposure time has no effect on the value of H_R/H_G. Actually, the effect of exposure time on the pixel value is not linear, because of the loss of the signal during the imaging process [9]. So the final calibration result is not a constant.

Five images are selected randomly when the parameter is 10 μs at 2073 K. The calibration results of 10 and 70 μs were used for calculating temperature. The calculated temperature is shown in Table 1. From the comparison of the measured results, the absolute error is 2.1 and 38.4 K after averaging five images. The parameter of exposure time should be fixed, and the temperature should be calculated with the corresponding calibration results.

The Projection Temperature Distributions of Blast Furnace Raceway

The images of raceway in 320 and 5500 m^3 blast furnaces are shown in Figs. 5 and 6, respectively. There are coal lance and the pulverized coal cloud in images. These

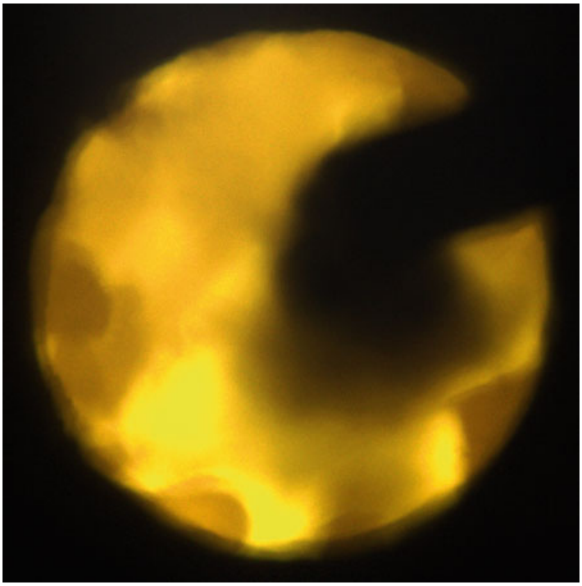

Fig. 5 The image of raceway in 320 m^3 blast furnace

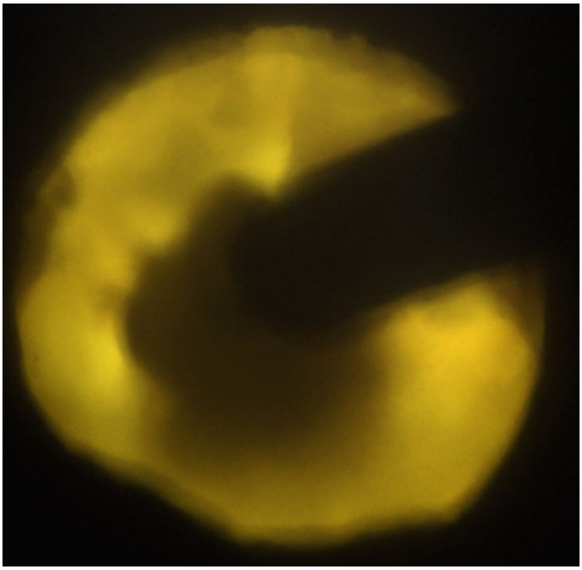

Fig. 6 The image of raceway in 5500 m^3 blast furnace

areas cannot represent the combustion, so they are removed by image processing before calculating the projected temperature field [10].

Figure 7 shows the two-dimensional projection temperature distributions of raceway of 320 m^3 blast furnace. The average temperature of the projected temperature field is about 2230.5 K. In 180 s, the temperature changed from 2205.6 to 2320.8 K. In addition, the average temperature of the raceway is 2260.5 K, and

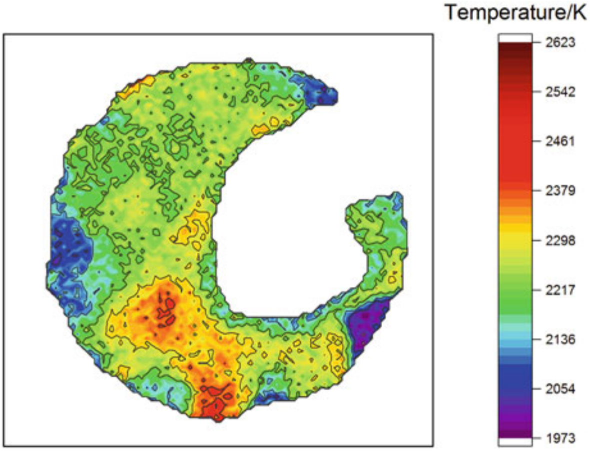

Fig. 7 The temperature distribution of raceway in 320 m^3 blast furnace

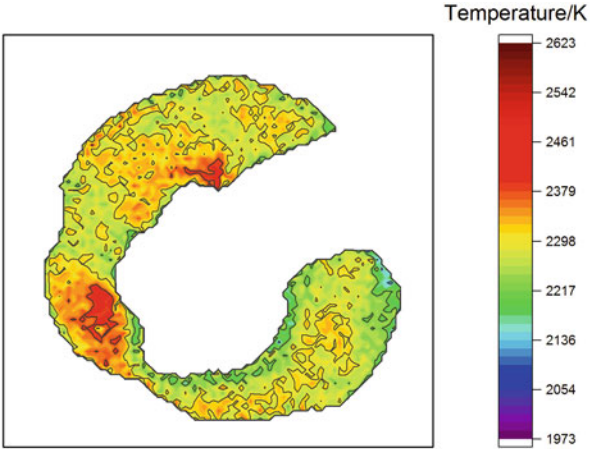

Fig. 8 The temperature distribution of raceway in 5500 m^3 blast furnace

the temperature difference is 115.2 K. The adiabatic combustion temperature of the blast furnace raceway can be a reference, and it is generally about 2273 K [11]. Due to the complex reaction before the tuyere, the theoretical combustion temperature is not the true temperature of blast furnace tuyere, but it has reference value. The measurement results are basically consistent with the adiabatic combustion temperature.

The two-dimensional projection temperature distributions of raceway of 5500 m^3 blast furnace are shown in Fig. 8. The average temperature is about 2287.2 K. The temperature changed from 2198.6 to 2384.6 K, the average temperature of raceway is 2266.8 K, and the temperature difference in 180 s is 186 K.

Comparing the images of raceway of 320 and 5500 m^3, the average temperature in 3 min of 320 m^3 is smaller than that of 5500 m^3 blast furnace. And more particles can be seen in the images of the raceway of 320 m^3 blast furnace. Two blast furnaces with different effective volumes were measured, including a small blast furnace and a large blast furnace. In previous research, 2000 and 2500 m^3 blast furnaces were successfully measured [12]. It indicates that this system can be applied to all kinds of blast furnaces.

Error Analysis and Future

To simplify the calculation of Eq. (1), the spectral response functions of the CCD camera are reduced to impulse functions approximately. It can be observed from Fig. 2 that the values of red and green channels of the CCD are obtained by the continuous spectral response.

After simplifying, the wavelength is selected according to the international regulations. Generally, the three primary colors of the CCD not necessarily use the wavelengths which they specified by CIE. However, it is necessary to consider the spectral response of the CCD. The wavelength with the largest response of the monochromatic spectrum is used as the representative wavelength, thus better reflecting the spectral intensity of the object [13].

The response values of the R and G channels are often used in the two-color method. To prevent the effects of noise and saturation, it is limited to the range of 11–245. The state of the B channel is ignored in blackbody furnaces test or industrial applications. Most of the values of B channel of images are less than 10. Ignoring the state of the B channel can interfere with the signal.

Considering the above errors, we have proposed a new optimization scheme that using a multipeak interference filter with a 3CCD camera. The filter blocks optical signals other than the designated bands [14]. There are three CCD chips in the 3CCD camera. The exposure time of the three channels can be controlled respectively [15]. The optimized system not only eliminates the above errors, but also makes the system more flexible. First, according to the temperature measurement environment and the object, the wavelength combination filter is selected. Moreover, it is possible to select the two-color method or the three-color method. In the future, we will study on the temperature measurement performance of the new system. Applications will not be limited to measuring blast furnaces, extending to other metallurgical processes such as converter steelmaking process and refining process.

4 Conclusions

The two-dimensional projection temperature measurement system based on CCD sensor was successfully established to capture the flame radiations in the tuyere raceway of 320 and 5500 m^3 blast furnaces, and the two-dimensional projection temperature distributions are gained by the two-color method.

Blackbody furnace as a standard reference was used to calibrate this system. The final calibration result is a relation between N_R/N_G and H_R/H_G. During the calibration process, parameters cannot be changed to avoid errors.

The average temperatures of images of raceway of 320 and 5500 m^3 in 3 min are 2260.5 K and 2266.8 K, respectively. The temperature of tuyere raceway changes in a short time in different blast furnaces. In the images of the raceway of smaller blast furnace, more particles can be seen.

Through error analysis, a new optimization scheme that using a multipeak interference filter with a 3CCD camera is proposed. Looking forward to more applications of CCD sensors in the metallurgical industry.

Acknowledgments This project is supported by the National Key R&D Program of China (2017YFB0304300&2017YFB0304302).

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