Application of a two-dimensional projection temperature measurement system based on charge-coupled device sensor in blast furnace tuyere raceway

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Abstract According to the principle of spectral radiation, a color Charge-coupled-Device (CCD)–based sensor 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 paper, 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 with image processing technology. The results show that the average projection temperature of 320 and 5500 m^3 blast furnace are about 2260.5K and 2266.8K, respectively. The measured results are basically agreed with the theoretical combustion temperature. It is indicated that the temperature measurement system developed in this paper can accurately valuate 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

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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]. Traditional contact temperature measurement techniques such as thermocouple temperature measurement can cause severe interference to the temperature field[2]. This method is difficult to implement for the blast furnace tuyere raceway. The non-contact temperature measurement method which has the advantages of short temperature response time and not affecting the operation of the blast furnace is suitable for measuring the temperature of the raceway[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 obtained 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 its measurement is not practical. F.Meriaudeau et al. 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 paper, the pyrometer based on CCD camera is used for monitoring projection 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 the temperature calculation was used different calibration parameters 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

2.1 Temperature measurement system based on digital imaging

The system used in this work is shown in Figure 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 Figure 2. The suitable focal length of lens is determind based on the distance from the measured object.

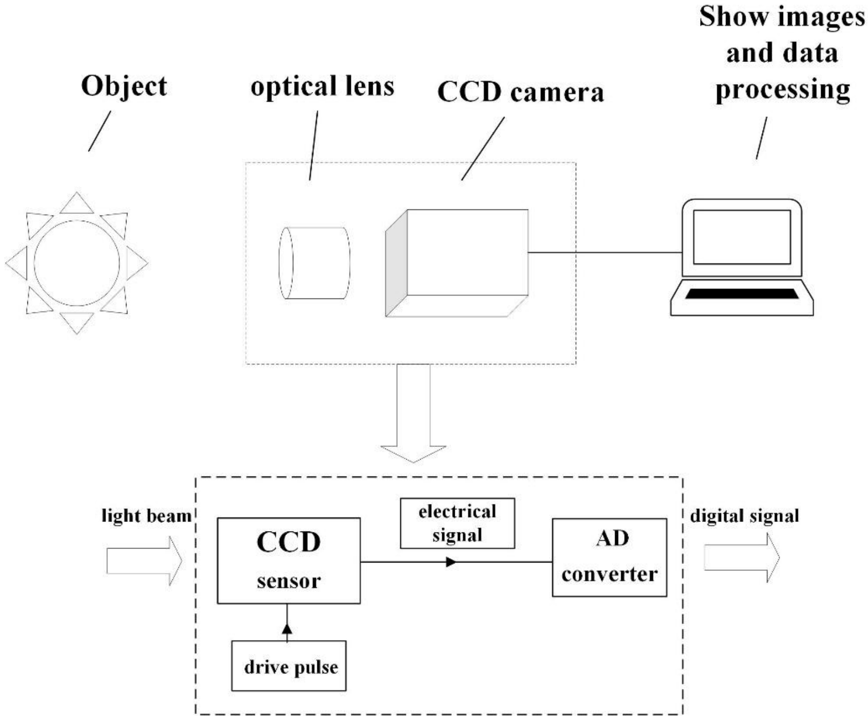

Fig. 1. Schematic diagram of the measuring system

Experiments are conducted on 320 and 5500 m³ blast furnaces by this system to detect the temperature of the blast furnace raceway. The flame of the blast furnace tuyere raceway is composed of combustion mediums in three-dimensional space. Any point on the flame image represents the accumulation of the amount of light radiation of the visible flame in the longitudinal direction. The temperature measured by the flame image represents the projected temperature field of the visible range.

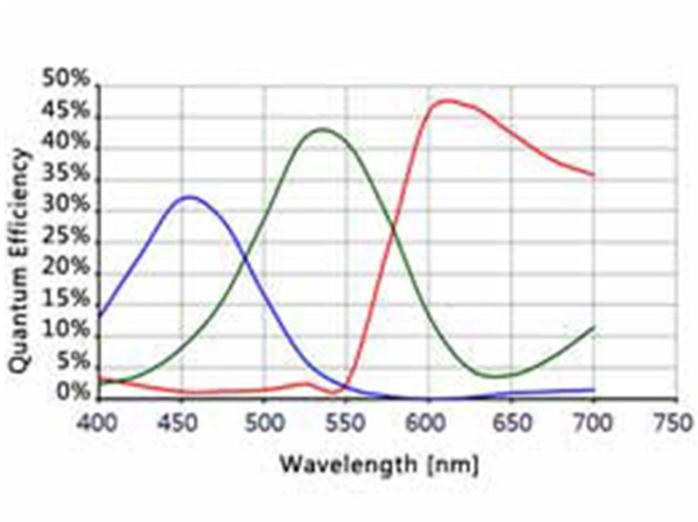

Fig. 2. Spectral response curve of CCD camera

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-tuned aimed at the image as much as possible in the center of the screen. Finally, the camera parameters are adjusted to avoid saturation or excessively small data values for the high-temperature measurements.

Fig. 3. Image processing routines

The projected temperature of radiation images could be obtained by two-color method and image processing techniques. The image processing procedures are shown in Figure 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. In this paper, the ROI is the flame of blast furnace raceway in visible range. Then temperature can be calculated by two-color method finally.

2.2 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 a 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:

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

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, ε(λ,T) is the emissivity of the object, E(λ, T) is the monochromatic Radiation power and V(λ) 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 to ideal, so that the integral in Equation 1 is simplified. According to the International Commission on Illumination (CIE), the three-channel wavelengths were selected to be 700.0 nm (R), 546.1 nm (G), and 435.8 nm (B), respectively.

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

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

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

$$\frac{H_R}{H_G} = \frac{N_R}{N_G}\frac{\mathrm{E}\left(\lambda_R,T\right)}{\mathrm{E}\left(\lambda_G,T\right)} \tag{3}$$

where N_R/N_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 1773–2273K. Images were captured at the interval of 100K. Over the course of the photo shoot, images with exposure times of 10μs, 30μs, 50μs, 70μs, 90μs and 110μs at the same temperature were taken.

3. Results and Discussion

3.1Calibration in Blackbody furnace

For images of blackbody furnace, the grey level of the two wavelengths can be obtained 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 different. The value of H_R/H_G at different exposure times in 2073K are shown in Figure 4. It can been 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 the loss of the signal during the imaging process[9]. The final calibration result is not a constant, but the relationship between N_R/N_G and H_R/H_G.

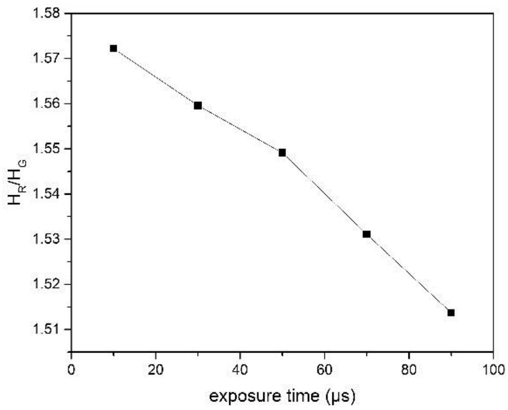

Fig. 4. The value of H_R/H_G at different exposure times

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

Table 1. Calculated temperature using different calibration results

The temperature of the black furnace /K	Calculated temperature /K	
	calibration results of 10μs	calibration results of 70μs
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

3.2 The projection temperature distributions of blast furnace raceway

The images of raceway in 320 and 5500 m^3 blast furnaces are shown in Figure 5 and Figure 6, respectively. There are coal lance and the pulverized coal cloud in images. These areas can not represent the combustion, so they are removed by image processing before calculating the projected temperature field[10].

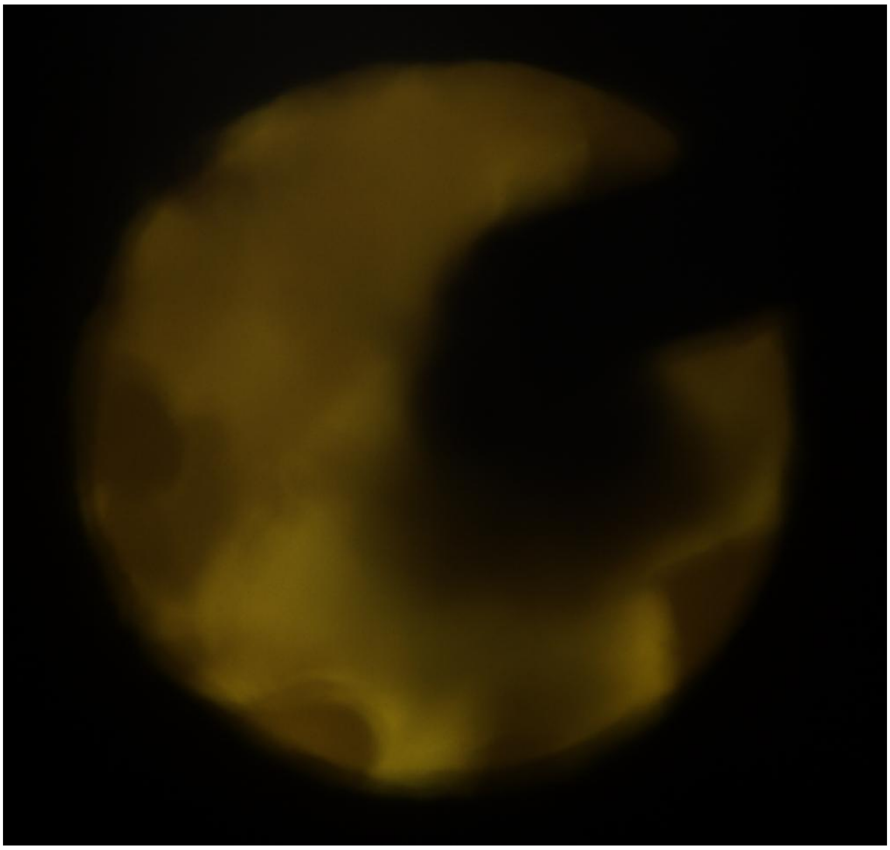

Fig. 5.The image of raceway in 320 m^3 blast furnace.

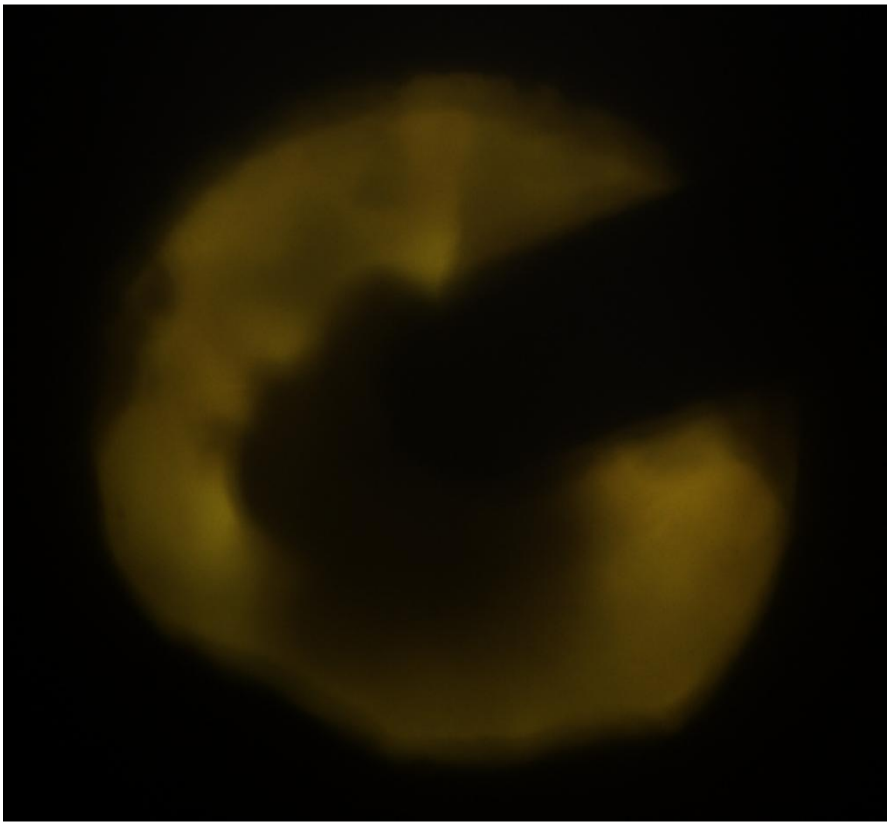

Fig. 6.The image of raceway in 5500 m³ blast furnace.

Figure 7 shows the two-dimensional projection temperature distributions of raceway of 320 m³ blast furnace. The average temperature of the projected temperature field is about 2230.5K. In 180 seconds the temperature changed from 2205.6 to 2320.8K. In addition, the average temperature of the tuyere zone is 2260.5K, and the temperature difference is 115.2K. 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.

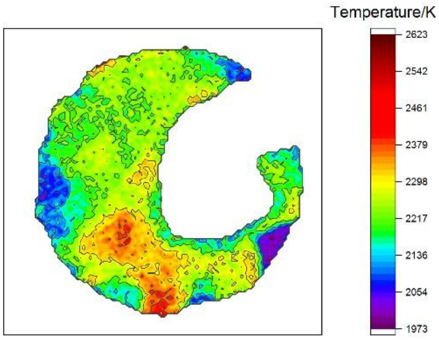

Fig. 7. The temperature distribution of raceway in 320m³ blast furnace

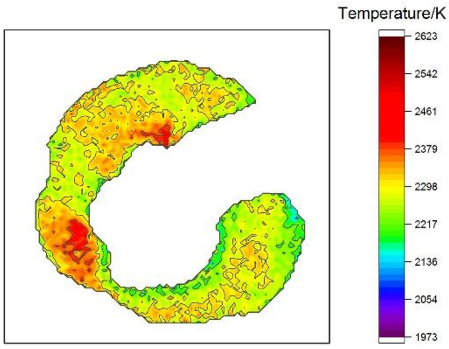

Fig. 8. The temperature distribution of raceway in 5500m³ blast furnace

The two-dimensional projection temperature distributions of raceway of 5500m³ blast furnace are shown in Figure 8. The average temperature of figure 8 is about 2287.2K. The temperature changed from 2198.6 to 2384.6K, the average temperature of the tuyere zone is 2266.8K, and the temperature difference in 180 seconds is 186K.

Comparing the images of raceway of 320 and 5500 m³, the average temperature in 3 minutes of 320 m³ is smaller than that of 5500 m³ blast furnace. And more particles can be seen in the images of the raceway of 320 m³ 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.

3.3 Error analysis and Future

To simplify the calculation of Equation 1, the spectral response function of the CCD camera is approximated to three monochromatic wavelength responses. 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 formula, the wavelength is selected according to the international regulations. Generally, the three primary colors of the CCD do not necessarily use the wavelength 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 dark current and noise and avoid saturation, it is limited to the range of 11 to 245. The state of the B channel is ignored in blackbody furnaces test or in industrial applications. Most of the values of B channel of images are less than 10. The color CCD camera has a Bayer filter, and the tricolor of color (RGB) is alternately generated on the CCD chip. Then the color image is formed after interpolation calculation. Ignoring the state of the B channel can interfere with the signal.

Considering the above errors, we has proposed a new optimization scheme that using a multipeak interference filter with a 3CCD camera. The filter is blocked from light signals off the two sides of the specified band, much similar to the monochromatic wavelength response[14]. There are three CCD chips in the 3CCD camera. After the prisms are split, the three optical paths correspond to one chip, and the exposure time of the three channels can be controlled without mutual interference[15]. The optimized system not only eliminates the above errors, but also makes the system more flexible. First, the appropriate wavelength combination filter is selected according to the temperature measurement environment and the object. Moreover, it is possible to use 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, refining process, etc.

4 Conclusions

The two-dimensional projection temperature measurement system based on charge-coupled device sensor was successfully established to capture the flame radiations in the tuyere raceway of 320 and 5500 m³ blast furnaces, and the two-dimensional projection temperature distributions are calculated by the two-color method.

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

The average temperatures of images of raceway of 320 and 5500m³ in 3 minutes are 2260.5K and 2266.8K, 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.

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