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# Temperature measurement of coal fired flame in the cement kiln by raw image processing

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ABSTRACT

This paper presents an experimental study on temperature measurement of coal fired flame in the cement kiln by raw image processing. Firstly the characterization of raw image was carefully examined on a calibration system, and then an improved ratio pyrometry based on raw image processing was proposed. The ratios of spectral color and exposure time in the raw image were calculated as the detection signals, in order to solve the temperatures from an implicit equation without making approximations of the filter profiles of CCD camera. The monochromatic emissivity detected by spectrometer was fitted with an exponential polynomial, and was utilized to correct the temperature solution. The experiments were conducted on a 5000 t/h cement rotary kiln, and the flame image temperatures and emissivity in different cases were detected on line. The results indicated that, the emissivity of coal fired flame in the cement kiln was slightly larger than that in the utility boiler. The temperatures measured by raw image processing were verified by an infrared pyrometer, and the errors were limited within 2%.

## 1. Introduction

The radiation thermometry by multi spectral colorimetric has proven to be an effective non-contact measurement method for flame temperature [1], and has derived several two or three dimensional thermal physical detection methods based on radiation image processing [2–4]. In these researches, it is very important to obtain the original image data with high precision.

The usage of single-chip CCD (Charge Coupled Device) camera to obtain the flame image is attractive from the standpoint of cost [5], but the precision and dynamic response range are the two major constraints. Jiang et al. [6] studied the performance of flame image detection by setting the white balance gain combination to obtain a wider range of dynamic response. Sun et al. [7] extended the numerical range of each spectral color channel of CCD by increasing the bits of AD conversion. With the development of CCD hardware and image processing technology, the raw image is tried to be used in the radiation temperature measurement [8]. As the original radiation information of the measured object is preserved, the raw image is more suitable for radiation image processing than the other image formats [9]. However, raw is not a standardized format (unlike BMP, JPG, etc.), and the characterization of raw image requires to be further studied.

In conventional ratio pyrometry applications, the signal ratio at two spectral bands was simplified to the finite filter widths and mean multipliers for each filter at the central wavelengths [10]. But in a strict sense, the assumption of single mean wavelength filter is not valid for the single chip CCD cameras. Kuhn et al. [11] evaluated the signal ratio of image without making approximations of the filter profiles, and calculated the flame temperature by two color ratio pyrometry using a lookup table approach. Yan et al. [12] calibrated the directional emissive power of R and G channels with consideration of the broad response spectrum of color bands of the camera, and reconstructed the two-dimensional temperature and soot volume fraction in the flame. Until now the filter profiles of CCD camera has not been analyzed in detail, and the error of assumption of single mean wavelength in color image processing needs to be accurately quantified.

The spectral distribution of monochromatic emissivity must be corrected when the CCD camera is used to detect the non gray radiation [13]. Fu et al. [14] researched the temperature measurement based on spectral bands, and proposed the universal function of spectral emissivity in narrow bands. Si et al. [15] has measured the distribution of soot aggregates absorption coefficients in flames by single wavelength imaging method. The detailed spectral information is lost in the CCD camera with band response, therefore the combined method based on spectral analysis and color image processing is proposed for detecting the particle temperature in flame. Liu et al. [16] detected the soot temperature and wavelength-dependent emissivity by the continuous band radiation intensity contained in the hyperspectral image. Xu et al.

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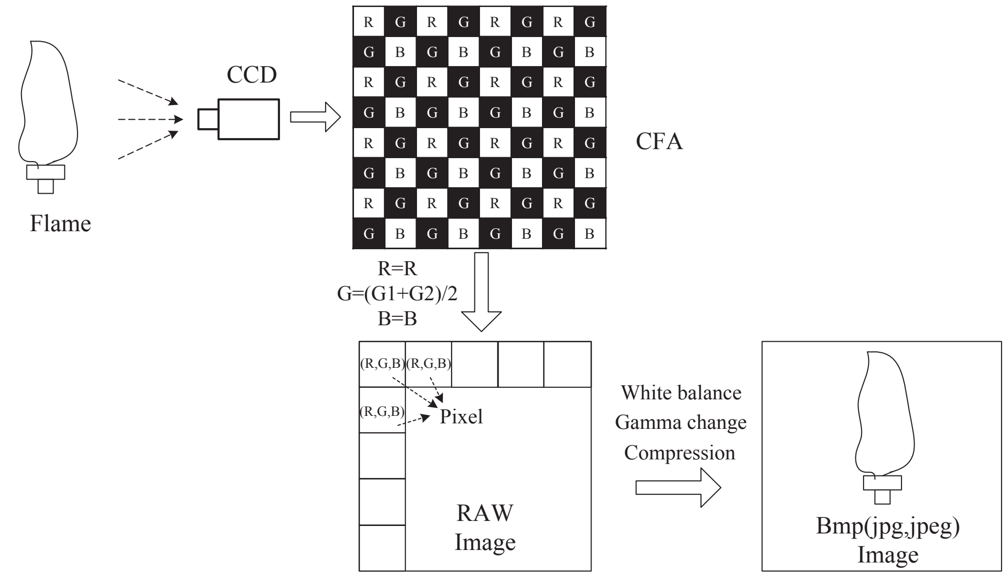


**Fig. 1.** Imaging process of raw image and bmp image.

[17] acquired the normalized spectral emission distribution of char particles in the visible light region by an Ocean2000 spectrometer, and then modified the lookup table for Ratio-Temperature of the Nikon camera.

In this paper, the raw image of CCD camera was characterized by blackbody furnace and monochromator firstly, and then an implicit ratio pyrometry based on raw image processing was proposed, in which the actual filter profiles of CCD camera were ultilized and the monochromatic emissivity was corrected. At last the image temperature and emissivity of coal fired flame in a cement kiln were measured on line, and some concluding remarks were given.

## 2. Characterization of raw image

The single-chip CCD camera is widely used in the radiation thermometry for the consideration of cost, and its imaging process is shown in Fig. 1. The radiation of flame is imaged at the three wavelengths of the camera's CFA (Color Filter Array), and then the RGB color signals saved in the color filter array are reassembled into the pixels in the raw image which is used by many camera manufactures as a designation for unprocessed images. In order to facilitate viewing and storage, the raw image is transformed to the bmp image after several nonlinear transformations such as white balance, gamma change and compression.

The CCD camera we used is Prosilica GT-1290C, which is based on the Sony ICX445 CCD detector with 1.2 million pixels (1280 × 960). The exposure time can be adjusted continuously, and the image data are transmitted through the gigabit ethernet. The all image enhancement options such as sharpness, noise reduction, contrast and saturation are set to none, and the white balance is set as (R + 90, B + 146). The image data can be saved in three formats, such as RAW16, RAW8 and RGB8. RAW16 is a sixteen bits lossless compressed raw format, and RGB8 is an eight bits bmp format. In the RAW8 image format, the first eight bits of RAW16 image is retained, and the gray value of each pixel is eight bits.

The characterization of the CCD camera is carefully examined on the calibration system, as shown in Fig. 2. The point light from xenon lamp is filtered in the monochromator firstly, and then is converted to surface light by the integrating sphere. The trap detector and the measured detector are fixed in the black box and are aligned to the perforation of integrating sphere. The optical throughput of the monochromator is obtained by imaging the spectrum with the trap and measured detector respectively. As the typical spectral response of trap detector has been tabulated by the manufacturer, the spectral response for the measured detector can be obtained from the ratios of the two measured signals, and the specific process can be inquired in the related literature [18]. Fig. 3 shows the typical spectral response of trap detector and the measured spectral response curves for GT-1290C, and the response range is between 380 nm and 780 nm. The RGB channels show similar characteristics – significant spectral overlap between channels, with a shape not accurately represented by a single Gaussian curve.

The blackbody furnace with a temperature range from 800 to 1800 °C is used to calibrate the spectral intensities of the measured detector, and the precision of temperature control is 0.25%. The RAW8 and RGB8 images in different exposure time are recorded when the temperature of blackbody furnace is 1273 K, and then the ratios of spectral color and exposure time are calculated, as shown in Table 1. It is observed that the ratios of spectral color and exposure time, and the ratios of different spectral color in the raw image are unchanged in different exposure time, while the ratios are varied in the bmp image. The results indicate that, the spectral color in the raw image increases linearly with increasing exposure time up to the point of saturation, while it is nonlinear in the bmp image. Thus the ratio of spectral color and exposure time is calculated to be the detected signal in the raw image, and then the influence of exposure time on radiation thermometry can be eliminated.

The relationships between the detected signals and the radiation intensities in the three image formats are calibrated by the blackbody furnace, as shown from Fig. 4 to Fig. 6. The calibration temperature is from 1173 K to 2000 K, with a data point every 20 K. As the spectral color is nonlinear with the exposure time in the RGB8 image format, the coefficients need to be calibrated separately for each exposure time, and the exposure time for Fig. 4 is 50 ms. In the RAW8 and RAW16 image format, the calibration coefficients are independent with the exposure time of camera, thus the calibration process of raw image can be greatly simplified. As shown in Figs. 5 and 6, the calibration curves of each filter are straight lines over the origin point, which means that the ratio of spectral color and exposure time varies directly with the incident radiation intensity in the raw image. At the same time, the range of the detection signals in the raw image is much wider than that of bmp image, indicating that the dynamic response range in the raw image is significantly improved.