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Research Paper

Study on the detection of three-dimensional soot temperature and volume fraction fields of a laminar flame by multispectral imaging system

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HIGHLIGHTS

- Multispectral flame images were used to reconstruct the soot temperature and volume fraction.
- The proposed multi-wavelength method and the original two-color method were compared.
- The effect of signal to noise ratio (*SNR*) was discussed.
- The best number of selected wavelengths was determined to be 6–11.

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ABSTRACT

Charge-coupled device (CCD) cameras with liquid crystal tunable filters (LCTF) were introduced to capture the multispectral flame images for obtaining the line-of-sight radiation intensities. A least square QR decomposition method was applied to solve the reconstruction matrix equation and obtain the multi-wavelength local emission distributions from which temperature and volume fraction profiles can be retrieved. Compared with the original two-color method, the use of a wide range of spectral data was proved to be capable of reducing the reconstruction error. Reconstruction results of the two methods with different signal to noise ratio (*SNR*) were discussed. The effect of selected wavelength number is analyzed and the best number is determined to be in the range of 6–11. The proposed multispectral imaging system was verified to be feasible for the reconstruction of temperature and soot volume fraction distributions according to the experimental measurement results.

1. Introduction

The coal-fired power plants are still the main source of electricity in China, and advanced technologies for combustion diagnostics are required to keep the operation of power plants safe and stable. Flame temperature distribution measurement is necessary in the combustion diagnostics because the temperature distribution dominates the thermal radiation process which is the primary heat transfer form in the high temperature furnaces. Soot volume fraction distribution measurement is also of great practical significance for the research of combustion systems because soot formation in the combustion process affects the flame radiation and heat transfer directly. Some common methods including thermocouples and pyrometers are not convenient for large plant furnaces because they need to be in contact with the measured flame. What is more, only very limited points in the flame can be measured and they are not available for 3-D reconstruction of temperature and soot volume fractions. Therefore a large number of nonintrusive optical methods have been developed for combustion research in recent years, including light extinction for concentration [1,2], laser scattering for soot size distribution [3], laser-induced incandescence (LII) [4,5], etc., which are becoming the key source of information about the soot characteristics in combustion environment. Tomography reconstruction based on CCD cameras is one of the most effective nonintrusive methods, which has had a rapid development in recent decade. Such 3-D tomographic data will assist scientists and engineers working in combustion and related fields to study the flame structures and reconstruct the temperature and soot volume fraction distributions [6]. Zhou et al. conducted a series of experiments in the pulverized-coal fired furnace of a 200 MW power generation unit to visualize the 3-D temperature distributions of combustion by the intensities obtained from eight CCD cameras [7]. Chu et al. developed a parameter model for the evaporation system of a controlled circulation boiler, which is based on the 3-D

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temperature distribution measured from the CCD cameras [8]. Bheemul et al. developed a novel instrumentation system including three CCD cameras for the 3-D reconstruction of a gas-fueled flame, where the obtained three 2-D images of the flame were applied to build the flame geometrical model, and a set of characteristic parameters were acquired from it [9]. Hossain et al. presented a tomographic system capable of 3-D reconstruction of combustion flames in a practical furnace, which uses two CCD cameras coupled with eight high-specification imaging fiber bundles to capture flame images from eight different directions around the burner [10]. Ishino et al. presented a tomography system consisting of forty cameras to reconstruct the 3-D propane turbulent flame structure and soot volume fraction distributions [11]. However this system is too complex and it is hard to be implemented for practical combustion diagnostics. Our previous work has developed a stereoscopic tomography technique to reconstruct the soot temperature and concentration distributions for an asymmetric diffusive flame using a single CCD camera [12]. A similarity among the researches introduced above is that, only three visible spectral channels including Red, Green and Blue (RGB) respectively are utilized for reconstruction, which makes the spectrally resolved information of a flame very limited in the reconstruction system based on CCD cameras. However, with liquid crystal tunable filters (LCTF) [13,14] fixed in front of the CCD cameras, monochromatic pictures of the flame from 650 nm to 1100 nm every 7 nm can be obtained. With respect to the practical application in the power plant, the measured result can be more convincible since the spectral resolution of the flame image has been increased a lot.

Actually, various kinds of spectroscopes have been utilized to measure the multi-spectra flame emission which is involved with local soot temperature and volume fraction distributions. De Iuliis et al. employed a low-resolution spectrograph (JY 200UFS) to measure the multi-wavelength emission of an ethylene diffusion flame. The obtained temperature and soot volume fraction result is compared to that calculated from extinction measurement of the same flame [15]. Snelling et al. developed a multi-wavelength technique for high-resolution determination of soot temperature and soot volume fraction using a spectrometer with a spectral range from 500 to 900 nm [16]. Liu et al. discussed the effect of self-absorption further in a laminar axisymmetric coflow diffusion flame from the spectrally resolved flame emission measurement [17]. Ayrancı et al. proposed an inversion scheme for an optically thin axisymmetric flame to obtain the soot temperature and volume fraction distributions by 1-D tomographic reconstruction of line-of-sight flame emission spectra, which is proved to be especially powerful in near-infrared range by Fourier-transform infrared spectrometry [18]. However, these researches were restricted to the 2-D measurement of soot temperature and volume fraction fields in an axisymmetric flame. While in our research, using the LCTF multi-wavelength system, the measured target can be extended to a large asymmetric flame in the coal-fired power plants. The result of temperature and soot volume fraction distribution is verified to be more accurate.

In this paper, the multispectral imaging system is proposed for the 3-D reconstruction of soot temperature and volume fraction distributions. A set of numerical researches have been made to verify the feasibility of multi-wavelength method used in the 3-D flame reconstruction system based on the multispectral imaging system. The comparison of results obtained from multi-wavelength method and two-color method is presented and the effect of wavelength number is analyzed. The results of numerical simulations provide guidance to the experimental measurements.

2. Reconstruction method

The reconstruction system shown in Fig. 1 is similar to that set up previously by our group [19]. Four CCD cameras were put around the flame marked from CCD (1), CCD (2), CCD (3) and CCD (4). The four CCD cameras are assumed to be identical. The sensor array size of the camera is 1280×1024 pixels with a pixel size of $5.2\ \mu m \times 5.2\ \mu m$. It is noteworthy that the LCTFs are fixed in front of the CCD cameras to obtain multispectral images of the reconstructed flame. It works by adding liquid crystal variable retarders to a Lyot filter design with no moving parts affecting the imaging quality. And a set of optical elements are connected in series with index-matching epoxy. The transparency of each element changes with the wavelength of the incident light and the transmitted light adds only in the desired bandwidth range. As a result, LCTF is an ideal technology for accurate multispectral imaging which provides images of an object at multiple wavelengths and generates high-resolution spectra at every pixel.

The reconstruction area is divided into discrete elements of $NX \times NY \times NZ$. Specifically in this paper, the reconstruction area is divided into $7 \times 7 \times 11$ grids according to the size of the real flame and the field angle of CCD cameras. The boundary of the flame is thought to be open to atmosphere. So the environmental temperature and pressure are used as the boundary conditions. Besides, β represents the angle between the line connecting two relative cameras and the midcourt line of the system, and M_r is assumed to be the discrete ray number of the field angle of every CCD camera. The soot emission measurement is based on the radiative transfer equation (RTE). The reconstruction process proposed here contains three assumptions as said in our previous work [12]: (a) the effects of flame species scattering and internal self-absorption are

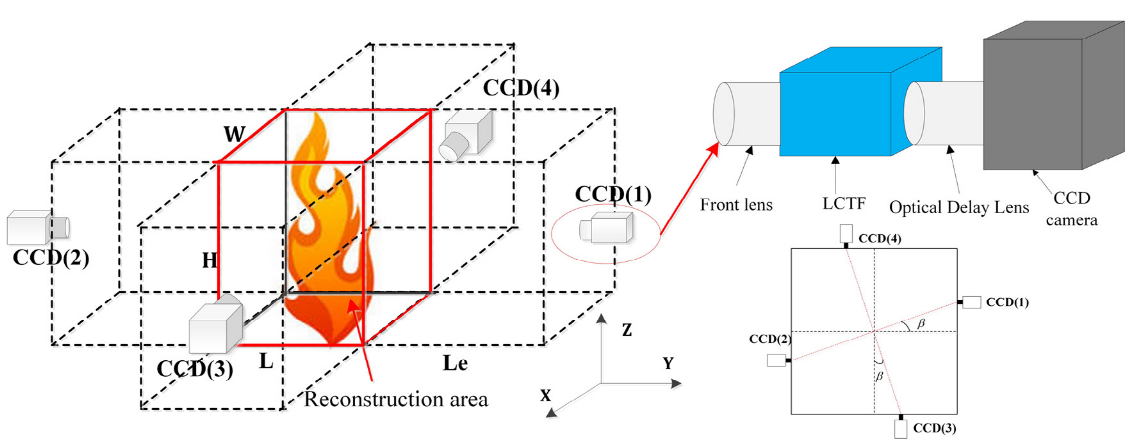

Fig. 1. Reconstruction system.