Fuel 211 (2018) 688–696

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Investigations of CH* chemiluminescence and blackbody radiation in opposed impinging coal-water slurry flames based on an entrained-flow gasifier

Chonghe Hu, Yan Gong, Qinghua Guo*, Lei He, Guangsuo Yu*

Key Laboratory of Coal Gasification and Energy Chemical Engineering of Ministry of Education, Engineering Research Center of Coal Gasification, East China University of Science and Technology, Shanghai 200237, PR China

ARTICLE INFO

Keywords:
CH* chemiluminescence
Blackbody radiation
Impinging flame
Coal-water slurry
Entrained-flow gasifier

ABSTRACT

The characteristics of excited CH radical (CH*) chemiluminescence and blackbody radiation in opposed impinging coal-water slurry (CWS) flames were investigated in this paper based on a bench-scale opposed multi-burner (OMB) gasifier. CH* chemiluminescence is a significant radical species in flame spectral diagnostics, and blackbody radiation can reflect the spatial distribution of solid particles produced in flame. A fiber-optic spectrometer and a CCD camera coupled with multiple bandpass filters are used to obtain the spectral emission lines and two-dimensional spectral distributions, respectively. The results show that CH* emission peak at 431 nm and continuous blackbody radiation can be detected in CWS flames. The differences of spectral distributions between diesel and CWS impinging flame are analyzed. Impinging zone is the core chemical reaction region, and solid particles are also concentrated in impinging zone, indicating that four-burner impinging can well restrict the reactants and flames in the impinging zone, thereby greatly reduce the damage to the refractory walls. Moreover, according to the time-averaged distributions, the intensity and area of CH* emission and blackbody radiation are enhanced with the increase of oxygen and carbon molar ratio (*O/C*), demonstrating that improving O_2 velocity promotes the chemical reactions, and flame temperature plays more dominant role than solid particle quantity in blackbody radiation. The time-dependent blackbody radiation evolution presents periodical change. Besides, it is found that *O/C* or syngas concentration can be feasibly estimated using CH* chemiluminescence in OMB gasifier.

1. Introduction

The efficient and clean utilization of coal resource is of significant interest in recent years. Coal gasification technologies, especially the opposed multi-burner (OMB) gasification technology using coal-water slurry (CWS) as feedstock, can achieve the clean production of syngas from coal. OMB gasification technology has been widely used by over 50 companies all over the world [1], due to the high efficiency, large scale and good economic benefit. Moreover, impinging stream can effectively strengthen heat and mass transfer, improve particle residence time and reaction efficiency [2]. Hence it has been utilized in many kinds of industrial reactors, also including the OMB gasifier. This paper was to explore the CWS impinging flame characteristics through flame spectral diagnostics, based on a bench-scale OMB gasifier.

Flame spectral diagnostics is an important and promising method to obtain the flame information and monitor the combustion or gasification systems [3], because the diagnostic method is non-intrusive and the spectral signals are easily measured. Excited CH radical (CH*) chemiluminescence is one of the most significant radical species, and much research has been reported on the capability of CH*. It was found that CH* can be used to predict flame structure, chemical reaction region, equivalence ratio, etc. [4–6]. However, the ability of CH* to estimate total or local flame heat release rate is still uncertain through the work of Hossain and Nakamura [7]. Most of such cases were focused on gas or oil flames, less work has been done on coal flames, especially the impinging-stream coal flames. Because the experiment and measurement systems are more complex, and the interference of broadband blackbody radiation on chemiluminescence is relatively stronger.

In the heterogeneous flames, high-temperature solid particles can emit strong and continuous blackbody radiation [8], and blackbody radiation is usually used to evaluate flame temperature on the basis of two-color, multi-color and other pyrometry methods [9–11]. Besides, some researchers have reported their study on blackbody measurements in flames using optical techniques. Pourhoseini and Moghiman

* Corresponding authors.
E-mail addresses: gqh@ecust.edu.cn (Q. Guo), gsyu@ecust.edu.cn (G. Yu).

http://dx.doi.org/10.1016/j.fuel.2017.09.094
Received 21 June 2017; Received in revised form 16 August 2017; Accepted 25 September 2017
0016-2361/

[12] used an IR filter coupled with a digital camera to photograph the qualitative distribution of soot particles in nature gas flame which was injected with pulverized coal. Liu et al. [13] provided a generalized method to estimate the temperature distribution and wavelength-dependent emissivity in sooty flames on the basis of spectroscopic radiation intensity. Liu et al. [14] also calculated the soot temperature, absorption coefficient and volume fraction in ethylene flames using hyperspectral imaging device and the iterative process. In this work, the two-dimensional blackbody radiation distributions of impinging flames were analyzed based on a bench-scale gasifier. For the CWS flame, the blackbody radiation is mainly derived from many kinds of solid particles such as soot particles, coal particles, coal char, ash and slag, etc. [15]. Should explain here the actual solid particle is not the idealized blackbody which can absorb all incident radiation. In the actual industry, the particle is generally regarded as the graybody which has lower emissivity independent of frequency [16]. Hence the statement "blackbody" in this paper was used to represent the solid particles produced in flame.

For the OMB gasifier, some research on the spectroscopic characteristics has been conducted. Hu and Song et al. [17,18] investigated the spectral characteristics in diesel and CWS flames using a HR2500+ spectrometer. It is a point measurement in the impinging zone, and only one-dimensional emission information can be measured. In this article, two-dimensional distributions of CH^* chemiluminescence and blackbody radiation in CWS impinging flames were firstly derived, through image processing method and a CCD camera coupled with multiple bandpass filters (420, 430, 440 and 700 nm). Using CWS as feedstock, the findings can be directly extended to the industrial OMB gasifier. Furthermore, the differences of spectral emissions between diesel and CWS impinging flame are analyzed. The effects of O/C on CWS impinging flames are discussed. And the feasibility of using CH^* chemiluminescence to predict O/C or syngas concentration is evaluated.

2. Experimental work

2.1. Experimental setup

As Fig. 1 shows, the experimental work was carried out in a bench-scale entrained flow gasifier operated in the ambient atmosphere. Two pairs of burners were oppositely mounted with 90° in the same horizontal plane (impinging plane). The distances of two opposed burners and impinging plane to endoscope are 300 mm and 600 mm, respectively. The burner has two coaxial channels, CWS is transported into the central channel by helical rotor pump, and oxygen is supplied into annular channel from Dewar tank. Diesel is used to preheat the gasifier, then the CWS is injected into gasifier. The temperature is monitored by several B-type thermocouples. Moreover, raw syngas flows downward from gasification chamber to quenching chamber, and the syngas concentration was online measured by a mass spectrometer (Type thermostar GSD 320 T2). The sampling and pretreatment processes of raw syngas have been reported by Niu [19] in detail.

Spectroscopic measurement system includes a fiber-optic spectrometer and a high resolution CCD camera coupled with multiple bandpass filters. The spectrometer (HR2500+, Ocean Optics Inc.) was used to detect the spectral signals of impinging zone. The fiber probe was stretched into the sampling port and protected by the cooling jacket. The detailed descriptions have been presented by Zhang and Song [18,20]. Besides, the flames in the gasifier can be visualized through a CCD camera (XCL-500, SONY) combined with a high temperature endoscope (CESYCO, Φ38 mm). The spatial resolution of CCD camera is 2448 × 2048 pixels. Cooling water and purging gas (Ar) can make the endoscope avoid high temperature and pollutants. The spectral images were obtained by setting the bandpass filters in the endoscope. As shown in Fig. 1, a filter slot is located in front of the CCD camera, which is convenient for changing different filters to satisfy experimental request. The filters at central wavelengths of 420 nm, 430 nm, 440 nm and 700 nm are used in the current work, and all filters can completely cover the camera sensor. The full width and peak transmission are approximately 10 nm and 50%, respectively.

2.2. Operating conditions

Diesel and CWS are used as feedstock, and oxygen is the oxidizer in this article. The analysis of diesel and CWS are given in Table 1 and Table 2, respectively. The CWS is prepared using Shenhua bituminous coal, and the solid mass content is 61%. The coal analysis meets the National Standards of PRC (GB/T 212-2008 and GB/T 31391-2015).

The operating conditions of each burner are listed in Table 3. All conditions are under gasification atmosphere. O/C is the calculated molar ratio of oxygen and carbon, and it is changed by varying the O_2 flow rate. To analyze the differences between diesel and CWS flames under the same O/C, should note that condition 1 and 8 have the same O_2 flow rate, and so on.

3. Results and discussion

3.1. Processing method of spectral image

The spectral lines of CH^* chemiluminescence and blackbody radiation exist in CWS flame, as shown in Fig. 2. Take condition 3 for instance, the emission lines around 367 nm arise from H∗, and the emission peak at 409 nm is from NO^*. CH^* chemiluminescence is taken at 431 nm. Continuous background radiation also can be observed. In the gasifier, the background radiation mainly includes blackbody radiation and ${CO_2}^*$ emissions [21]. As mentioned above, blackbody radiation was caused by soot particles in diesel flame and solid particles in CWS flame. The broadband range of ${CO_2}^*$ emissions are from CO_2 excitation mainly at 310–600 nm [22–23].

From Fig. 2, CH^* emission intensity is significantly influenced by the background radiation. Hence, in order to obtain correct CH^* chemiluminescence image, the blackbody radiation and ${CO_2}^*$ emissions should be subtracted according to Eq. (3.1):

$$I_{CH^*} = I_{430nm}^{measurement} - (I_{430nm}^{blackbody} + I_{430nm}^{CO_2^*}) \tag{3.1}$$

where I means the emission intensity. On the basis of this principle, Karnani et al. [24] put forward the filtering and image subtraction method to produce the soot-free image of CH^* chemiluminescence in ethylene flame. Zhang et al. [25] verified the processing method and obtain CH^* image of diesel flame. In this work, the method was adopted to obtain CH^* chemiluminescence in diesel and CWS flames.

Taking condition 6 for example, the detailed subtraction procedure is illustrated in Fig. 3. The first step is to obtain the background radiation at 430 nm, and it can be calculated by the flame images through 420 nm and 440 nm filters according to Eq. (3.2). The specific derivation processes are also reported by Karnani and Zhang [24,25].

$$I_{430nm}^{background} = 0.6361 \times I_{420nm}^{background} + 0.3486 \times I_{440nm}^{background} \tag{3.2}$$

The second step was to subtract the background radiation from the filtering image captured at 430 nm. Then the CH^* chemiluminescence distribution in CWS flame was derived. Should mention that the time-averaged filtering images are processed by averaging at least 50 time-dependent images. Besides, as for blackbody radiation images, a 700 nm filter was used to photograph the flames in order to avoid the interference of ${CO_2}^*$ emissions.

3.2. Spectral emissions in diesel and CWS flames

In the experimental process, diesel was used to heat the furnace up. Usually, when the furnace temperature reached about 1400 °C, CWS was injected into a pair of opposed burners, then into the other two burners. Diesel flame is gas-liquid two phase, and CWS flame is gas-