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Experimental study on particle characteristics in an opposed multi-burner gasifier

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HIGHLIGHTS

- Particle behaviors in gasifier under hot condition are observed for the first time.
- Particle characteristics are studied by multiplicate visualization techniques.
- The particles in gasifier are mainly classified to five different types.
- Larger size particles exist as particle groups with three different types.

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ABSTRACT

Based on the bench-scale opposed multi-burner (OMB) coal-water slurry (CWS) gasifier, temperature distributions of particles at different spatial regions, reactivity characteristics of particles and their interactions were studied with a variety of visualization techniques. The particles in gasifier are mainly classified to five types, and the principles of transformation between them are concluded as: low temperature particle without wake (LTP) could transform to low temperature particle with high temperature wake (LTP-HTW) when contacted with high temperature flame, then transform to LTP as reactions terminate and the particles become non-reactive; low temperature particle with low temperature wake (LTP-LTW) would transform to LTP-HTW when transfer to high temperature regions; as LTP-HTW adhere to the refractory wall, their wakes vanish and particles transform to high temperature particle without wake (HTP); high temperature particle with high temperature wake (HTP-HTW) could finally transform to HTP after the end of reactions. Particle groups with irregular shapes, flake-shaped and hollowed spherical structure are the forms of existence for larger size particles in gasifier.

1. Introduction

As one of the key clean coal technologies, coal gasification is the basic technology for developing coal-based industries, such as chemical products, liquid fuel, combined cycle power generation, multiple co-generation system, hydrogen production and fuel cell, etc. (Gasification Technologies Council, 2013). The entrained-flow gasification, especially the high pressure and large capacity entrained-flow gasification, is the most widely used and mature technique in clean coal technology which has gained favourable economic and social benefit. Under the support of national high technology research and development program (863 program), East China University of Science and Technology (ECUST), Yankuang Lunan Chemical Fertilizer Plant and China Tianchen Engineering Corporation Co. Ltd (TCC) developed the coal-water slurry gasification technology with opposed multi-burner (OMB) and made its industrial demonstration, which greatly promotes the development of coal chemical industry and makes technical support for the energy structure adjustment in China (Higman and Burgt, 2008; Yu, 2011; American Council for an Energy-Efficient

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Economy, 2013). So far, ECUST's OMB gasification technology has become one of the three leading technologies in world gasification market by capacity and numbers of gasifiers (Gasification Technologies Council, 2013).

As the key equipment of entrained flow gasification process, gasifier is operated at high temperature and pressure, which could increase carbon conversion and avoid generation of tar and phenols (Wang et al., 2007). However, improper operating conditions would cause exceeding of temperature in local region of gasifier, and incompletely reacted large size particles generated by non-uniform atomization would decrease carbon conversion and erode the refractory wall. Such conditions could reduce operating life of burners and refractory wall, which are unfavorable for long period operation of gasifier and influence the production system. Thus the research on flame structure, temperature distribution, particle characteristics and relevant visualization techniques has vast importance to temperature monitoring, avoiding temperature exceeding, prolonging operating life of burners and refractory wall, diagnosing gasification process, etc.

Many studies on particle characteristics were carried out by numerical methods due to the complicated environment in furnace (Zhang et al., 2005; Mermoud et al., 2006; Yang et al., 2008; Sadhukhan et al., 2009; Zhang, 2010). Based on the bench-scale OMB gasifier, numerical studies for OMB gasifier were successively made by Guo et al. (2008), Ni et al. (2008, 2009), Li et al. (2012). Further experimental studies were carried out by Zhang et al. (2013), particle size and compositions were characterized by Malvern laser particle size analyzer, infrared coal analyzer and SEM/EDS, while particle distribution and formation in gasifier were analyzed at different positions and experimental conditions. The results were based on the particle sampling system, but the particle behaviors could not be obtained unless using optical imaging techniques. For a long period, it was difficult to accomplish the visualization of particles in furnace under hot condition because of the low effective resolution of industrial cameras, the small dimensions and low sensitivity of the sensors in cameras, the complicated optical structure and poor dust-resistance ability of endoscopes, etc.

Aiming at combustion process, Niksa et al. (1985) utilized an in situ optical method to determine the temperature, size and velocity of individual particles of burning pulverized fuels in the early 1980s. Later, many studies were carried out to investigate single particles (Essenhigh et al., 1989; Chen et al., 1994; Du and Annamalai, 1994; Davini et al., 1996). Zhu et al. (2009) conducted experimental study on ignition and combustion of single particles at normal gravity and microgravity for three high volatile coals with different initial diameters, and a mathematical model considering thermal conduction inside the coal particle was developed to simulate the ignition process. Levendis et al. (2011), Bejarano and Levendis (2008) observed the combustion of individual particles in air with three-color pyrometry and high-speed high-resolution cinematography to obtain temperature-time-size histories by using a transparent drop-tube furnace. In these studies, the characteristics focusing on a single particle were relatively easier to achieve, but statistic characteristics under hot conditions are hard to obtain.

In order to capture images for large amount of particles in high temperature furnace or gasifier, high temperature endoscopes are essential. For certain purposes of measurement, customed high temperature endoscopes are necessary. Rottier et al. (2010) designed and manufactured a high temperature endoscope for endoscopic particle image velocimetry (PIV) system adapted to high temperature furnaces. Yan et al. (2009) reconstructed temperature distributions of flame sections by the method of Filtered Back Projection by using a customed imaging system manufactured by Anhui University. Due to the relatively small dimensions of the bench-scale OMB gasifier, durable endoscopes with high temperature resistance, low flow field influence, anti-dust and high image quality in long period operation were introduced. Gong et al. (2012) reconstructed the three-dimensional (3-D) temperature distribution of the OMB gasifier based on a high quality industrial high temperature endoscope combined with high resolution industrial cameras. By applying more endoscopes to the imaging system, Gong et al. (2013) studied the impinging flame height and pulsation frequency in OMB gasifier by using an industrial light field camera and high speed cameras combined with image processing methods. These new techniques formed the base of imaging system for particles in gasifier.

With the smooth running of bench-scale OMB gasifier and the application of advanced visualization equipments, studies on particles in gasifier are now feasible. Based on a variety of visualization techniques, temperature distributions of particles at different spatial regions, reactivity characteristics of particles and their interactions with each other were studied, and the results could provide direct experimental evidences to the deposition, impinging and fragmenting of particles in gasifier.

2. Measurement principles

A large number of particles will be generated during the operating process of bench-scale OMB gasifier. Basically, carbon and minerals are the main components of particles. Carbon converts to CO_2 and CO as gasification proceeds, while unreacted carbon is discharged from gasifier with slag and particles in gas flow in the form of residual carbon.

The particles in gasifier are generated by the interaction of minerals and chars, which manifests in the fragmentation and aggregation of minerals, as well as the fragmentation and combustion of chars. The aggregation of included minerals would increase the particle size, while the decrease of particle size is caused by the fragmentation of excluded minerals, the fragmentation, combustion and gasification of chars. Since particles move with the flow field, the characteristics of them, such as temperature and reactivity, show different features at different spatial regions. The flames in gasifier can also be interacted with particles.

In order to record the movement of particles and flames in gasifier, Photron high speed camera combined with CESYCO Φ38 mm high temperature endoscope was applied to capture images under low luminance. A monochrome CMOS sensor with a monochromatic filter was used in the high speed camera, and radiation gray-scale images could be obtained under certain shutter speeds or exposures. Based on the principle that there being a one-to-one correspondence between the gray level and apparent temperature in radiation gray-scale images, (Li et al., 2007) the empirical relationship between gray level and radiation temperature would be calibrated by high temperature blackbody furnace, thus the temperature corresponding to each pixel in monochromatic radiation images could be calculated.

The temperature in gasifier could easily exceed 2273 K, especially in the impinging area. For the purpose of keeping a one-to-one correspondence between the range of gray-scale and temperature, while ensuring that the fitting function of gray level and temperature is accurate and suitable for use in all unsaturated gray level conditions without extrapolation, a blackbody furnace with wider working range of temperature is needed.

A WJL-11 horizontal blackbody furnace produced by Yunnan Boao Instrument Co., Ltd was applied in the study in order to calibrate the Photron high speed camera mounted with a 546.9 nm monochromatic filter implanted in the high temperature endoscope. The calibrating temperature ranged from 800 K to 3273 K, and the target surface temperature was measured and controlled by CIT-1MK2 infrared thermometer and high-precision