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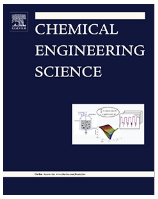

In-situ atomization and flame characteristics of coal water slurry in an impinging entrained-flow gasifier

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HIGHLIGHTS

- A hot model gasifier combined with a novel in-situ visualization system was applied.
- The morphology and oscillation of the flame near the burner tip were presented.
- Droplet size distribution was obtained to investigate the atomization efficiency.
- Time-resolved droplet concentration and size were obtained to show the atomization stability.

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ABSTRACT

Based on the bench-scale impinging entrained-flow gasifier with coal water slurry (CWS) as the feedstock and the development of advanced visualization techniques, the in-situ atomization and flame characteristics of CWS were investigated. A new imaging system was applied to capture the images around the burners in the operating condition. After image post-processing, the instantaneous flame, time-averaged flame and oscillation of the flame were discussed. With the statistical method, the droplet size distribution, oscillation of the droplet concentration and time-dependent droplet size were obtained to analyze the efficiency and stability of the atomization process. The instantaneous flame shows that the atomization and gasification process is turbulent. The time-average CWS flame shows that the atomization angle decreases with an increase in the ratio of elemental oxygen to elemental carbon (O/C ratio). The oscillation of the flame and the atomization process demonstrate that in-situ atomization is closely related to the CWS flame. The diameter and number of droplets after primary atomization decrease with the increase of the O/C ratio. The decreases in median diameter and unconsumed CWS rate demonstrate that the increase in O/C ratio improves the efficiency of the atomization process. The reduction in oscillation scopes of the droplet concentration and size demonstrates that the increase in O/C ratio improves the stability of the atomization process. In addition, the droplet concentration c in three different O/C conditions is 17.8 kg·m^{-3}, 5.9 kg·m^{-3} and 1.6 kg·m^{-3} which demonstrates that the CWS is the dilute phase in the OMB gasifier.

1. Introduction

Gasification is a flexible, reliable, and commercial technology that converts various low-value feedstocks, such as coal, petroleum coke, biomass or waste, to syngas, which can be used as a clean alternative source of base load electricity, fertilizers, fuels, and chemicals (GSTC, 2017). The entrained-flow gasification technology, which has been widely used for industry, is one of the most efficient gasification technologies (Higman and Van Der Burgt, 2008). Many research groups focus on this topic.

As an outstanding entrained-flow gasification technology, the opposed multi-burner (OMB) impinging entrained-flow gasification technology, which adopts coal-water-slurry (CWS) as feedstock, was developed by East China University of Science and Technology (ECUST) (Yu et al., 2011). The OMB impinging entrained-flow gasification technology adopts four oppositely mounted burners to gasify the CWS and produce syngas, which strengthens the mixture of fuel and oxygen to increase the gasification efficiency. At present, the OMB gasification technology of ECUST has become one of most advanced technologies in the world and continuously promotes the gasification technology (Higman, 2014). The atomization process and flame of the CWS in the gasifier are highly related to the gasification efficiency and stability

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(Chan, 1994; Miccio et al., 1989). To understand certain effects of the atomization process and flame on the gasification efficiency and stability, their concrete relationship in the operation condition should be investigated.

Atomization behaviors have been studied with cold model test for decades. The primary atomization of Newtonian liquid is defined as four modes: Rayleigh-type breakup, membrane breakup, fiber-type breakup and atomization mode (Chigier and Farago, 1992; Lasheras and Hopfinger, 2000; Varga et al., 2003; Marmottant and Villermaux, 2004; Dumouchel, 2008). The secondary atomization modes of Newtonian liquid droplets are also divided into no breakup, bag breakup, multimode breakup and shear breakup (Theofanous, 2011; Hinze, 1955; Nicholls and Ranger, 1969; Krzeczkowski, 1980; Hsiang and Faeth, 1992; Liu and Reitz, 1997). Guildenbecher et al. (2009) considered that the primary and secondary atomization processes of non-Newtonian liquid were similar to those of Newtonian liquid. Zhao et al. (2012, 2011) investigated the primary and secondary atomizations of the CWS in a series of conditions. The experimental results showed that the membrane breakup mode disappeared in non-Newtonian liquid atomization, and the atomization mode was divide into deformation, multimode breakup (including hole breakup and tensile breakup), and shear breakup. In addition, the effects of the particle concentration (Miglani and Basu, 2015), particle size (Addo-Yobo et al., 2011), intense radiation (Xu et al., 2014) and rheological properties (Zhao et al., 2014) on the atomization behaviors were investigated. The atomization behaviors of Newtonian liquids were also studied using numerical simulations (Jiang et al., 2012; Delteil et al., 2011; Jones et al., 2017). Sarchami et al. (2010) introduced an atomization model for nozzles. Li et al. (2012) simulated the CWS atomization in the OMB gasifier. However, because of the high temperature, violent reactions and particles, few studies investigated the atomization characteristics in the entrained-flow gasifier.

As an important phenomenon of coal gasification, the flame was investigated with diagnostic techniques in many studies. A high-speed video camera was used by Rezaei et al. (2013) to study the flame stand-off distance of coaxial oxy-fuel turbulent diffusion flames. Ramadan et al. (2016) also investigated the diffusion flame using the visualization method. To visualize a gas flame, a similar method was applied for coal flame studies. Zhou et al. (2014) and Michalski et al. (2017) presented new systems to image pulverized coal flames and analyze the detailed characteristics. Both systems were useful but did not provide sufficient visualizations. Xu et al. (2016) studied the ignition behavior of pulverized coal particle clouds in a turbulent jet, and the captured images clearly showed the flame and ignited particles. Similar systems were applied to study a single particle and its flame (Levendis et al., 2011; Khatami et al., 2012; Shaddix and Molina, 2009). With the development of visualization techniques, an advanced approach was used by the bench-scale gasification system investigation (Gong et al., 2013; Yan et al., 2009; Fan et al., 2014; Gong et al., 2012; Zhang et al., 2017). The impinging flame height, flame characteristics and temperature distribution were studied based on the impinging flame. However, because of the difficulties in overcoming the high temperature and complex atmosphere, a detailed study on flame characteristics near the burner tip in the operating gasifier has not been conducted

Based on the bench-scale OMB impinging entrained-flow gasification system, aiming at atomization and gasification characteristics of the CWS, the visualization system was mounted at the burner plane to image CWS atomization and gasification process in the CWS jet flame. Considering the high temperature and complex atmosphere at the burner plane, the imaging system and experimental platform were improved. A PCO color high speed camera was used to capture a series of time-resolved images, whose time interval was 0.25 ms, to show the atomization process and flame. The purge system was strengthened to ensure a clear camera lens. The position of the imaging system was improved to change from a high-temperature area to a low-temperature area when recording the images, which is helpful to protect the imaging system from a high-temperature atmosphere. CWS is atomized into droplets, which are dried to generate particles and combusted to form flames. Therefore, the turbulent flame, particle characteristics, droplet size distribution and time-resolved evaluation were investigated to discuss the efficiency and stability of the atomization process.

2. Experimental setup

Based on the bench-scale OMB impinging entrained-flow gasification platform with the new imaging system, experimental studies on the in-situ atomization and turbulent flame of the CWS were conducted. Compared to the previous system, the new image system had improved temperature resistance and imaging capability, and the new image system can image objects in different directions. The main experimental apparatus and schematic diagram of the platform are shown in Fig. 1. The gasifier includes three parts from inside to outside: refractory wall, low thermal conductivity fiber blanket and stainless steel casing. The inner diameter of the refractory wall is 300 mm, and the external diameter of the stainless steel casing is 800 mm. The gasification chamber and quench chamber in the gasifier are 2500 mm and 2000 mm high, respectively. Four burners are oppositely mounted at the horizontal plane, which is 600 mm away from the dome. The burners include a central channel, an annulus channel and a cooling water channel (Fig. 2). The central channel is used to transport CWS, the annulus channel is used to transport high-velocity pure oxygen to atomize CWS, and the cooling water is used to protect the burner tip from the high temperature. The cooling water is at the same temperature as the air.

Different cameras and endoscopes are used in two different imaging systems for various purposes. One system is mounted at the top of the gasifier. To monitor the situation of the gasifier and ensure the smooth running of the gasifier, this system is fixed on the top of the gasifier during the entire experiment process. In this system, a cooling jacket and a D38-mm high-temperature endoscope with 0° optical axis-to-target angle and 60° view field are used and combined with the JAI camera to monitor the gasifier from the axial direction. The other system is mounted at the sample connection at the burner plane. The D38-mm high-temperature endoscope with 70° optical axis-to-target angle and 60° view field is mounted at the horizontal sample connection, and the PCO dimax S4 color high-speed camera (Gong et al., 2017) is combined to capture images around the operating burner to study the CWS in-situ atomization and particle combustion in the CWS jet flame. Both types of high-temperature endoscopes are equipped with cooling water and purge gas (Ar) system to ensure that the lens of the imaging system is not affected by high temperature and particles. The parameters of the cameras in the two imaging systems are listed in Table 1. The thermocouples are used to monitor the temperature of the refractory wall at different axial positions.

Diesel is supplied to preheat the bench-scale gasifier. When the temperature of the refractory wall around burner plane reaches 1573 K, the fuel is changed to CWS for gasification. The CWS contains Shenfu bituminous coal, water and a few additives. The corresponding properties of coal and CWS are listed in Table 2. Table 3 shows several operating conditions of the fuel and pure oxygen for CWS gasification. In this study, O/C is the ratio of elemental oxygen to elemental carbon. In each condition, the four burners remain consistent.