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Flow behavior of high-temperature flue gas in the heat transfer chamber of a pilot-scale coal-water slurry combustion furnace

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ABSTRACT

The flow characteristics of high-temperature flue gas are important in the heat transfer of coal-water slurry (CWS) combustion furnaces. The flow field of a 250 kg/h vertical-type slag tap cyclone furnace was non-intrusively investigated, using two-dimensional particle-image velocimetry (2D PIV). The method was verified using traceable fly ash particles in high-temperature flue gas. The flow field of the flue gas was analyzed with a time-averaged method, based on which the effects of excess air ratio and loading were investigated. The flue gas separated by a gas separator maintained good rigidity near the furnace wall, rather than eroding the heating surface. Numerical simulations validated the reliability of PIV under the actual circumstances within the furnace. This study provides guidelines for applying 2D PIV in analyzing flue gas in thermal test boilers.

1. Introduction

Increasing energy demands have increased the competition for oil, and have underpinned a worldwide dependence on coal, especially in the PR China. Coal-water slurry (CWS) has in the last few decades become a substitute for oil in many industries, power station boilers, gasification technologies, and fluidized bed combustors (Cheng, Zhou, Li, Liu, & Cen, 2008). CWS combustion generally emits less fly ash, SO_2, and NO_x than that of coal-fired boilers. Applying slag tap cyclone furnaces in CWS combustion can further reduce the emission of fly ash, and provide clean high-temperature flue gas for industrial application. Many studies have investigated the preparation, atomization, and combustion of CWS (Gong, Guo, Liang, Zhou, & Yu, 2012; Liu, Jiang, Zhou, Wang, & Han, 2009; McHale, Scheffee, & Rossmeissl, 1982). Understanding the flow field characteristics of high-temperature CWS flue gas is important for enhancing mass and heat transfer.

Measuring the flow field in high-temperature flue gas presents obvious practical difficulties. Non-intrusive techniques are more convenient and less likely to disturb the tested flow field. Particle-image velocimetry (PIV) is an optical flow visualization method used to obtain instantaneous velocity measurements and related properties in fluids. The fluid containing traceable particles is illuminated so that the particles are visible. The motion of these particles is used to calculate the velocity field of the flow. Adrian (1996) detailed the historical development of PIV, and Adrian (1991) and Raffel, Willert, Kompenhans, and Wereley (2007) described different PIV techniques in their studies. PIV can simultaneously provide information on different points in a flow field. PIV has recently been used to fundamentally investigate various complex flows, including steady to unsteady, low to high speed, and single to multiphase flow (Laverman, Roghair, Sint Annaland vanAnnaland, & Kuipers, 2008; Lecordier et al., 1994; Miyazaki et al., 1999; Shi, 2007). PIV can also be used to measure vortex fields and spatial correlations (Stewart & Vlachos, 2012; Tokgoz, Elsinga, Delfos, & Westerweel, 2012). PIV can potentially provide more information on flow mechanisms than conventional techniques, such as pressure-based meters and hot-wire anemometry (Raffel et al., 2007).

The development of optical and computer technology has significantly improved the accuracy of PIV. Gas–solid and turbulent flow (Hearst, Buxton, Ganapathisubramani, & Lavoie, 2012) have been investigated in many studies. Most gas–solid flow studies using PIV have been based on cold flow fields, without including the thermal flow field of high-temperature flue gas (Agarwal, Lattimer, Ekkad, & Vandsburger, 2011; Giddings, Azzopardi, Aroussi, & Pickering, 2011; Han, Zhang, Cheng, & Xiao, 2007). Thermal flow field studies have particularly focused on gas combustion (Kwark, Jeong, Jeon, & Chang, 2004). An example is that by Kim, Arghode, and Gupta (2009), where PIV was used to examine the combustion

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Table 1
CWS characteristics investigated in this study.

Proximate analysis (as received basis)		Ultimate analysis (as received basis)	
Moisture (%)	37.49	C (%)	44.26
Ash (%)	7.31	H (%)	3.11
Volatile matter (%)	20.50	N (%)	0.66
Fixed carbon (%)	34.70	S (%)	0.43
Concentration (%)	65.67	O (%)	6.73
Net calorific value (kJ/kg)	17,238.00		

characteristics of hydrogen-enriched methane-air flames at fixed thermal loads, under various swirl strengths. Legrand, Nogueira, Lecuona, Nauri, and Rodriguez (2010) used stereo PIV to investigate the reactive flow of a small-scale lean premixed prevaporized burner. Stopper et al. (2010) investigated the instantaneous planar flow field inside lean premixed natural gas/air flames of an industrial swirl burner using PIV. Difficulties with PIV measurements in high-temperature reacting flows are frequently commented on, including low-particle density (Chaves, Herbst, & Skupsch, 2012), thermophoretic forces (Reinhold-Lopez, Braeuer, Schmitt, Popovska-Leipertz, & Leipertz, 2012; Stella, Guj, Kompenhans, Raffel, & Richard, 2001), and image distortion (Rottier, Godard, Corbin, Boukhalfa, & Honore, 2010). Sophisticated studies have combined PIV with simultaneous measurements of temperatures and reactive species (Bohm et al., 2007; Gamba, Clemens, & Ezekoye, 2013). Applying PIV in high-temperature flue gas is limited by the background noise from lightened particles near the furnace measurement areas. This disrupts PIV acquisition and affects measurement accuracy.

PIV usually involves seeding the tested fluid flow with traceable particles (Hu, Zhou, Luo, & Xu, 2013; Liu, Jiao, & Zheng, 2006). The current study is the first to directly use traceable particles in high-temperature flue gas, while applying two-dimensional (2D) PIV in a thermal test boiler. The flow field and particle velocities of high-temperature flue gas in the heat transfer chamber of a CWS slag tap vertical cyclone furnace is investigated. The potential of PIV in thermal flow fields is demonstrated, and a comprehensive description of the high-temperature flue gas flow field is obtained.

2. Methodology

Experiments were conducted on a vertical-type slag tap cyclone furnace, with a burning capacity of 250 kg/h, as shown in Fig. 1. The furnace consisted of a CWS burner, combustion chamber with dimensions of $\Phi 450 \times 3000$ mm, heat transfer chamber with dimensions of 1100 (width) mm × 1000 (depth) mm × 3500 (height) mm, gas separator, and a set of bundled pipes as the heating surface. The entrance to the heat transfer chamber was separated by the gas separator into two narrow channels, each of 75 mm × 1000 mm. CWS characteristics investigated in this study are shown in Table 1. The CWS was pneumatically injected into the burner using compressed air, and then mixed with preheated primary and secondary air. The high-temperature flue gas from the combustion chamber entered the heat transfer chamber, after separated by the gas separator. This was designed to secure the heating surface, by retaining the particles near the wall.

Fig. 2 shows the 2D PIV measurement system. A double-pulsed Nd:YAG laser with wavelength of 532 nm and pulse energy of 200 mJ was transformed into a vertical laser sheet by a cylinder lens. The laser was then guided into the heat transfer chamber through the back wall, using a laser light arm. A frame-transfer charge-coupled device (CCD) camera was placed perpendicular to

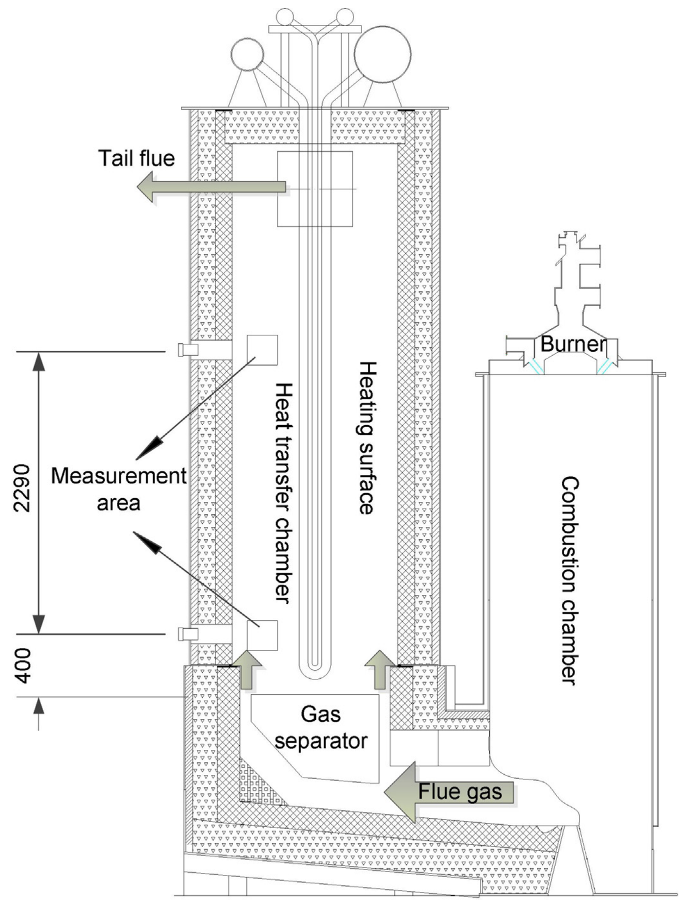

Fig. 1. Schematic diagram of the vertical-type slag tap cyclone furnace (in mm).

the laser sheet, through the left/right wall. A measurement area of 120 mm × 90 mm in the laser sheet plane was selected by the camera lens. Four measurement areas were set at different positions in the heat transfer chamber, as shown in Figs. 1–3. Areas

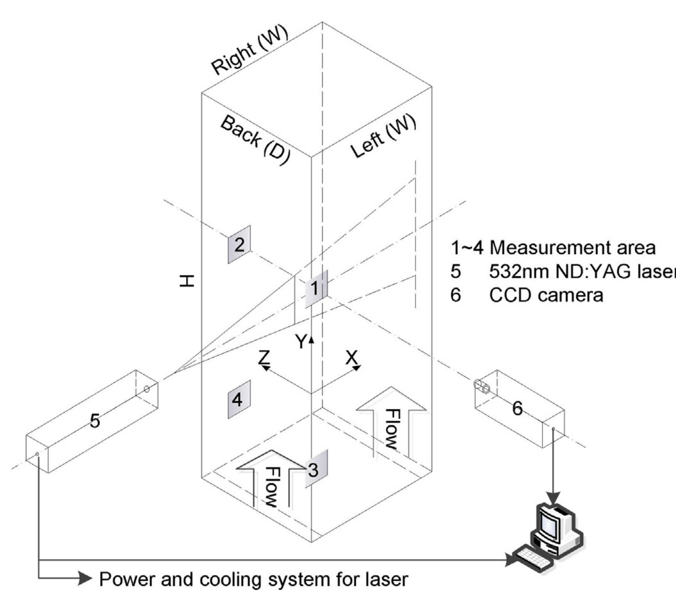

Fig. 2. Schematic diagram of the 2D PIV measurement system.