Fuel 182 (2016) 558–567

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Coal-particle size effects on NO reduction and burnout characteristics with air-staged combustion in a pulverized coal-fired furnace

Yonmo Sung, Cheoreon Moon, Seongyong Eom, Gyungmin Choi *, Duckjool Kim

School of Mechanical Engineering, Pusan National University, Busan 46241, South Korea

HIGHLIGHTS

- Effect of particle size on NO emission and burnout performance was evaluated in a pulverized coal fired furnace.
- In-furnace measurements of gas temperature and gas concentrations were performed in both unstaged and staged flames.
- There is a linear correlation between NO emission and particle size from 40 μm to 120 μm.
- Effectiveness of air staging on NO reduction burnout performance is significant in flames with fine coal particles.

ARTICLE INFO

Article history:
Received 16 March 2016
Received in revised form 6 May 2016
Accepted 27 May 2016
Available online 10 June 2016

Keywords:
Particle size
Pulverized coal combustion
Air staging
NO_x reduction
Burnout performance
Detailed measurements

ABSTRACT

The influence of coal-particle size on nitrogen oxide (NO_x) emission and burnout characteristics was experimentally investigated in a pulverized coal-fired furnace. This study was carried out for a range of particle sizes, namely, mean sizes of 52, 73, 102, and 107 μm. Detailed in-furnace measurements of gas temperature and gas species concentrations (O_2, CO_2, CO, and NO) were performed for two particle sizes (52 and 107 μm) in both unstaged and air-staged flames. The results show that the overall temperature of the flames with a mean particle size of 52 μm is higher than that of the flames with a mean particle size of 107 μm, because burning of fine coal particles improves the heating rate of other larger pulverized coal particles. The value of the NO emission measured at the furnace outlet depends on the pulverized coal-particle size and decreases by 20% with an increase in the mean particle size from 46 μm to 118 μm. Two trends are observed in the NO emission with a mean particle size. For the unstaged combustion, a linear relationship exists between the NO emission and mean particle size, whereas the NO emission is constant at the air-staged combustion. The burnout performance increases with an increase in the level of coal fineness. The effectiveness of air staging on the NO reduction and burnout performance is significant in the flames with fine pulverized coal particles. The NO-reduction efficiency for flames with mean particle sizes of 52 and 73 μm is almost twice that for flames with mean particle sizes of 102 and 107 μm. For the burnout performance, the deteriorating effect of air staging is more profound at the flames with high level of coal fineness. The reduction rate in the burnout performance is 1.7% for flames with fine particles (52 and 73 μm) and 0.7% for flames with coarse particles (102 and 107 μm).

1. Introduction

Because the grinding process to produce pulverized coal results in a broad size distribution, the specific size fraction when pulverized coal particles are injected into a furnace significantly influences the combustion and emission characteristics [1]. In particular, the emission of nitrogen oxide (NO_x) and carbon burnout are of great interest because the pneumatically injected pulverized coal particles are preferentially distributed in the burner region at a given aerodynamic condition according to the particle size, resulting in a highly intensive or a well-distributed flame. In this context, research works have been carried out to investigate the relationship between particle size and combustion characteristics, including NO_x emission in thermogravimetric analyzers (TGAs), electrically heated drop tube furnaces (DTFs), and large-scale coal-fired furnaces.

* Corresponding author at: School of Mechanical Engineering, Pusan National University, 2, busandaehak-ro 63beon-gil, Geumjeong-gu, Busan 46241, South Korea.

E-mail address: choigm@pusan.ac.kr (G. Choi).

http://dx.doi.org/10.1016/j.fuel.2016.05.122

For the TGA experiments, the ignition characteristics and reactivity improve with the decrease in the coal-particle size, according to the works of Chen et al. [2] and Rubiera et al. [3]. Li et al. [4] also showed that the burning rate of coal increases and the burnout time is reduced with the decrease in the coal-particle size, which indicates that higher coal fineness is propitious to the improvement of the combustion process. Nugroho et al. [5] investigated the effect of coal-particle size on the combustion characteristics. They found that a larger surface area available for the presence of fine particles can promote oxidation with a consequent higher heat generation rate when the coarse coal particles are mixed with fine ones. Yu et al. [6] and Xiumin et al. [7] concluded that the coal-particle size has significant influence on the coal physical properties and combustion histories because the specific area and pore volume increases with a decrease in the coal particle, which leads to the improvement in the combustion processes by the rapid heating and early devolatilization of the fine particles. Yi et al. [8] also confirmed that the surface area and pore volume of the pulverized coal decrease as the particle size increases; hence, a smaller particle size leads to high reactivity of coal char.

For the NO_x emission obtained from one-dimensional electrically heated DTFs, its value gradually increases with a decrease in the coal fineness at the unstaged combustion; however, the reduction efficiency of the NO_x emission between the unstaged and air-staged combustions significantly improves regardless of the coal ranks such as lignite [9], bituminous [10–12], and anthracite [13]. Du et al. [14] investigated the effect of coal-particle size on coal burnout characteristics. They reported that the burnout performance increases at a smaller coal size. However, no linear relationship exists between the particle size and burnout. Although the TGA and DTF experimental results are effective in providing fundamental information for understanding the coal-particle ignition and NO_x emission with the variation in particle sizes, a little more practical information is necessary to obtain the correlation between particle size and NO_x emission because real combustion systems have highly turbulent flow fields and not laminar and steady flows.

For the NO_x emission characteristics, which are controlled by the burner aerodynamics, Gu et al. [15] investigated the effect of coal-particle diameter on the particle penetration depth (L_d) in the internal recirculation zone (IRZ). We can observe that L_d increases with decreasing particle diameter, resulting in considerably low NO_x formation. Gu et al. [16] also reported that the co-firing of fine (25 μm) and conventional-sized (75 μm) pulverized coal can improve ignition and combustion performance as well as NO_x reduction. The effect of coal-particle size on the NO_x emission was experimentally and numerically investigated in pulverized coal-fired furnaces, which have a swirl burner to generate the IRZ near the burner, without [1,17] and with [18,19] air staging. Abbas et al. [1,17] and van der Lans et al. [20] showed that the flame structure and ignition patterns are dependent on the degree of spread of the particles and the rate of devolatilization, which results in a variation in NO_x emission with the coal-particle sizes. Therefore, the correlation between the particle size and NO_x emission is not straightforward. Casaca and Costa [21] reported that the intermediate particle size as a biomass re-burning fuel is more effective for NO_x reduction than the smaller and larger particles, whereas the effect of size on the burnout performance is minor. This result indicates that an optimum particle-size distribution exists for NO_x reduction in low-NO_x combustion systems.

Several researchers [18,22–24] reported that a flame with smaller particles has higher NO emission owing to the rapid ignition and devolatilization of the fine particles; however, Maier et al. [19,25] reported results contradictory to the aforementioned articles. Because all the above-mentioned studies on the effect of particle size on the NO emission have no overlap in the range of particle-size distribution, more correlation between the coal-particle size and NO_x emission with standard particle size (mean size of 75 μm for bituminous coal), which is used in actual coal-fired thermal power plants, remains indispensable. In particular, the effectiveness of air staging on the NO_x-reduction efficiency and burnout characteristics with the variation in the coal-particle size should be evaluated. Little or no relevant results have been reported and even fewer studies have been attempted in terms of the coal-particle size effects on the combustion characteristics with detailed in-furnace measurements and without air staging [1,17] as well as with air staging and without detailed in-furnace measurements [18,19].

In this study, therefore, we report more correlations of the coal-particle size in a range from 40 μm to 120 μm with the combustion characteristics, including the NO emission and burnout characteristics in the unstaged combustion. Then, we also evaluate the effectiveness of air staging on NO reduction and burnout performance using different coal-particle sizes in a laboratory-scale pulverized coal-fired furnace. Furthermore, in-furnace gas temperature and species concentrations (O_2, CO_2, CO, and NO) are measured to enhance the understanding of relevant physical phenomena involved in the air-staged combustion using two coal-particle sizes (mean sizes of 50–100 μm) on the combustion characteristics.

2. Experimental setup and methods

2.1. Experimental apparatus and methods

The measurements were made at the 16-kW_{th} Pusan National University pulverized coal-fired furnace, as shown in Fig. 1. The design and operation of the system have been described elsewhere [26–28]. Therefore, only essential information is restated here. The cylindrical combustion chamber is down-fired, and it is composed of three individual water-cooled steel segments with a 200-mm internal diameter and a 500-mm height. The roof section and all the segments are lined with a layer of refractory materials (width: 130 mm). Each segment has four pairs of diametrically opposite 120-mm round ports to allow observation of the combustion. R-type thermocouples and gas-sampling ports for recording the in-furnace temperatures and gas concentration, respectively, are installed in every segment. The axial position of the air-staging level from the burner port is at 585 mm, whereas the lances for the in-furnace temperature and gas species measurements from positions 1 to 5 are placed at 65 (Z_1), 210 (Z_2), 355 (Z_3), 535 (Z_4), and 680 mm (Z_5). The in-furnace data are measured at the furnace center in radial directions at an interval of 10 mm for the temperature and 20 mm for the gas species in each axial measurement position Z, as shown in Fig. 1. Two-dimensional (2-D) half contours are then obtained from the measured point data. The empty values among the axial positions (Z_1–Z_5) are filled interpolation values using Tecplot 360 (Tecplot, USA). Fig. 1 shows that 50 and 30 measurement points to measure the temperature (filled symbol) and gas species (open symbol), respectively, are required to provide 2-D half maps. Basically, the high-velocity gradient regions near the burner zone require more measurement points. Nevertheless, several works have applied the in-furnace measurements for temperature and gas species concentration to more easily visualize their variations in combustion test conditions with a resolution similar to the 2-D maps of the current study [29–31].

The burner has a coaxial dual-piping structure with a main burner port (inner diameter: 10 mm) and an annular slit (width: 5.5 mm) installed outside the main burner port. Primary air is used to transport the coal sample from the coal feeder into the furnace. Secondary air enters the combustion chamber through the annular slit port and encounters an axial swirler with a vane angle of 60°. A