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Synergistic effect of co-firing woody biomass with coal on NO_x reduction and burnout during air-staged combustion

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A B S T R A C T

Hybrid technologies combining fuel blending and air-staging processes have been applied to a pulverized coal fired furnace to reduce NO_x emissions. In this study, an Australian bituminous coal (Whitehaven), an Indonesian sub-bituminous coal (Adaro), and an Indonesian woody biomass were selected as fuel with blending ratio of 10%, 20%, and 30% of the low-rank fuels, and the air-staging levels were set to 235 mm, 390 mm, 585 mm, and 760 mm. The purpose of this study was to investigate the synergistic effect of woody biomass co-firing on the level of NO_x emissions and the degree of carbon burnout under air-staged conditions. For single coals, sub-bituminous coal was more favorable than that for bituminous coal to reduce NO_x emissions due to low fuel-N composition. This tendency was more dominant with increasing the air staging levels. In the co-firing of woody biomass with coal, as the biomass is highly volatile but has a low carbon content, it could be successfully applied to low-NO_x combustion under air-staged conditions. In addition, the degree of carbon burnout and the flame temperature both increased. As a result of this research, we determined that hybrid NO_x reduction technologies have the potential to reduce exhaust gas emissions and enhance combustion performance. A dominant synergistic effect on NO_x reduction and carbon burnout was observed when woody biomass co-firing with coal was applied to air-staged combustion.

1. Introduction

Coal-fired thermal power plants in Korea currently co-fire bituminous/sub-bituminous coal because of the difficulty in obtaining high-grade coal. The importance of fuel blending technology is being emphasized as it opens up the possibility of using low-rank fuels such as biomass or waste material. Recently, the utilization of both woody biomass and sewage sludge has become commonplace in existing coal-fired thermal power plants because Korea's renewable portfolio standard (RPS) obligates electricity providers to produce a specified fraction of their electricity from renewable energy, with the remainder being generated from fossil fuel and nuclear reactors. In Korea, 13 electricity providers have been mandated to generate 2% of their gross power output from renewable energy sources, such as solar, wind, hydro, tidal power, fuel cells, hydrogen, biomass, and waste, as a result of the implementation of the RPS regulation in January 2012. This percentage is set to rise to 10% in 2022 [1]. Most coal-fired thermal power plants in Korea determined that the best way for them to satisfy the RPS regulations was to introduce the co-firing of biomass since it is the fourth largest source of energy after coal, petroleum, and natural gas [2]. Environmental issues, especially NO_x emissions, continue to be one of the most important challenges facing coal-fired utilities. The regulations limiting NO_x emissions are actually very severe [3]. For example, as of 2008, the NO_x emission limit imposed on power plants over 500 MW_{th} in the European Union (EU) has been 500 mg/Nm^3 at 6% O_2. This limit will drop to 200 mg/Nm^3 at 6% O_2 from 1 January 2016. In this context, emission limits for primary air pollutants such as NO_x, SO_x, and dust from coal-fired thermal power plants in Korea have been continually reinforced, shown in Table 1 [4,5]. The air quality preservation act by Korean ministry of environment requires that new facilities must reduce NO_x emissions as 103 mg/Nm^3 at 6% O_2 from 1 January 2015.

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Table 1
Permissible emission standards for NO_x, SO_x, and dust from coal-fired thermal power plant in South Korea.

Pollutants	Facility division	Limit before 2014.12.31	Limit after 2015.1.1
NO_x (mg/Nm^3@6%O_2)	Installed before 1996.6.30	<308	<287
	Installed after 1996.7.1	<164	<144
	Installed after 2015.1.1		<103
SO_x (mg/Nm^3@6%O_2)	Capacity > 100 MW	<286	
	Installed before 1996.6.30		<286
	Installed before 2014.12.31		<228
	Installed after 2015.1.1		<143
	Capacity < 100 MW	<428	
	Installed before 1996.6.30		<371
	Installed before 2014.12.31		<228
	Installed after 2015.1.1		<143
Dust (mg/Nm^3@6%O_2)	Capacity	>500 MW	>100 MW
	Installed before 2001.6.30	<28	<23
	Installed after 2001.7.1	<19	<19
	Installed after 2015.1.1		<9
	Capacity	<500 MW	<100 MW
	Installed before 2001.6.30	<37	<37
	Installed after 2001.7.1	<28	<28
	Installed after 2015.1.1		<28

To satisfy this impending tightening of the NO_x emission limits, technologies such as in-furnace removal (i.e. air-staging, reburning, the use of low-NO_x burners, etc.), flue gas purification (i.e. selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR), etc.), and other combustion methods (i.e. coal-water slurry combustion, circulated fluidized bed combustion etc.) have been widely used for coal-based power generation applications [6]. Among the existing methods, air-staged combustion is one of the most efficient and attractive technologies for reducing NO_x emissions, because it does not require expensive new equipment, such as SCR systems [7]. Unfortunately, there are also serious disadvantages such as high operating costs, ammonia slip (the passing of ammonia through the SCR reactor), and the easy deactivation of the catalyst in SCR applications [8]. Ammonia slip, in particular, can lead to a blockage in the SCR catalyst due to an unwanted reaction between un-reacted ammonia and unburned carbon. Generally, biomass co-firing should reduce NO_x emissions simply because most forms of biomass contain less fuel-N than the coal they replace [9]. Therefore, it is important to minimize the initial formation of NO_x by in-furnace removal methods including air-staging and biomass co-firing to avoid having to implement flue gas purification or minimize its operation.

Numerous articles dealing with NO_x reduction technologies such as air-staged combustion and low-rank fuel blending have been published [10–18]. Ribeirete and Costa [19] investigated the impact of air-staging on the overall performance of a large-scale laboratory furnace fired by an industrial pulverized coal swirl burner. The influences of the axial position of the staged-air injector, the primary zone stoichiometric ratio, the coal type, and the configuration of the staged-air injectors on the pollutant emissions and particle burnout were quantified [18]. Munir et al. [20] showed that the addition of biomass has a positive effect on NO_x reduction and carbon burnout under the optimum conditions that were identified as part of their study. Daood et al. [21] investigated NO_x control in coal combustion by combining biomass co-firing, oxygen enrichment, and SNCR in a 20-kW combustion facility. It was found that NO_x control by SNCR and the oxygen-enriched co-firing of biomass in power station boilers would result in lower NO_x emissions and a higher CO_2 concentration that would lead to more efficient scrubbing with better carbon burnouts.

When a furnace is co-firing biomass and coal, it is important to consider the slagging, fouling, and tube corrosion that may occur as a result of the presence of unburned carbon. This study focused on the effect of air-staged combustion and woody biomass co-firing on the overall performance, including NO_x emissions and carbon burnout, since there are still doubts about the effect on gas emissions of low-rank fuel blending. For having nearly same coal properties of two sub-bituminous coals, NO_x emissions from two sub-bituminous coals (Wara and Adaro), which were blended with bituminous, exhibited an inverse tendency with increasing sub-bituminous coal blending ratio although the moisture contents of them were different [22]. The effect of biomass co-firing on NO_x emissions was found to be dependent upon the particle size, with smaller particles reducing NO_x emissions as the biomass co-firing ratio increased [23].

Air-staged combustion is used to reduce the stoichiometric ratio in the primary combustion zone, and thus the fuel-rich condition causes the NO_x to act as a reducing species. This reducing environment can be locally intensified by adding low-rank fuels such as woody biomass. In particular, the nitrogen content in woody biomass is relatively lower compared to straw and other agricultural residues, although the woods and the straws decompose in different ways in terms of the release of the N-components [24,25]. Moreover, air-staged combustion is, in general, desirable for reducing NO_x emissions; if, however, there is insufficient air in the primary combustion zone, the flame temperature is typically applied to low-temperature processes [23]. Different components in the biomass, i.e., lignin, and semi-cellulous/cellulous materials, decompose at different temperatures, and thus the biomass starts to release its volatile components at a relatively low temperature [26]. This behavior could help alleviate the drop in temperature caused by deep air-staging through possible synergistic effects when coal is co-fired with woody biomass. There are lots of studies on low-rank fuel blending with air-staged combustion. However, woody biomass co-firing with air staging is rarer to produce synergy effects on reducing NO_x emissions and enhancing carbon burnout performances simultaneously, and even fewer studies have been attempted under the combination of several parameters as oxy-firing, air staging, and agricultural biomass co-firing for the synergy of NO_x and burnout [20,21].

In this study, a hybrid technology combining fuel blending and air-staging was applied to reduce the NO_x emissions from a pulverized coal fired furnace. The combustion and emission characteristics of different blends of coal (bituminous and sub-bituminous) and woody biomass were investigated using a pulverized coal fired furnace. To understand the details of the air-staged combustion, in this study we undertook detail measurements of gas species concentration, temperature, and carbon burnout under