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Performance evaluation of dry and wet electrostatic precipitators used in an oxygen-pulverized coal combustion and a CO_2 capture and storage pilot plant

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ABSTRACT

The electrical and particle collection characteristics of a 1200-m^3/h-dry electrostatic precipitator (ESP) and a 400-m^3/h-wet ESP for a 0.7 MW-oxygen-pulverized coal (Oxy-PC) combustion and carbon capture and storage (CCS) pilot plant were evaluated under varying air and oxygen combustion operational parameters of the ESPs. The corona current of a dry ESP reduced by oxy-firing was compared with that for the same applied voltage with air firing, which resulted in a decreased collection performance during oxy-firing at the same applied voltage. However, the decreased collection performance could be avoided by simply increasing the applied voltage to reach the same corona power consumption as with air firing because the collection performance of the ESP was an exponential function of the power consumption divided by the gas flow rate regardless of combustion conditions. The wet ESP used here had a thin water film on the collection plates due to the patented design of the collection plates, with water supplied by gravitational force from holes on the collection plates with TiO_2 nanoparticles coated on ball blasted surface. The system only consumed water at a rate of 1.7 L/min/m^2. The collection efficiency of the wet ESP was higher than 90% even for fine particles and mists, which enabled an overall particle collection efficiency of 99.98% to be achieved with both the dry and wet ESPs, corresponding to total gravimetric emission of 1.8 mg/m^3 at the inlet of the CCS facility. The wet ESP had the additional effect of removing SO_2 and SO_3 at 64.5% and 23.1% efficiency, respectively.

1. Introduction

Energy supply is currently an issue of great importance. Fossil fuels are currently the world's most important energy sources, and will continue to be dominant for many decades because alternative clean energy technologies such as solar, wind, and fuel cells are still not cost effective. Due to this technical and economic situation, coal, the most abundant fossil reserve according to the US Energy Information Administration and the International Energy Agency, will play a significant

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role in global power generation for the foreseeable future. However, burning coal in air also presents many challenges, including the control of particulate matter, mercury, trace metals, and carbon dioxide (CO_2) emissions. In particular, emissions of CO_2, an important greenhouse gas, should be reduced in order that coal can continue to be used in a CO_2-constrained future (Wall, 2007).

As a means of capturing CO_2 gas during combustion, the technology of oxy-fuel combustion has recently received considerable interest (McCauley et al., 2009; Czakiert et al., 2010). The basic concept of oxy-fuel combustion is to replace the combustion air with a mixture of oxygen and recycled flue gas; the resulting flue gas consists of primarily CO_2 and H_2O vapor with some N_2, O_2, and pollutants such as S*Ox* and particulates. The flue gas can be processed relatively easily to enrich the CO_2 content to over 90% in the product gas, which can be simply dried and compressed for storage (Levasseur et al., 2009).

For successful and stable CO_2 compression and purification by a CO_2 compression and purification unit (CPU), a state-of-the art flue gas cleaning system for oxy-fuel combustion is necessary to clean the flue gas to a high standard so that the CPU can work effectively over an extended period of time (Stanger & Wall, 2011; Bäck et al., 2011).

Electrostatic precipitators (ESPs) have been widely used for the collection of particles from air-pulverized coal combustion. However, due to the technical limitations of conventional dry ESPs, including particle re-entrainment during the periodic rapping of electrodes and collection plates, it is difficult for the dry ESPs to achieve the low particle emissions that are required (approximately 1 mg/m^3) for carbon capture and storage (CCS) (Burchhardt, 2009). Wet ESPs have been evaluated to achieve a better collection performance than dry ESPs for long-term operations (Lin et al., 2010, 2013).

On the other hand, changes in the design and operational parameters of conventional ESPs for oxygen-pulverized coal (Oxy-PC) combustion are inevitable because the gas composition of the flue gas from the Oxy-PC combustion is significantly different from the flue gas produced by air combustion.

Several studies of the use of ESPs in oxy-fuel combustion have been conducted (Suriyawong et al., 2008; Han et al., 2010; Bäck et al., 2011). Suriyawong et al. (2008) studied the collection characteristics of submicron particles in a cylinder-wire ESP following the combustion of coal in oxy-fuels with various O_2–CO_2 and N_2–CO_2 compositions and found that particle penetration in an O_2–CO_2 fuel was one to two orders of magnitude higher than that in an O_2–N_2 fuel. Han et al. (2010) also investigated the collection efficiency of submicron particles for a laboratory scale ESP in a CO_2-enriched environment with a changing gas mixture and found that the low electrical mobility of ions resulted in a low corona current under CO_2-enriched conditions. However, these studies have been conducted with a laboratory-scale ESP and used submicron particles that are not representative of the particles emitted from industrial combustion plants. Thus they offer limited information about the design and operation of a full-scale ESP for use with oxy-fuel combustion and CCS. The Alstorm ESP research group has studied the characteristics of a dry ESP, which was operated for a 30 MWth oxyfuel pilot plant that incorporated flue gas desulfurization (FGD) and a flue gas condenser (FGC) as gas cleaning technology. However, the study focused on the particle collection performance of a dry ESP and has not evaluated changes in the collection efficiency of the ESP under different combustion conditions, such as air and oxygen firing.

In this study, we used a novel wet-type ESP with thin water films on the collection plates (water consumption <2 L/min/m^3) and it was located at downstream of a dry ESP and FGC that removed particles produced from oxy-PC combustion to ensure a level of approximately 1 mg/m^3. We also investigated changes in the performance of the ESPs of a 0.7 MW-Oxy-PC combustion pilot plant when the combustion conditions and operational parameters of the ESPs were varied. The plant also included desulfurization technology in the form of an in-furnace deSO*x* system that sprayed limestone directly into the oxy-PC combustor.

2. Theoretical analysis

The collection efficiency of the ESP is the most important consideration for ESP researchers. The collection efficiency can be estimated using several equations, which give a theoretical prediction of the size-dependent collection efficiency of an ESP when it is operated under ideal conditions. The most popular and easiest equation for calculating the collection efficiency of an ESP is the Deutsch equation, which has been used in many previous studies (Parker, 1997; Park & Chen, 2002; Xiangron et al., 2002). The Deutsch efficiency formula is as follows:

$$\eta = 1 - \exp\left\{-\frac{W_m(d_p, E_C)A}{Q}\right\}, \tag{1}$$

where η is the collection efficiency, W_m is the migration velocity to the collection plate for a particle with a diameter of d_p that results from the electric field (E_C), A is the collection area, and Q is the gas flow rate through the ESP. Assuming that Stokes' drag law is valid, the theoretical migration velocity of particles at a steady state resulting from a balance of the drag and electrical forces on particles is as follows:

$$W_m(d_p, E_C) = \frac{q_p E_C Cu}{3\pi\mu d_p}, \tag{2}$$

where μ is the viscosity of gas, and q_p is the particle charge.

The charging processes is divided into the diffusion charging for particles smaller than 1 μm, and a field charging for those larger than 1 μm. Many researchers have developed charging theories for the field charging, diffusion charging, and their combination because various sized particles even including nanoparticles are present in an ESP (Lin & Tsai, 2010; Lin et al., 2012). Among various theories, in this study we used Cochet's charging theory which has been used by previous