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An experimental study on the effects of temperature and pressure on negative corona discharge in high-temperature ESPs

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HIGHLIGHTS

- An additional corona current induced by high temperature was proposed.
- The reason for the additional corona current was investigated.
- Electron current has the most important function at 873 and 973 K.
- The additional corona current is smaller in gas with strong electronegativity.

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ABSTRACT

High-temperature ESPs are proposed to improve energy efficiency and avoid damage to downstream equipment in integrated gasification combined cycle and pressurized fluidized-bed combustion. In this study, the effects of temperature and pressure on negative corona discharge characteristics were compared. Gas temperature varied from 373 K to 1073 K, and pressure varied from 30 kPa to 100 kPa to achieve the same gas density. The additional corona current ΔI_t induced by high temperature was calculated, and the additional ion current ΔI_i and electron current ΔI_e were studied. A wire-type electrode, a spiral electrode, a ribbon electrode, and four gas compositions ($N_2/CO_2/SO_2$/air) were investigated in the plate-type discharge configuration. Results show that corona current increases more rapidly with increasing gas temperature than that with decreasing pressure at the same gas density. The current density is 0.87 mA/m at 973 K and atmosphere pressure, which is higher than 0.45 mA/m at 30.9 kPa and room temperature. An additional temperature effect on corona discharge is proposed apart from the decrease of gas density as temperature increases. ΔI_t increases with increasing temperature because of enhanced molecule kinetic energy and ionization rate. The electron-carried current is important at temperatures above 873 K. $\Delta I_e/\Delta I_t$ increases from 0 to 0.941 when temperature increases from 773 K to 973 K. Compared with the ΔI_t of wire and spiral electrodes, the ΔI_t of ribbon electrode is significantly larger because of the enhanced electron avalanche and secondary electron emission. Negative corona discharge does not occur in N_2, and corona onset voltages are in the following sequence: $CO_2 > SO_2$ (6000 ppm) > air, which is determined by gas molecule ionization energy. $\Delta I_t/I_P$ is smaller in gas atmosphere with strong electronegativity.

1. Introduction

Worldwide environmental concerns has led to new designs for advanced power generation with high thermodynamic efficiencies and low emissions, such as coal-based integrated gasification combined cycle and pressurized fluidized-bed combustion technologies{Chau, 2009 #2} [1–4]. High-temperature gas cleaning, which aims to remove dusts from high-temperature gasified gases, is a common challenge for advanced power generation technologies. This method improves system energy efficiency and by-product quality and avoids erosion and high-temperature corrosion difficulties in turbine blades [5–8].

Several hot gas cleaning methods have been proposed, including ceramic filtration [9], metal filtration [10], granular bed filtration [11], and electrostatic precipitation (ESP), which can be operated in various working conditions and achieve high particle removal efficiency with small pressure drop. ESPs are widely used

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Nomenclature

μ	ion mobility ($m^2/V/s$)	P	gas pressure (Pa)
D	discharge gap (m)	T	gas temperature (K)
d	wire diameter (m)	V_a	applied voltage (V)
E	electric field strength (V/m)	k_B	Boltzmann constant
I_s	saturation unipolar ion current density (mA/m^2)	α	Townsend's first ionization coefficient
I_e	electron current density (mA/m^2)	n	relative gas density
I_T	current density in temperature experiments (mA/m^2)	ε_0	dielectric constant (F/m)
I_P	current density in pressure experiments (mA/m^2)	ρ	unipolar ion density
ΔI_t	total added temperature current density (mA/m^2)	ρ_s	saturation unipolar ion density
ΔI_i	added temperature ion current density (mA/m^2)		
ΔI_e	added temperature electron current density (mA/m^2)		

in particle removal from industrial flue gases at temperatures lower than 450 K [12–15]. However, studies on ESP operations at above 600 K are limited. The increase in the kinetic energy of gas molecules, which leads to highly conductive gases, is one of the limitations of high-temperature ESP [16,17].

Corona discharge characteristics are significant in high-temperature ESP because ion and electron concentrations play important functions in particle charging [18,19]. Numerous studies have been conducted on corona discharge, streamer development and space charge distribution in the discharge region have been observed [20,21]. Ionic species have also been detected [22]. Previous studies on corona discharge performed at various temperatures showed that the increase in the kinetic energy of gas molecules lead to highly conductive gases and that a large discharge current was induced at high temperature. Corona onset and spark voltages decreased with increasing temperature, but spark voltage decreased more rapidly than corona onset voltage; as a result, the operation span decreased [6]. Most researchers attributed the increase in current and decrease in voltage operation span to the decrease in gas density, because ion mobility increased and the collision frequency decreased with the increasing mean free path of gas molecules [23,24].

However, some researchers indicated that electrons were detached from negative ions in the drift region under a high-voltage electric field [25], and many free electrons were produced at high temperatures [24]. Gu et al. [26] reported that high temperature lowered the effective work function of cathodes, thus causing the production of secondary electron emission and thermionic electrons from the cathode surface. Moreover, cluster ions, such as O_4^+ and N_4^+, which are the main cause of electron loss in electron–ion recombination into gas molecules, could be decomposed at high temperatures [27,28]. As a result, electron loss was reduced significantly, which also increased the number of free electrons. However, whether the appearance of free electrons will also lead to an additional temperature effect on negative corona discharge, apart from low gas density in high-temperature ESP, is still uncertain. Research results of Huiskamp [23] about temperature and pressure effects on positive streamers showed that the effect of temperature on average streamer propagation velocity was higher than the effect of pressure at the same gas density.

A plate-type negative corona discharge system was designed in this study. In this system, both the temperature and pressure could be adjusted. To obtain the same gas density, the temperature was varied from 373 K to 1073 K at atmospheric pressure (temperature experiments) and the pressure was varied from 30 kPa to 100 kPa at room temperature (pressure experiments). The effects of temperature and pressure on negative corona discharge characteristics were compared. A wire-type electrode, a spiral electrode, a ribbon electrode, and four gas compositions ($N_2/CO_2/SO_2$/Air) with different electronegativity were investigated. The additional corona current ΔI_t induced by high temperature was calculated, and the effects of applied voltage and gas atmosphere on the additional corona current were investigated. Ion-carried current and electron-carried current were calculated to identify the reason for the additional corona current at high temperature. This study mainly aims to obtain the electron-carried current at high temperatures and its contribution to additional corona current.

2. Experiment setup

A schematic of the experimental system is illustrated in Fig. 1(a). The system consisted of three parts: a wire–plate discharge configuration with a negative DC power supply, a temperature and pressure-controlled furnace, and an electric measurement system.

2.1. DC corona discharge setup

The wire–plate negative DC corona discharge configuration consisted of a wire discharge electrode and two grounded plates, which were all made of heat-resistant stainless steel TP310S. Spiral electrode, ribbon electrode, and wire electrode with diameters of 5 mm were used as the discharge electrodes. The discharge electrodes were 150 mm long. The two grounded plates were L-shaped, i.e., 150 mm × 140 mm for the long sides and 150 mm × 25 mm for the short sides (Fig. 1(b)). The discharge gap could be adjusted by moving the two L-shaped grounded plates. The short sides were insulated by two 10 mm-thick corundum plates. The high-voltage power supply generated an adjustable DC negative voltage from 0 kV to 30 kV and current up to 40 mA. The negative high voltage was applied to the discharge electrode.

2.2. Temperature and pressure adjustment

The wire–plate discharge configuration was placed in a sealed furnace, with a maximum designed temperature of up to 1,400 K and a minimum pressure of 20 kPa. The temperature was measured by thermocouples (Range: 273–1373 K; Precision:±1 K) that were fed back to the programmable temperature controller to adjust the heating power of furnace. The pressure in the setup could be adjusted between 20 and 101 kPa by a vacuum pump and was measured by a digital pressure gauge (Testo 511, Range: 200–1200 hPa; Precision:±3 hPa). The furnace shell was isolated from the high-voltage electrode by corundum, which was a perfect insulator at temperatures up to 1473 K. No leakage current was detected from the insulator during the experiments.