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An analytical method for DC negative corona discharge in a wire-cylinder device at high temperatures

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ABSTRACT

This paper proposes an analytical solution for DC negative corona discharge in a wire-cylinder device based on experimental results in which both the corona and drift regions are considered; this approach aims to provide a theoretical method for analyzing electrostatic precipitation at high temperatures. The inter-electrode space is divided into three zones, namely, the ionization layer, the attachment layer (corona region) and the drift region, to investigate the space charge concentration and the electric field distribution. The boundary of the ionization layer is assumed to be the radius at which the rate of ionization balances that of electron attachment. The radius where the value of E/N equals 110 Td is recommended as the boundary of the attachment layer. It was determined that an increasing temperature leads to a decrease in the largest space charge number density and the largest electric field in the drift region that can be provided by a discharging device. With respect to the device in the present work, when the temperature increases from 350 °C to 850 °C, the largest electric field decreases from $\sim 9 \times 10^6$ V/m to $\sim 3 \times 10^6$ V/m, and the largest charge number density decreases from $\sim 1.3 \times 10^{15}$ m^{-3} to 6.4×10^{14} m^{-3}. The radius of the corona region, the space charge number density and the electric field increase as the applied voltage increases at a given temperature. For example, at a temperature of 550 °C, when the applied voltage increases from 10,500 V to 18,879 V, the radius of the corona region increases from ~2.9 mm to ~4.9 mm. It appears to be unreasonable to use a constant value that is calculated from Peek's formula as the electric field at the surface of the cathode under all of the conditions.

1. Introduction

Particle separation from gas at a high temperature is of great importance for the integrated gasification combined cycle (IGCC) and for the pressurized fluidized bed combustion (PFBC) technologies, which promise electricity generation that has substantially greater thermodynamic efficiency and reduced environmental effects [1,2]. Ceramic candle filters and granular bed filters represent promising methods for hot gas clean-up. Candle filters are effective in separating particles from gas and have a high cleaning efficiency, which is ~99.8% [3]. Several ceramic barrier filters are nearing commercialization at a temperature range of 250–400 °C [4]. However, ceramic filters quickly become clogged with deposited particles, which result in a large increase in the pressure drop across the filters and require a method for cleaning the surface of the filters [5,6]. With respect to granular bed filters, more experimental studies at high temperatures (e.g., 600 °C and above) are needed to evaluate their comprehensive performance.

Electrostatic precipitation is currently the most common method that is used in separating particles from power plant flue gases for its high collection efficiency (as high as 99.9%) and its suitability for dealing with particles of different sizes (even particle sizes below 1 μm) and variable flue gas volumes [7–11]. Mathematical simulations for different electrostatic precipitators, i.e., wire-plate [12–15] and wire-cylinder [16,17] precipitators, are widely reported.

However, most of these reports confined their temperatures to being less than 400 °C. With regard to the gasification gas and pyrolysis gas, the temperatures are usually greater than 500 °C. To apply electrostatic precipitation for separating particles from gas at high temperatures (e.g., gasification gas and pyrolysis gas), one of the key issues is to build an appropriate corona discharge, where the electric field and charge concentration should meet the requirement of the particle charging and collection. Therefore, it is significant to understand the property of corona discharge at high temperatures. In our previous studies [18,19], we investigated the

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characteristics of DC discharge and conducted current analysis of DC negative corona discharge in a wire-cylinder device at high temperatures (approximately 350–850 °C). It is found that corona discharges at high temperatures are different from those at room temperature. First, the corona onset electric field decreases with increasing temperature and is lower than the value that is calculated by Peek's formula. Second, at high temperatures, in the DC negative corona discharge gap, some electrons are not attached to the electronegative gas molecules, and they move to the anode tube. Those electrons then form an electron current, which could account for most of the total discharging current. As a result, mathematical simulations for corona discharge that assume that the electric field at the surface of the cathode is determined using Peek's formula and the discharging current in the drift region is only carried by negative ions might not be applicable at high temperatures. In this work, we attempt to propose an analytical solution for the DC negative corona discharge in a wire-cylinder device based on the experimental results, which takes both the corona and drift regions into consideration, aiming to provide a simplified theoretical method for the analysis of electrostatic precipitation at high temperatures. In a word, electrostatic precipitation includes two key issues, namely, particle charging and collecting. The particle charging mechanisms include the field charging and the diffusion charging, where the electric filed and the space charge concentration play important roles [20,21]. Particle collecting is directly related to the electric filed and the charges carried by particles. As a consequence, the analytical method in this work mainly investigates the space charge concentration and the electric field distribution in the DC negative corona discharge.

2. Experimental setup

Fig. 1 is the schematic of the experimental setup, which is composed of a furnace that is controlled by a programmable temperature controller, a negative high voltage DC power supply, a discharging device, gas tanks and pipelines, a camera, an oscilloscope and a galvanometer. A detailed description of the experimental setup and experimental procedure is reported in our previous work [18].

3. Mathematical equations

3.1. General introduction

A simple schematic of the DC negative corona discharge is shown in Fig. 2. The inter-electrode space is usually divided into two zones, i.e., the corona region and the drift region. In the corona region, there are electrons, negative ions, positive ions, and gas molecules, among which the electrons are the most active. Reactions occur between the electrons and the gas molecules would include ionization, excitation, dissociation and attachment. When the electrons interact with negative ions, they can exchange their charges, and when electrons interact with positive ions, they can recombine [22]. In this study, we focused on the ionization process and the attachment process (including direct attachment and dissociative attachment) in the corona region, which is demonstrated to be reasonable by Chen and Davidson [23]. The ionization process is described by the ionization coefficient α, and the attachment process is described by the attachment coefficient η. These two coefficients can be directly measured through experiments or can be calculated from measurement results of basic cross sections for ionization and attachment [24]. The radius at which the rate of ionization balances the rate of electron attachment is set as the boundary of the ionization layer [22,25]. At this boundary, for the air, the value of E/N equals 120 Td (1 Td = 10^{-21} V m^2) [24]. Near the discharge electrode, ionization prevails over attachment, and new electrons are produced. Beyond the ionization boundary, attachment prevails over ionization, and the number of electrons gradually decreases. As a result, the present work assumes that the corona region should be divided into an ionization layer (where ionization and attachment reactions occur) and an attachment layer (where only attachment reactions occur). According to experimental results, the radius at which the value of E/N equals 110 Td is set as the boundary of the attachment layer. In the model

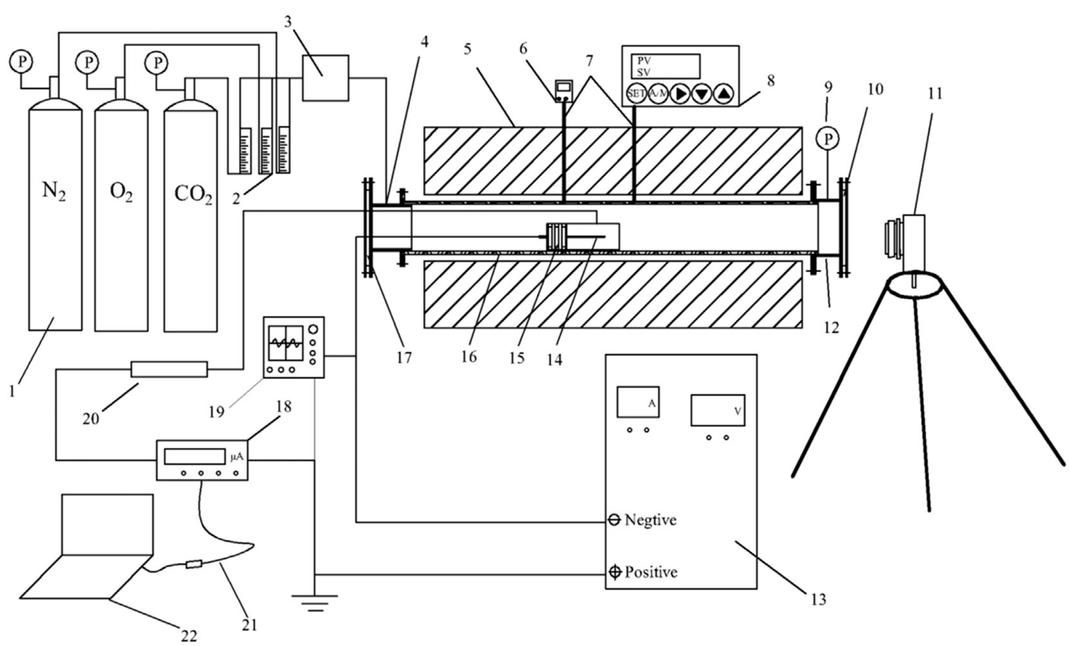

Fig. 1. Schematic of experimental setup. 1 – gas tank, 2 – flow-meter, 3 – gas mixing tank, 4 – stainless sleeve tube, 5 – heating furnace, 6 – temperature indicator, 7 – thermal couple, 8 – programmable temperature controller, 9 – pressure gauge, 10 – quartz glass, 11 – camera, 12 – gas outlet, 13 – negative high-voltage DC power supply, 14 – electrodes, 15 – porcelain, 16 – corundum tube, 17 – tetrafluoroethylene gasket, 18 – galvanometer, 19 – oscilloscope, 20 – protecting resistor, 21 – RS232 convertor, 22 – computer.