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An experimental investigation of electrostatic precipitation in a wire–cylinder configuration at high temperatures

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ABSTRACT

High-temperature electrostatic precipitation is a potentially convenient method for hot gas clean-up. This paper reports the characteristics of electrostatic precipitation in a wire–cylinder configuration for a temperature range of 350 °C to 700 °C. Three parameters, i.e., particle collection efficiency, energy consumption index and the outlet mass concentration of particles, are investigated to evaluate the comprehensive performance of an electrostatic precipitator at high temperatures and to propose a method to choose an optimum combination of the operation parameters for different conditions. The collection efficiency can be greater than 0.996 when the gas temperature is 350–700 °C and the inlet mass concentration of particles is 200–3600 mg/Nm^3. When the voltage applied to the two electrodes is high enough (greater than 15,900 V in this work), the collection efficiency is hardly influenced by the inlet mass concentrations of particles in the testing range. For example, at 620 °C when the applied voltage is 15,925 V, the fluctuations of the collection efficiency are within ~0.2% even if the inlet mass concentration increases ~10 times. For a given inlet mass concentration of particles, the collection efficiency increases rapidly as the applied voltage increases from the first stage to the second stage, while the collection efficiency increases slowly as the applied voltage increases from the second stage to the third stage. The relationship between the energy consumption index, the applied voltage and the inlet mass concentration of particles is given by $\varphi = CU_p^2(U_p - U_c)/m_{in}$. As the temperature increases from 350 °C to 700 °C, the value of C increases from 1.0×10^{-5} to 3.2×10^{-5} and the value of U_c decreases from 20,860 to 12,503. The electric energy consumed by an electrostatic precipitator increases rapidly with the increase in the temperature.

1. Introduction

Hot gas clean-up is an important issue for integrated gasification combined cycles (IGCC), pressurized fluidized bed combustion (PFBC) and other advanced combined cycles that promise electricity generation with substantially greater thermodynamic efficiencies and reduced environmental impacts [1,2]. Several technologies were proposed for hot gas clean-up, e.g., ceramic candle filters, granular bed filters and high-temperature high-pressure electrostatic precipitators [3,4]. Generally, a ceramic candle filter has a high collection efficiency of approximately 0.998 [5], but the filter is easily clogged, resulting in a great increase in the pressure drop. In addition, further improvements in the mechanical behavior of ceramic filters are suggested before commercial application [6]. Granular bed filters are flexible [7] and have a collection efficiency that can be greater than 0.99. However, for a fixed bed, the large pressure drop across the filter is a problem that requires a way to clean the surface from time to time. For a fluidized bed, the collection efficiency is low, especially for small particles. For a granular moving bed filter, most of the experiments so far are carried out at less than 600 °C, creating a potential problem where the hot gas would be cooled down to a low temperature. Experimental and theoretical investigations at high temperatures (greater than 600 °C) are needed to know the comprehensive performance of this filter [2]. Electrostatic precipitation (ESP) is widely applied in many fields, especially for conditions at less than 400 °C, e.g., separating dusts from combustion flue gases and removing hazardous powders from industrial flue gases [8–12]. Advantages of the electrostatic precipitator include suitability for dealing with particles of different sizes and variable flue gas volumes, convenient operation and negligible pressure loss [13,14]. Electrostatic precipitation would be a potential method for hot gas clean-up with a temperature greater than 400 °C.

In the 1950s, Thomas and Wong [15] experimentally studied the characteristics of corona discharge in air using stainless steel and Pt as cathodes for temperatures and pressures ranging from room temperature to 827 °C and 1 atm to 8 atm, respectively. Bush et al. [16] investigated the characteristics of corona discharge at 260–1093 °C and 1–35 atm under atmospheres of air and flue gas. Thomas and Wong [15] and Bush et al. [16] focused on the properties of corona discharge under different conditions, especially the V–I characteristics, and no electrostatic precipitation experiments were conducted. Fulyful [17] simulated the performance of an electrostatic precipitator at

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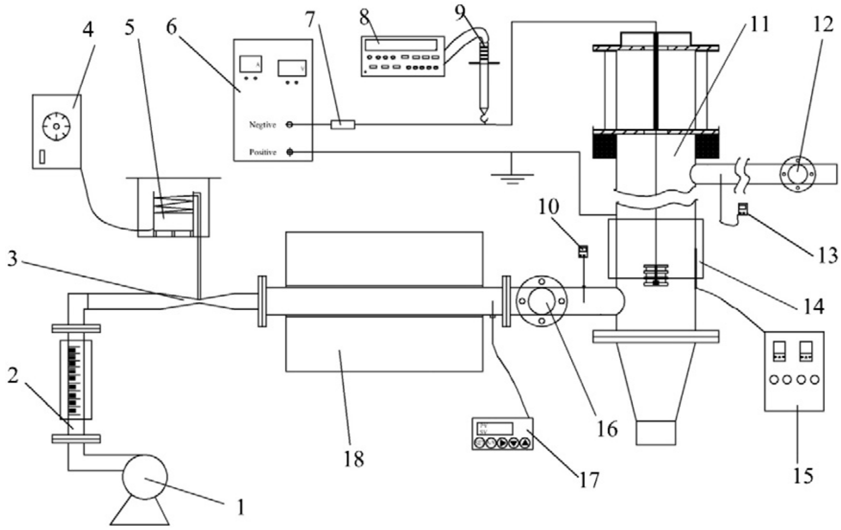

Fig. 1.1. Schematic of the experimental system. 1—blower; 2—gas flow-meter; 3—Venturi tube; 4—vibration controller; 5—electromagnetic vibrating feeding device; 6—high voltage power supply; 7—protection resister; 8—6514 electrometer; 9—P7400 high-voltage probe; 10—thermocouple 1; 11—electrostatic precipitator; 12—sampling port 1; 13—thermocouple 2; 14—tubular heating elements; 15—programmable temperature controller 1; 16—sampling port 2; 17—programmable temperature controller 2; 18—heating furnace.

20–427 °C and 1–4 atm. In recent years, Villot et al. [18] conducted syngas filtration tests at temperatures of 510 °C and 680 °C and pressures of 1–10 atm and obtained an average efficiency greater than 95%. Gu et al. [19] published experimental results of dust removal at temperatures up to 1100 °C, but the method reported by Gu et al. [19] was different from the traditional ESP technology. Space charges were produced by thermionic emission of the cathode in Gu's work rather than by the ionization of gas molecules as in traditional ESP. Above all, the reports on high-temperature ESP at atmospheric pressure are limited. However, it is important to separate particles from gas at high temperatures (over 500 °C) and atmospheric pressure for poly-generation system combined coal combustion and pyrolysis systems [20,21]. Coal is pyrolyzed in the gasifier, the produced gas containing tar and particles goes into a purifier for cleaning. In order to recover tar, particles should be separated from gas at a temperature of ~500 °C or above. It is because tar would become liquid and mix with particles at low temperatures, which is very hard for further usage [20].

We have attempted to provide a comprehensive understanding of high-temperature ESP. In previous studies [22–24], we investigated the characteristics of direct current (DC) negative corona discharges, analyzed the current composition in the discharging current and proposed an analytical method for calculating the space charge and electric field distributions in a wire–cylinder device at high temperature and atmospheric pressure. In this paper, we design a wire–cylinder electrostatic precipitator to further explore the particle collection characteristics of high-temperature ESP and to evaluate the overall performance of this design at a temperature range of 350–700 °C.

2. Experimental setup and methods

2.1. General introduction

Fig. 1.1 shows a schematic of the experimental system. The system consists of a blower, a gas flow-meter, a particle feeding device, connecting pipelines, programmable heating devices, an electrostatic precipitator and a high voltage electric circuit.

2.2. Particle feeding and measurement

The particle feeding system includes an electromagnetic vibrating feeding device (as shown in Fig. 1.2), a vibration controller and a Venturi tube. The electromagnetic vibrating feeding device, produced by Hangzhou Feiyu Magnetism & Electricity Equipment Ltd., has a maximum feeding dosage of 5 g/min. As shown in Fig. 1.2(b), the electromagnetic vibrating feeding device is driven by four springs and an electromagnet system. When the electromagnet is magnetized, the springs are pressed and the spiral base moves down. When the electromagnet is demagnetized, the springs go back and the spiral base moves up. Ash sample moves forward with vibration of the spiral base, going into the Venturi tube through a connecting pipe. The mass of the particles mixed in the gas stream is controlled and adjusted by the vibration controller. Applying a Venturi tube could reduce the pressure at the minimum cross section, which makes the particles travel smoothly and mix in the gas stream. The mass concentration of the particles in the gas stream is measured by a Dekati PM10 impactor and an electronic

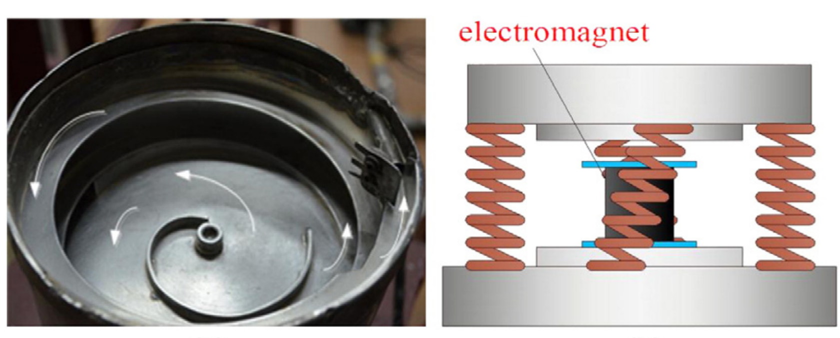

Fig. 1.2. Schematic of the electromagnetic vibrating feeding device; (a) physical map, (b) vibration principle diagram.