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Mechanism study of electrostatic precipitation in a compact hybrid particulate collector

Gongming Tu, Qiang Song *, Qiang Yao

Key Laboratory of Thermal Science and Power Engineering of Ministry of Education, Department of Thermal Engineering, Tsinghua University, 100084 Beijing, China

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ABSTRACT

Hybrid structure significantly affects the collection mechanism and performance of a hybrid particulate collector. The electrostatic precipitation of particles in the wire-perforated plate structure of a full-scale compact hybrid particulate collector is numerically simulated in this study. The distributions of electric and flow fields and the charging, motion, and precipitation of particles in this specific structure are studied. The results show that the distribution of electric field in the final stage is asymmetrical because of the baffle plate at the end of the channel. The field distributions of other stages are identical to that of wire-plate electrostatic precipitator. The openings increase the electric field strength in the region adjacent to the perforated plate. The electric field passes through the openings, which is then distributed to the back side of the perforated plate. The aerosol cross flow rate along the perforated plate varies periodically under the effect of electric body force. Whereas, the overall cross flow rate of each stage is the same, except the first stage. Two counter-rotating eddies are formed behind the perforated plate between every two openings. Particle charge exceeds 80% of the final charge when the particles move to the position of the first wire. The 10 μm particles finish their charging processes faster than 1 μm particles with a final charge of approximately 100 times that of 1 μm particles. The charge acquired by a particle under the wire-perforated plate structure is 3% higher than that under the wire-plate structure. Particle trajectory result shows three modes of electrostatic precipitation in a compact hybrid particulate collector, namely, collection on the front, flank, and back sides of the perforated plate. Particle transport by eddies on the back of the perforated plate plays an important role in particle deposition on the back side. Variation in the capture probability of particles released from different positions corresponds to the opening structure. High and low probability areas separate with each other. The collection efficiency of 10 μm particle is higher than that of the 1 μm particle. The results can explain hybrid mechanism and optimize hybrid structure.

1. Introduction

Particulate matter has become the principal atmospheric pollutant in China. Studies and statistics showed that industrial emissions are the main source of primary particles [1]. The development of high efficient and low-cost particle removal technology is the fundamental solution to this problem. The most widely used particle removal methods include electrostatic precipitator (ESP) and fabric filter (FF) [2, 3]. Both methods are extremely expensive to satisfy the new ultralow emission standard for coal-fired power plants. Hybrid particulate collector, which integrates ESP and FF in series, was developed within this context [4]. Hybrid particulate collectors combine the advantages of the two traditional techniques. ESP removes most of the particles at low cost, whereas FF catches the remaining particles with high efficiency. In addition, fabric filtration is enhanced by particle charging. Thus, hybrid particulate collectors were rapidly adopted in recent years [5, 6]. The University of North Dakota developed a compact type of hybrid particulate collector [7]. This type of hybrid particulate collector adopts perforated plates as collection plates in the ESP zone. The unique structure has the same advantage as the previous hybrid device and solves the problems of re-entrainment and re-collection in conventional FF. A full-scale proto device was installed in Big Stone Plant, USA in 2002. This device provides ultrahigh collection efficiency at the initial stage, but fails to maintain high efficiency during long-term operation [8] due to the unreasonable dust load distribution. This limitation is attributed to the lack of electrostatic precipitation on perforated collection plates related to unreasonable design. Thus, the collection mechanism in wire-perforated plate structure must be examined.

The most commonly used configuration in industrial ESPs is wire-plate type. The principles of the wire-plate ESPs are well described in literature [9–11]. Particle transport in ESPs is a result of the interactive coupling of corona electric field, gas flow field, particle charging, and particle motion. These results provide physical and mathematical models to study wire-perforated plate ESP. Long et al. [12, 13] calculated the corona electric field under the wire-perforated plate structure. Their

* Corresponding author.
E-mail address: qsong@tsinghua.edu.cn (Q. Song).

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results showed that the openings change the electric field distribution on the plate surface. The curve of the field strength distribution reached its peak values at non-open areas, whereas valley values were achieved at open areas. The ratio of mean electric field strength in the opening areas to the other areas is approximately 0.67. Space charge density distribution is not significantly affected by the openings. They also noticed that the electric field passes through the plate openings and distributes on the filter surface. This mechanism may cause sparks on the bags. Different opening structures were evaluated to protect the bags from electrical damage [14]. Their valuable results provided an insight into the special electric field distribution under the wire-perforated plate structure. Tu et al. [15] built a laboratory-scale hybrid particulate collector to investigate the effect of opening structure on dust collection performance. They found that total collection efficiency change little when the percentage of open area is increased from 0.19 to 0.45 due to complementary effect. The opening type exhibits a minimal effect on the total collection efficiency. These results provided the preferred opening structures for the design of perforated plate in a hybrid particulate collector.

Another important factor that influences particle motion is the distribution of flow field. Industrial ESPs usually operate at an inlet velocity of 1 m/s with turbulent flow. The air ions in the ESP migrate toward the grounded electrode under Coulomb force. These ions transfer their momentum to neutral gas molecules upon collision, which results in macro gas flow called electrohydrodynamic (EHD) flow [16]. Research shows that the Coulomb force on the ions acts as a body force on the gas. The body force is equal to the product of the electric field vector and space charge density [17]. The main flow and EHD flow interact to form a complex flow state in the ESP. EHD flow in wire-plate ESPs was numerically calculated in previous studies [18–22]. Results showed that the flow state is characterized by a dimensionless EHD number, which is defined as the ratio of electric body force to fluid inertia [23]. When the EHD number is low, the main flow is barely affected by the electric field. When the EHD number is high, the electric effect is strong, which creates a vortex in the channel. Some studies focused on the effect of EHD flow on particle motion. Results showed that EHD flow facilitates the capture of micron particles [24, 25]. Only a few studies examined the flow field under the wire-perforated plate structure. The main flow significantly differs from traditional ESPs because of the openings on the plate. The openings also change the electric field and the body force on the gas. Both elements significantly affect particle motion.

A particle begins to acquire charge and migrate toward the plates under the effect of electrostatic force after entering ESP. The rate of particle charging and the amount of charge acquired are crucial in the design of ESPs given that the electrostatic force on a particle is proportional to its charge. The two classical models used to predict the particle charging process include field charging theory [26] and diffusion charging theory [27]. Ion diffusion is neglected in the field theory, whereas the external field is neglected in the diffusion theory. A combined field and diffusion charging approach is employed in ESP particle charging. The sum of field theory and diffusion theory is not theoretically justified, but it is often used to predict particle charging in ESPs as if other mechanisms were not present. Attempts have been exerted to develop a combined theory for particle charging in ESPs [28, 29]. Long and Yao [30] developed a complete summary of all these particle charging theories. Although various theories were developed based on different assumptions, it is accepted that the charge on particles increases with residence time, and charging rate increases with electric field strength and ion concentration. The openings of the plate change the distribution of the electric field, whereas the particles leave the ESP zone through the openings, thereby reducing particle residence time. These conditions affect the particle charging processes and may result in insufficient particle charge.

The unique structure of the ESP zone in the compact hybrid particulate collector leads to the distinctive distribution of electric and flow fields. The particle collection of perforated plates also differs from that of traditional wire-plate ESPs. Deep research on the collection mechanism with a perforated collection plate remains lacking. Therefore, the current study developed a numerical model to simulate the electrostatic precipitation in a compact hybrid particulate collector. The distributions of electric and flow fields under the perforated plate structure were calculated. Particle charging and deposition processes were simulated and analyzed based on field distributions. The results provide guidance to the development of compact hybrid particulate removal techniques.

2. Numerical

2.1. Precipitator geometry

The structure of a compact hybrid particulate collector can be divided into an ESP zone followed by a FF zone. An industrial-scale collector is composed of a plurality of ESP zones and FF zones with identical structures in parallel to handle the large flow of gas. Given its symmetry, the two-dimensional feature structure was examined from the overall structure of the compact hybrid particulate collector. Fig. 1 shows the structure of a compact hybrid particulate collector with a five-wire ESP zone. Boundaries $y = 0$ mm and $y = 1125$ mm are symmetrical boundaries. The aerosols initially move into the ESP zone, and the perforated plates capture most of the particles. The aerosols simultaneously

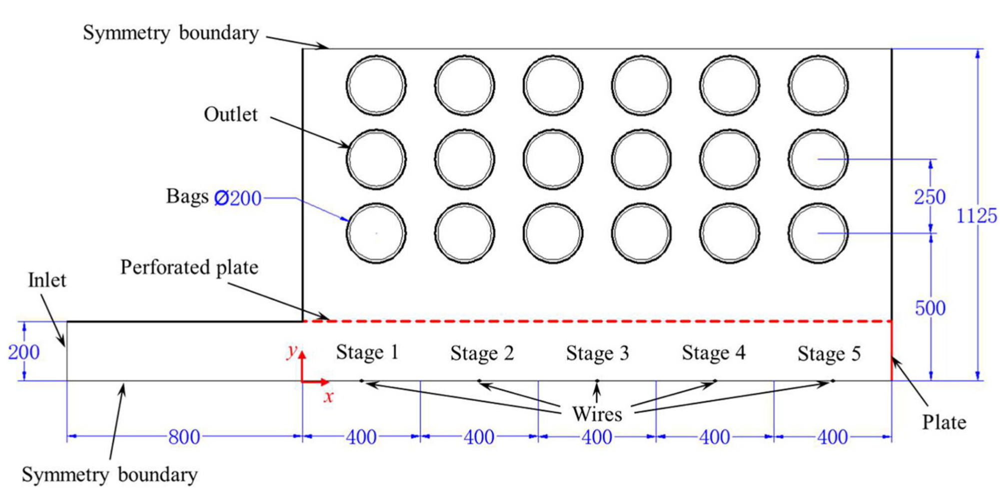

Fig. 1. Structure of the five-stage compact hybrid particulate collector.