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Voltage-current characteristics of needle-plate system with different media on the collection plate

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Abstract

The hybrid electrostatic precipitator and media filtration system is significantly more promising than traditional filtration methods. This paper investigated the electrostatic characteristics of different filter media types used in the hybrid filtration system. The voltage-current (V-I) characteristics of needle-plate system, the collection plate of which is covered by filter media, were measured. Seven types of filter media and collection plate including iron plate, iron grid and activated carbon layer were considered. The glass fiber and polyethylene media reduce approximately 20% of the current value. The bag filter increases the current value because of the back corona effect. Polyester and polyethylene terephthalate materials with activated carbon attached can increase the current value significantly. In addition, this paper studied the effects of cake thickness on V-I characteristics. The results show that the cake layer has little influence on the V-I character when its thickness is not very big.

Keywords: Particulate matter; Electrostatic precipitator; Filtration; V-I characteristics; Cake

Introduction

Particulate matter in enclosed environments is related to the health of occupants. Exposure to particulate matter has adverse effects on human health, such as respiratory and cardiovascular diseases, asthma attacks, and cardiac arrhythmia [1]. Filtration and electrostatic precipitation are two efficient methods used to remove particulates in the air [2-4]. However, both methods have their respective defaults. Electrostatic precipitators (ESP) cannot reach a removal efficiency of 90% for ultrafine particles with size ranging from 0.1 μm to 1 μm [5]. Problems persist even though certain types of air filters can capture submicron particles with a high efficiency of 99%. The cake layer on the media surface can pollute fresh air and reduce the service time of the filter [6].

A possible solution is to develop a hybrid system that combines electrostatic precipitation and media filtration. The hybrid electrostatic and filter media system can take advantage of the two methods. ESP can capture coarse particles and extend the service time of the air filter. Ions generated by the corona discharge can improve the submicron particle removal efficiency of the air filter. The relatively thin cake layer on the filter media would not pollute fresh air significantly. Many researchers have proposed some types of the hybrid system and investigated their performances. A hybrid air filtration system was designed with carbon fiber ionizer upstream of the glass fiber air filter. Ions generated by the ionizer can improve the ultrafine particle removal efficiency of the air filter by 25% [7]. A new filtration equipment was developed, which consists of a negative ion emitter and the high-efficiency particulate air (HEPA) installed in the heating, ventilation, and air conditioning (HVAC) system. The system was tested by virus-carrying liquid droplets with a diameter below 3 μm. The ion emitter can enhance air filter efficiency from 10% to 40% [8]. Several other papers have studied similar filtration systems combining ESP and air filter [9, 10]. The ESP and hybrid electrostatic filtration systems are also investigated by numerical methods [11-15]. Although these studies have been done, the fundamental research is still very lack. The filter media in the hybrid system will be charged due to the electric field. The filter media can be several types, such as glass fiber, the polyethylene, the bag filter, the polyester and polyethylene terephthalate materials, and the activated carbon media. The collection plates in the hybrid system also include some types, such as the iron plate, iron grid and the activated carbon layer. The charge characteristics of the filter media in the hybrid filtration have significant influence on the filter performance. The higher current through the filter media can improve the particle removal efficiency. However, the back corona phenomenon would occur in air channels in the filter media if the current is too high due to the high volume resistivity and porosity [16-18]. Thus, it is necessary to evaluate the charge characteristics of different filter types.

In this paper, an experimental system was designed to investigate the charge characteristics of different filter media types used in the hybrid filtration system. The filter medias include the glass fiber, the polyethylene (PP), one type of bag filter media, the polyester (PE), the polyethylene terephthalate (PET), the non-woven media and the refined cotton media. Some types of collection plate were also considered, including the iron plate, the iron grid and the activated carbon media. Finally, the influences of the cake layer on the surface the filter media on the charge characteristics were studied.

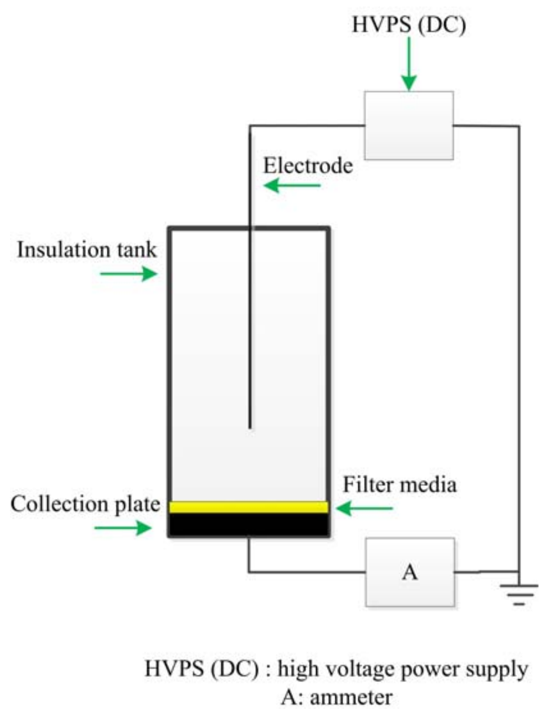

Fig. 1 Experimental system setup for the V-I characteristics.

Experimental setup and materials

Figure 1 shows the experimental test rig for measuring the voltage-current (V-I) characteristics of the needle-plate system, which has compact structure but accurate for electrostatic study. The needle to plate system consists of a high-voltage equipment, discharge electrode, collection plate, insulation tank, and ammeter. The high-voltage equipment includes a control box, a high-voltage generator (DC) with negative polarity, and a grounding system. The polarity of the point electrode is negative and the high-voltage range is from 0 kV to 50 kV. The accuracy of the ammeter is 0.1 μA. The discharge electrode is composed of stainless steel wire and the radius of the needle electrode is 0.5 mm. The length of the discharge electrode is 224 mm, and the distance between the discharge peak and the surface of collection plate is 70 mm. The insulation cuboid vessel provides discharge space and the laboratory air has no access to the enclosed space. The cross section of the cuboid vessel is square with 200 mm side length and the cuboid height is 245 mm. The laboratory environment is controlled by the HVAC system, with air temperature of 22 ℃ and relative humidity of 45%. The insulation tank is made of the Plexiglas material. It can be charged in the experiments. But the measured V-I characteristics of the system with and without the insulation vessel have no obvious differences, as the charge of the insulation tank is very small. Besides, the practical collector is placed in the insulation duct in the HVAC system.

Table 1 Experimental cases.

Case no.	Filter media type	Collection plate
1	None	Iron plate
2	None	Iron grid/Activated carbon media
3	Glass fiber	
4	PP (polyethylene)	
5	Bag filter media	
6	PE (polyester)	Iron plate/Iron grid/Activated carbon media
7	PET (polyethylene terephthalate)	
8	Non-woven media	
9	Refined cotton media	

The collection plate in the needle-plate system is covered by different filter media types to investigate the electrostatic characteristics of the filter media. The activated carbon layer, iron grid and iron plate are utilized as collection plates. Detailed information on the collection plates and filter media are presented in Table 1. All experimental cases are based on the structure of a practical air filter, the filter media, activated carbon later and iron grid are widely used in air filtration system. The filter media can capture particulate matter and the activated carbon layer removes the gaseous pollutant. The hybrid filter media combing activated carbon layer and common filter media layer has the dual effects. The air filter with iron grid fixed on the media surface would increase structural strength and avoid serious deformation. The collection plate in Cases 1 and 2 is iron plate or iron grid without filter media. Activated carbon media is used as the collection plate in Case 2. This investigation had tested six types of activated carbon media, including activated carbon fiber media, activated carbon spongy media, activated carbon photo catalyst media, cold catalyst media, and hybrid activated carbon media. The structure of the activated carbon layer is non-woven. In other cases described in table 1, the filter media is placed on the collection plate. The activated carbon media used in Cases 4 to 10 is non-woven activated carbon fiber media with a thickness of 5 mm. The iron grid used in this study is composed of an iron wire, with a radius of 0.5 mm, and the distance between the two iron wires is 10 mm.

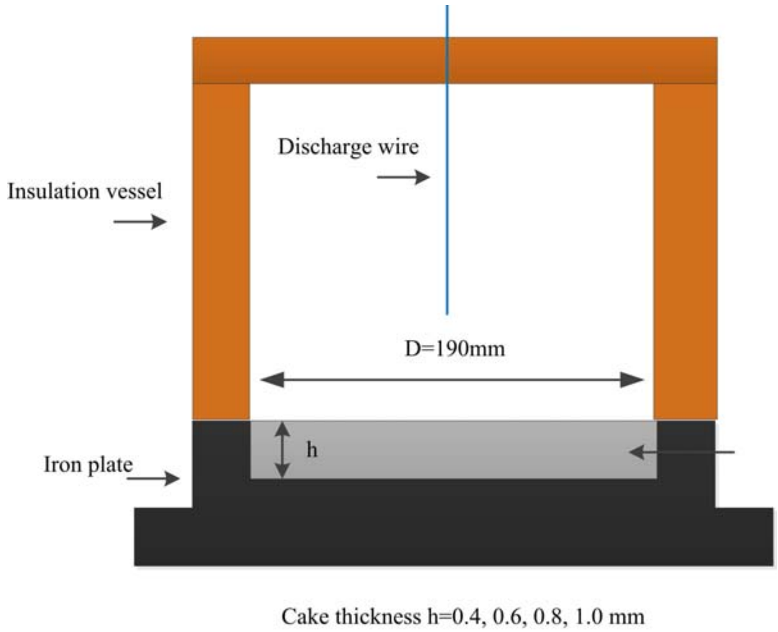

Fig. 2 Setup of the experimental system for the cake layer with different thickness.

This research also investigates the effects of cake thickness on the electrostatic characteristics of the system. The V-I characteristics of the needle-plate system with cake layer on the collection plate is measured. The insulation cylindrical vessel is composed of Plexiglas (245 mm-high and 200 mm in diameter). The collection plate on the bottom of the insulated vessel is made of iron, with radius of 100 mm and thickness of 3 mm. The distance between the discharge peak and iron plate is 70 mm. The cake thickness includes 0.2 mm, 0.4 mm, 0.6 mm, 0.8 mm, and 1 mm. Figure 2 describes the process of changing the cake layer thickness on the dust collection plate. Thickness accuracy is controlled by the fine finishing. The total cake porosity of all the cases is 0.6. The cake zone is divided equally into six subzones, with each subzone filled up with 1/6 of the total cake weight to ensure a relatively uniform porosity distribution. The dust cake is composed of fly ash, with the grain diameter following the Rosin-Rammeler distribution, and the dust density is 2460 kg /m^3 .

Results

The volume resistivity of different filter types

The volume resistivity values of all types of filter media material are summarized in table 2. The resistivity of glass fiber/PP/bag/PE/PET is above 1×10^{13} Ω•m. The non-woven media/refined cotton media have lower resistivity value. Because the volume resistivity of all types of filter media is above 5×10^{9} Ω•m, all the filter medias have the potential to generate back corona phenomenon [18]. The measurement method is based on the Chinese specification GB/T1410 [23].

Table 2 The results of volume resistivity measurement.

Filter type	Volume resistivity (Ω•m)
Glass fiber	3.3×10^{15}

PP	2.1×10^{14}
Bag	6.0×10^{13}
PE	1.3×10^{13}
PET	2.5×10^{16}
Non-woven	1.3×10^{11}
Refined cotton	2.8×10^{9}

Case1 and 2: No filter media

For the air filter used in the hybrid filtration system, the iron grid fixed on the filter media surface can avoid serious filter deformation and act as collection electrode. The iron grid electrode would affect the hybrid system electric field. This study tested the V-I characteristics of the needle-plate system, the collecting plate of which is iron plate or iron grid. V-I characteristics for both the iron plate and iron grid cases are shown in figure 3. The current value of Case 2 with iron grid is less than Case 1 with the iron plate at the same voltage, but the current difference become smaller when the voltage increases. The ratio of the current value of iron grid case to iron plate case is 0.83 if the discharge voltage is 20 kV. Therefore, the V-I characteristics of iron grid case are similar to the iron plate.

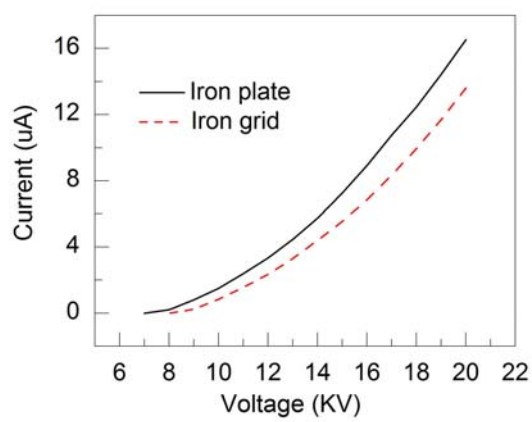

Fig. 3 V-I characteristics of the iron plate/grid as the collection plate without filter media.

The activated carbon media in the hybrid filtration system can remove volatile organic compound (VOC) pollutants/particulate matter and act as a collection electrode. There are different kinds of activated carbon media, so it is necessary to choose the suitable ones for hybrid filtration system. The activated carbon fiber media, activated carbon spongy media, activated carbon photo catalyst media, cold catalyst media, and hybrid activated carbon media are tested. The cold catalyst- and photo catalyst-activated carbon media have higher gaseous pollutant-removal efficiency because of the catalyst material (such as TiO2) deposited on the activated carbon fiber. The catalyst particles may change the electric characteristics of activated carbon media. The hybrid carbon media consists of an activated carbon layer and a non-woven fabric layer to remove the particles and gaseous pollutant. Figure 4 shows the V-I characteristics of different needle-plate systems when several activated carbon media types are used as the collecting electrode. The activated carbon fiber media with thickness of 10 mm and 5 mm, and activated carbon spongy media have the same V-I characteristics, with the measured V-I characteristics similar to those of case 1. The current of the hybrid activated carbon media is significantly small because of the presence of non-woven filter media. However, the current of the two catalyst media are lower than that of the common activated carbon media because of the catalyst material deposited on the fiber surface. Thus, the hybrid activated carbon media, activated carbon photo catalyst and cold catalyst media would add resistance and reduce current for the needle-plate system.

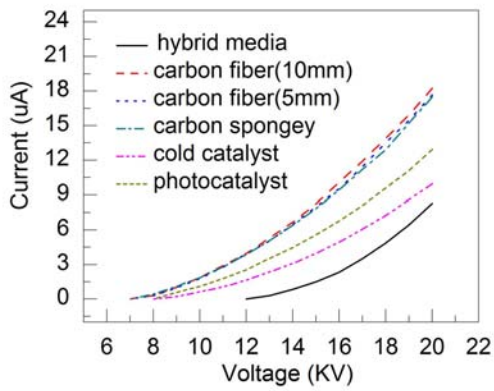

Fig. 4 V-I characteristics of the activated carbon as the collection plate.

Case 3: Glass fiber media

Figure 5 shows the V-I characteristics of the needle-plate system with glass fiber filter media. Glass fiber filter media are highly efficient and can remove small particles that can penetrate the ESP zone in the hybrid filtration system. Although the glass fiber material is not electret, this filter media can capture submicron charged particles more efficiently [7]. All glass fiber cases have less current value compared with Case 1 under the same voltage. Thus, the filter media add resistance to the needle-plate system. The ratio of the current value of the case with iron plate to Case 1 is 0.77 when the voltage is 20 kV. As such, the effect of the filter media resistance is reduced when voltage value is higher. The case with the activated carbon layer has a larger current value than the case with the iron plate, but the difference is not noticeable. The case with iron grid has the same V-I characteristics with the case with iron plate. When the glass fiber media is placed on the iron plate/iron grid/activated carbon layer, the transient time of the charging current in the needle-plate system is of the order of a few seconds. The measurement of V-I characteristics is conducted in the steady condition.

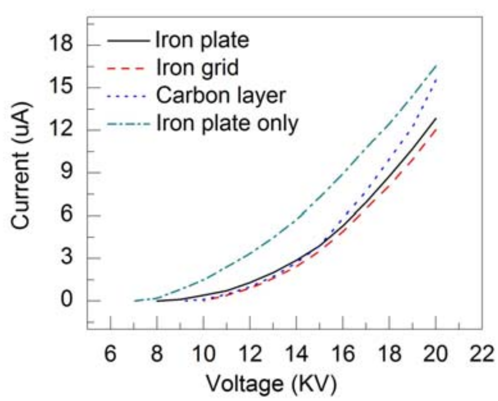

Fig. 5 V-I characteristics of glass fiber with different collection plates.

Case 4: PP media

Figure 6 shows the V-I characteristics of the needle-plate system with PP filter media. PP filter media are highly efficient and can remove small particles in a hybrid system. Unlike glass fiber media, PP is an electret type, which can be charged and can remove submicron particles more efficiently. The electrostatic potential of PP media will decay for a single electret filter, but ESP in a hybrid system can maintain the charge stored in the electret media. The current value of the case with iron plate is less than that of Case 1, with the ratio of the current value of the former to the latter at 0.82 when the voltage is 20 kV. The case with activated carbon layer and the case with iron plate have similar V-I characteristics. The case with iron grid has less current value than the case with iron plate. The onset voltage of cases with the PP media is larger than that of Case 1 because of the added media resistance.

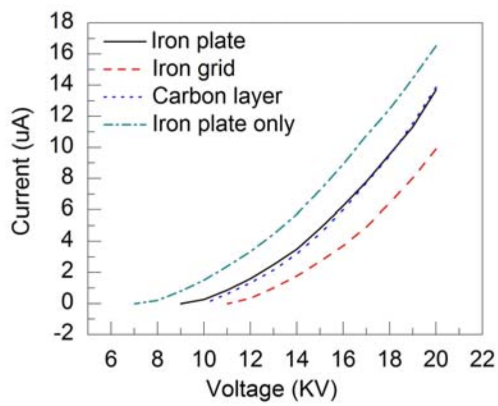

Fig. 6 V-I characteristics of PP media with different collection plates.

Case 5: Bag filter media

Figure 7 shows the V-I characteristics of needle-plate systems with bag filter media. Bag filter is composed of a polymer fiber compound, and its efficiency for particulate matter with diameter below 1 μm is 20% to 70%. Although the bag filter is not a typical electret, it can remove charged particle more efficiently. The electrostatic and bag filter hybrid system can improve the performance of a single bag filter and extend its service time. The case with iron plate and the case with activated carbon media have higher current value than Case 1 when the voltage is above 15 kV. The current value of the case with iron plate is 20% higher than that of Case 1 without any filter media if the voltage is 20 kV. This phenomenon may be caused by the back corona effect. The current value of the case with iron grid is 0.77 of the case with iron plate when the voltage is 20 kV.

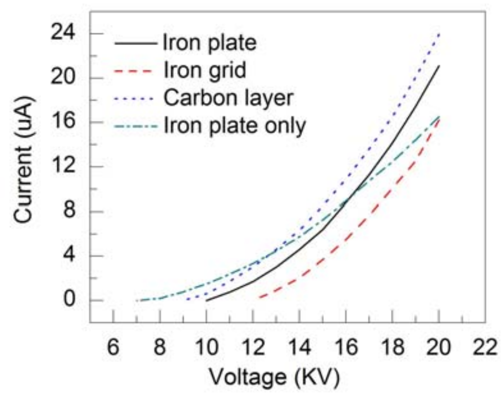

Fig. 7 V-I characteristics of the bag fiber with different collection plates.

Although all types of the porous filter media in this study are dielectric material, the current value of the needle-plate system with filter media covered on the conductivity plate may be higher due to the back corona effect. The charge accumulates in the porous filter media and added electric field is generated. If the electric intensity in air gap of filter media exceeds the critical value E_c, the local partial discharges in air channels will occur. The back corona phenomenon would cause a decrease of charge stored in the filter media and simultaneously a maximum value of its surface potential. The intensity of back corona effect is influenced by the following factors: the external and polarizing field, the air channel width and the electric permittivity of filter material. The E_c and surface charge value σ can be calculated by equation 1 on the basis of Paschen law and equation 2 [18].

$$E_c = 6.72\sqrt{\frac{p}{d}} + 24.4p \quad (1)$$

$$\sigma = \varepsilon_0 E_c \quad (2)$$

where P is the atmospheric pressure (hPa), d the air channel width (m), ε_0 the air permittivity.

The glass fiber, PP and bag filter media are porous material and have the potential to generate back corona phenomenon in needle-plate system. The obvious media surface discharge is observed in presence of bag filter media but this phenomenon is not obvious for the glass fiber and PP media. The solid volume fraction (SVF) may cause the difference. The glass fiber and PP media are high efficiency filter type with high pressure drop and SVF, and the bag filer media is middle efficiency filter type with lower SVF. According to the Ashrae standard, the high efficiency filter would remove 99.9% of the 0.5 μm particles and the efficiency of bag filter is 70% for 1μm particle. The average SVF value can be calculated by the following equation 3. This validated equation is based on the theory that air pressure drop across the filter media increase with higher value of SVF [24]. The calculated SVF value of PP media is 30% and bag filter is 7%.

$$K = \frac{3r^2}{20\alpha}(-In\alpha - 0.931) \quad (3)$$

where r is the fiber radius (m), α the SVF value of media, K the permeability (m^2). The value of r is provided by the filter media manufacturer (3 μm for PP and 10 μm for Bag filter) and the K is obtained by the experiment.

The lower SVF value and broader air channels would lead to a deeper penetration of the channel space by the ions and to a shortening of charge stored in the filter media [18]. Decrease of the channel breakdown voltage and increase of back corona current should be observed with lower SVF value. It is assumed that if the SVF value of filter media is close to 1 and the back corona phenomenon will not occur. The electric permittivity value for PP material is 1.25. The bag filter media is made of polyester resin and the electric permittivity value is 3.5. Because of the mirror effect [18], the electric field strength in the air channel of porous media would increase with an increase of electric permittivity value. An increase in permittivity of the fiber material would increase the electrical field in the air channel, the intensity of the local air discharge as well as the generation of a higher concentration of the charge carriers. The back corona phenomenon is observed in presence of the bag filter with lower SVF but the glass fiber/PP media do not generate obvious back corona phenomenon. Similar experimental results are described in the literature, there are no surface discharge in the needle-plate system in presence of PP film on the metallic plate [20]. The back corona effect will reduce the amount of charged particles and filtration efficiency for the hybrid electrostatic filtration system.

Case 6: PE media

Figure 8 shows V-I characteristics of needle-plate system with PE media. PE filter media is composed of polyester and is a typical chemical fiber material. PE media is not a typical electret but it can be used in a hybrid filtration system for efficiency and economy. Surprisingly, the case with activated carbon media has higher current value than Case 1. This phenomenon may be caused by the back corona effect described previously. The case with iron plate and Case 1 have a similar V-I characteristic curve, but it does not mean that the PE media do not add resistance. This phenomenon is caused by the contact resistance (air gap) between PE media and iron plate and the back corona effect. The current value of the case with iron grid is 93% of the case with iron plate when the voltage is 20 kV, the difference can be ignored when voltage is above 20 kV.

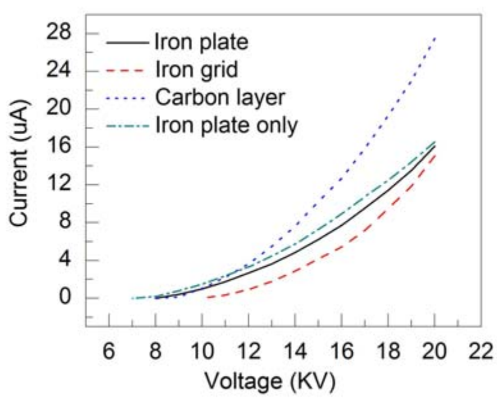

Fig. 8 V-I characteristics of PE media with different collection plates.

It is surprising that the current value of PE media case with activated carbon layer is much higher than the case with iron plate. In fact, the surface discharge phenomenon of PE can be observed for both of the two cases. The difference of V-I characteristics may result from the contact resistance between the PE media and conductive collection plate. The air gap exists between the filter media and collection plate. The contact resistance has a significant influence on the V-I characteristics of needle-plate system. According to the specification of measuring the volume and surface resistance of dielectric material [23], the conductive material must be placed between the dielectric layer and metallic electrode in order to avoid the contact resistance. For the PE case with activated carbon layer, the fibers of PE and carbon layer may contact well in presence of the electrostatic force resulting in the lower contact resistance. For the glass fiber/PP/bag filter, the current value of case with activated carbon layer is higher than the case with iron plate. But for the PE media this phenomenon is much more obvious.

Case 7: PET media

Figure 9 shows the V-I characteristics of needle-plate systems with PET media. PET filter media is composed of polyethylene terephthalate material. The experimental results of PET cases are similar to the PE cases. All three PET cases have higher current value than Case 1, which may be caused by the back corona effect. The case with activated carbon layer has a higher current value than the case with iron plate because of contact resistance described above.

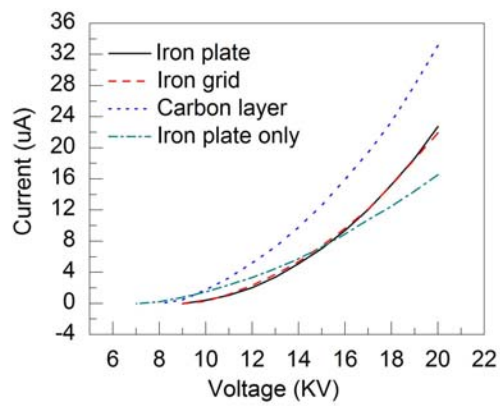

Fig. 9 V-I characteristics of PET media with different collection plates.

Case 8 and 9: Non-woven media and refined cotton media

Figure 10 and 11 shows the V-I characteristics of needle-plate systems with non-woven media and refined cotton media. There are two filtration mechanisms for filter media: filtration of media and particle cake layer. For the filter media with thickness of 100-300 μm (such as glass fiber/PP/PE/PET), the particles are mainly captured by the cake layer formed on the filter media surface. But for the non-woven media and refined cotton media with thickness of 3-6 mm, the main filtration mechanism is media filtration. The hybrid electrostatic and non-woven filtration system is suitable for industrial buildings because of the economy and efficiency.

In figure 10, all three cases with non-woven filter media have less current value than Case 1 without filter media. The case with activated carbon layer has a higher current value than the case with iron plate, and the current value of the case with iron grid is less than that of the case with iron plate. The non-woven media on the iron grid/activated carbon layer reduce the current significantly, and the slight surface discharge phenomenon can be observed clearly. This experimental phenomenon can be illustrated by the back corona theory developed by Bacchiega [25]. This validated model can predict the V-I characteristics of ESP with porous cake layer on the metallic collection plate accurately. The model has the following equations [17].

$$U_a = U_d + E_l \times l \tag{4}$$

$$E_l = \rho \times J_t \tag{5}$$

$$J_t = J(U_d) + J_b \tag{6}$$

$$V_s = \frac{1}{\varepsilon} l E_{bk} \tag{7}$$

where U_a is the electric potential of discharge electrode, U_d the electric potential difference between the discharge electrode and porous media surface, E_l the electric strength in the porous media on the collection plate, l and ρ the thickness and volume resistivity of porous media, J_t the total current value, J_b the back corona current, $J(U_d)$ is the V-I characteristics of needle-plate systems with nothing on the metal collection plate.

Because of the thickness of non-woven media (5 mm), the surface potential of non-woven media is much higher based on equation (7). So the values of U_d and $J(U_d)$ are lower due to the high porous media surface potential. Therefore, the total current value of needle to plate system in presence of thick porous media is reduced significantly. The ESP should have the other collection electrode plate in the duct to ensure the V-I characteristics and the particle removal efficiency of electrostatic precipitator. The results of refined cotton media cases are similar to the non-woven cases.

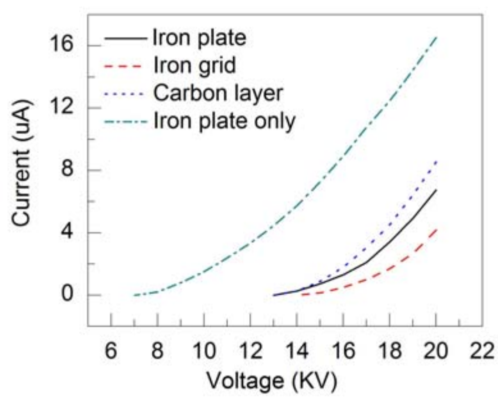

Fig. 10 V-I characteristics of non-woven media with different collection plates.

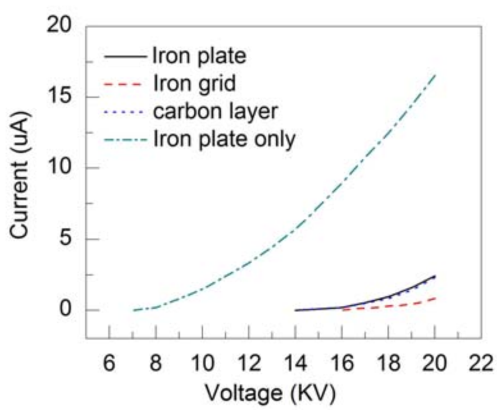

Fig. 11 V-I characteristics of refined cotton media with different collection plates.

Case 10: Particle cake layer

The effects of particle cake layers of the collection electrode on the V-I characteristics of needle-plate systems is not noticeable. Figure 12 shows the V-I characteristics of needle-plate systems with various cake layers on the collection electrode, with the thickness of the cake layer from 0.2 mm to 1 mm. Three V-I characteristic curves of the case without cake layer and cake layer cases with 0.2 mm and 1 mm thickness coincide approximately. This phenomenon results from the low volume resistance of particles. The volume resistance of fly ash in this measurement is $2\times10^{8}\ \Omega\bullet$m but for filter media the value is about 10^{14}-$10^{17}\ \Omega\bullet$m. Therefore, the unsuitable use of filter media in the hybrid electrostatic filtration system may cause more serious back corona phenomenon than the common electrostatic precipitator.

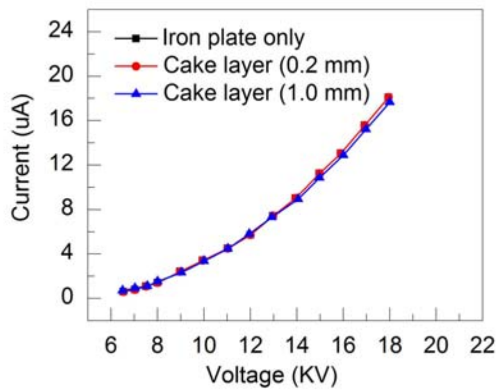

Fig. 12 V-I characteristics of the cake layer cases.

Discussion

The iron grid or activated carbon layer has a significant influence on the V-I characteristics of the needle to plate system. A charge coefficient η is defined as equation (8). In equation (8), the A_{fil} is the current value of the cases with filter media on the iron grid or carbon layer, whereas the A_{re} is the current value of Case 1 without filter media. Figure 13 shows the results when the applied voltage is 20 kV. For all filter media types, the carbon layer is better than the iron grid due to surface area and contact resistance. However, in the hybrid filtration system, the cost of the activated carbon layer is high and the electrostatic characteristics of used and invalid carbon media may be poor. The iron grid can enhance the structural strength of the air filter. Thus, the two conductors have their respective advantages. Both of the two conductive materials can be used in the hybrid filtration system, but the choice is based on the practical conditions.

$$\eta = \frac{A_{fil}}{A_{re}} \tag{8}$$

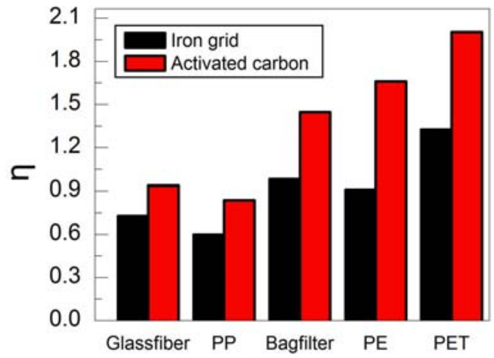

Fig. 13 Comparison of the charge efficiency between the iron grid and the activated carbon layer.

Conclusion

This paper conducted experiments in the needle-to-plate system to study the charge characteristics of different filter media types and collection plates used in the hybrid filtration system. The following conclusions are obtained based on the above results:

(1) The iron grid and common activated carbon media can be used as collection plate in the hybrid electrostatic filtration system. The current value of the needle-plate system with activated carbon layer is higher than the iron grid. The electric resistance of catalyst- and photo catalyst-activated carbon media is obvious because of the catalyst material deposited on the carbon fiber surface.

(2) All of the filter media have the potential to generate back corona phenomenon due to the high volume resistivity and porosity. For the bag filter/PE/PET media with low solid volume fraction, the media surface discharge and increase of system current value are observed. But for the glass fiber/PP media, the back corona effect is not obvious because of their high solid volume fraction. The non-woven media reduce the current value of needle to plate system significantly due to the thickness.

(3) For all the cases with filter media on the collection plate, the current value of case with activated carbon layer as the collection plate is higher than the iron plate/iron grid because of the contact resistance between the filter media and conductive collection plate, especially for the PE/PET filter media.

Acknowledgments

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