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Removal of adhesive dusts from flue gas using corona discharges with spraying water

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Abstract: Effective removal of adhesive and fine dusts from flue gas is very difficult. A new method of electrostatic precipitation of the corona discharges with spraying water(CDSW) was introduced. A new electrode configuration and the circulation spraying of water were employed in the method. The efficient electrostatic precipitation for adhesive and fine dusts can be accomplished without any drain water during a long operating period. The fundamental structure, discharge characteristics, mechanism of spraying and precipitation principle of the electrostatic precipitation using CDSW were described and analyzed. The V-I characteristics, spraying state, supplying water quantity, influence of temperature and clean of the electrodes were researched in series experiments. The treating effects of circulating spraying using the corona plasma at the same time of electrostatic precipitation were investigated. The fundamental theories and experimental data were proposed, in order to effectively remove the adhesive dusts from flue gas using CDSW in practice.

Keywords: aerosol with adhesive dusts; corona discharges with spraying water; electrostatic precipitation

Introduction

In the varied contamination sources of atmosphere there are some kinds of exhaust gases. A large number of adhesive and fine suspending particles with the diameters of micrometers or submicrometers occur in the gases, for example, the flue gases of asphalt or tar as well the cooking fume in Chinese catering trade. It is very difficult to remove the adhesive dusts or droplets from flue gas using the traditional precipitation methods. Although the filtrating method is able to remove the fine dusts, the adhesive dusts are easy to stop up the filtrating holes and can not be cleaned. Therefore the frequent changes of filtrating materials are necessary and the increases of both equipment maintenance and operating cost are unavoidable. The traditional wet electrostatic precipitation is able to remove the adhesive and fine dusts as well to keep the plate electrode cleaning, but the discharge electrodes have to be covered by the adhesive dusts, even though the intermitted scrubbing with water is employed. Therefore the corona discharges are quenched and the precipitation effects of the equipment lost.

A kind of charged droplet scrubbing was developed to form the sprays of high voltage jets according to the principle of electrohydrodynamic (EHD) spraying (Lear, 1975). The high-voltage insulation of the supplying water system was formed by an extraordinary long water piper. Although the semi-wet electrostatic precipitator with discharge electrode spraying was able to keep both discharge and plate electrodes cleaning(Xu, 2001), the safety and stable operation during a long period was difficult, because the high-voltage insulation of the supplying water system was accomplished by mechanic sprayers.

An electrostatic precipitation method using the corona discharges with spraying water(CDSW) was introduced in this paper. The method employed new electrode configurations and avoided the difficulty of high-voltage insulation in the supplying water system. The CDSW was formed on the discharge electrodes, according to the EHD spray and corona discharge mechanisms. The discharges not only keep the cleaning of both the discharge and collecting electrodes using a small amount of water, but also can treat the spraying droplets, which were formed by the circulating water on the discharge electrodes. Therefore the efficient electrostatic precipitation for a long period is realized and a large amount of drain water is avoided in some applications.

In this paper the experimental researches of the CDSW were introduced in detail. The discharge

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mechanism and precipitation principle were analyzed. The treating process of discharges on circulating sprays was preliminary researched

1 Experimental apparatus

The experimental apparatus for the electrostatic precipitation of CDSW is shown in Fig.1.

In the contrast with the traditional electrostatic precipitation, in the electrostatic precipitation of CDSW the plate electrodes 2 were connected to the HV power supply through cable 7. The discharge electrode 1 was grounded through the tube dividing water 12, soft tube 3, valve 4 and water container 5. All the processes of precipitation, the scrubbing for electrodes and the plasma treatment for circulating water were conducted between the discharge electrode and the plate electrodes. The water droplets between the electrodes flowed down into a water basin 9, then were pumped by the pump 10 into the water container 5 through water tube 6. Therefore the circulating water was formed. The supplying water system connecting with the discharge electrode was grounded and the difficult HV insulation of supplying water system in traditional method was avoided by this way. The discharge electrode with smaller curvature radius can form non-uniform electric field and produce stable corona discharges under the induction effects of HV plate electrodes. The discharge electrode was made from the stainless steel wire with 1 mm diameter and the length of the electrode was 700 mm. The water on the discharge electrode flowed down from a hale of the tube dividing water and there are some approaches for avoiding blockage in the hole. The HV plate electrodes of stainless steel were 500 mm in width and 900 mm in height. The HV electrodes were suspended and fixed on the insulating frame. The spacing D between two plate electrodes was adjustable as 300 mm or 400 mm.

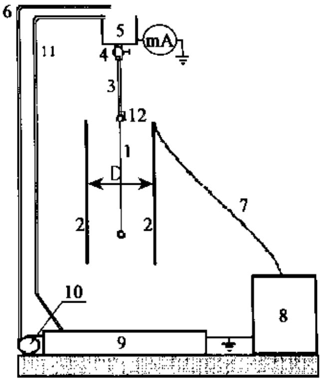

Fig. 1 Schematic of experimental apparatus for electrostatic precipitator of corona discharges with water spraying
1. discharge electrode; 2. HV plate electrode; 3. soft tube; 4. valve; 5. water container; 6. water tube; 7. HV cable; 8. HV power supply; 9. water basin; 10. pump; 11. overflow tube; 12. tube dividing water

In most electrostatic precipitators negative corona discharges are produced, because they have stable Thichel discharge model(Zhang, 1990). Therefore in the electrostatic precipitation of CDSW the positive HV DC power supply was employed, in order to generate negative corona discharges on the discharge electrode. The HV value was measured by the HV probe from the plate electrodes. Between water container and grounded wire an amperemeter was inserted in order to determine the electric current values, which are not necessary in the practical applications. When we was reading the current value in the experiments, the pumping water should stop, in order to insure all the discharge current to flow through the amperemeter.

The experiments were carried out in room temperature. When we measured the influences of water temperature on the discharges, the heated water was put in the water container and the water temperatures were respectively measured before and after applying HV under the water hole.

2 Experimental results and discussions

2.1 Spraying process of discharge electrodes

When positive HV is applied on the plate electrodes opposite to the water-wire electrode, the non-uniform electric field is formed between wire and plate electrodes. The very strong electric field occurs near the surface of the water-wire electrode, because the curvature radius of the electrode is much smaller than that of plate electrodes. The electric field produces an electrostatic force, which is outward and perpendicular to the water surface. The electrostatic force is proportional to the electric field strength.

Therefore the instability of water surface increases and the Taylor Cone is formed. At first the water surface is uneven, after that the protrusions are forced by both the electrostatic force and the gravity then extend outward to form filament flows. When electric field is strong enough, the numbers of filament flows increase and at their ends EHD spray phenomena are produced(Hara, 1981; Jaworek, 1999; Borra, 1999). The spraying droplets with diameters bigger than 20 μm were observed in the similar condition(Huneiti, 1997; Peter, 2000). When voltage is higher than the onset voltage of corona discharges, besides the mechanism of EHD spray, the water sputtering is produced too(Moon, 1998). At this time, the positive ions were produced by corona discharges and bombard the water surface of water-wire electrode.

The spraying droplets of CDSW were analyzed by microscope, when the discharge electrode was grounded. The spacing between discharge electrode and plate electrode was 50 mm. When HV was 12.7 kV, the stable corona discharges occurred and perfect multi-dispersion spray was formed. A lot of droplets with a diameter about 100 μm existed in the aerosol. But there are only a few droplets with a diameter above 1mm in it. The mass of the droplets with a diameter above 80 μm was above 99.6% of total droplet mass. Therefore the droplets above 80 μm produced by EHD spraying play a very important role in the electrostatic precipitation of CDSW.

2.2 Discharge characteristics and capture for particles

After the water-wire electrode produced EHD spraying, we continually increased the voltages of plate electrode to the onset corona voltage. At this moment, the electric field near the wire electrode was high enough to accelerate the free electrons, which occurred in this region. The electrons bombarded gas moleculae and ionized a few of them at first. Though treated flue gases usually were negative electric ones and water moleculae had high electron attachment coefficient, electron avalanche was easily produced and corona discharges were formed near the wire electrode.

The critical electric field(Ec) for the formation of corona discharges on the surface of water-wire electrode is determined by Peek formula.

$$Ec = 3100 f\delta[1 + k/(\delta r)^{1/2}](\mathrm{kV/m}). \qquad (1)$$

Where f is the roughness coefficient of surface($f = 0.6 - 1$); δ is the relative density of flue gas with spraying droplets; $k = 3.08 \times 10^{-2}(\mathrm{m}^{1/2})$; r is the radius of discharge electrode. The corona onset voltage Vc in a wire-plate system with a single wire electrode can be shown as follows(Moor, 1972):

$$Vc = r\, Ec\, \ln(4s/\pi r). \qquad (2)$$

Where s is the spacing between wire and plate electrodes.

In the CDSW, although the wire electrode is grounded, it can form discharge electrode and produce stable corona discharges according to the electrostatic induction principle. Moreover the discharges keep the principal mechanism of corona discharges. The discharge model and its purifying function are obviously different from traditional corona discharges, because the water layer takes part in discharge process.

When the spacing D between two HV positive plate electrodes was 200 mm or 300 mm, discharge characteristics of the corona discharges with dry discharge electrode or spraying one were respectively measured. Their V-I characteristic curves are shown in Fig.2 and Fig.3.

Fig.2 and Fig.3 show that the onset voltages of negative corona with spraying water were obviously lower than that of dry corona discharges, whenever the spacing between plate electrodes was 200 or 300 mm. This phenomenon is attributed to the different radius of discharge electrode according to Eq.(2). The radius of dry corona discharge electrode was 0.5 mm. In negative CDSW, the onset voltages were determined by the radius of filament flows, which were produced by EHD instability of water surface. The filament flows extended from discharge electrode downwards and outwards. Their radius can get smaller than 0.2 mm, which were much thinner than that of dry corona discharges. Therefore the onset voltage of negative corona with spraying water was lowed.

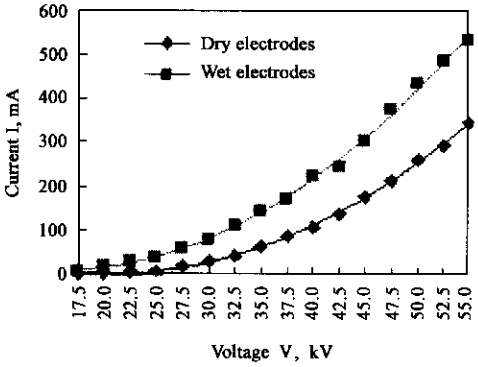

Fig.2 I-V characteristics curves of corona with 300 mm spacing

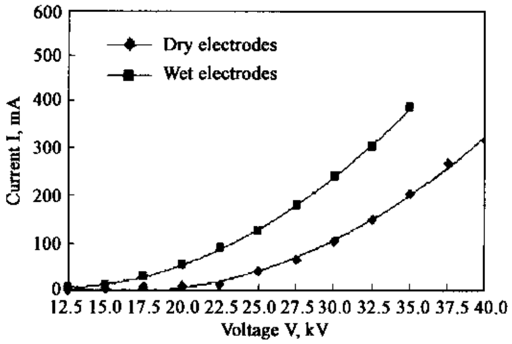

Fig.3 I-V characteristics curves of corona with 200 mm spacing

The curves demonstrated that current of negative CDSW was higher than that of dry negative corona discharges under the same voltages. In dry negative corona discharges, discharge current consisted of free electrons and negative ions existing between two electrodes. There were a lot of free electrons and negative ions produced by electron attachment on molecular of negative electric gases in the ionized region near the discharge electrode. Both electrons and negative ions moved to positive plate electrodes under the electric field. Because the electric field strength decreases steeply with the increase of distance, the free electrons out of ionized region had no enough energy to ionize gas molecular. Therefore more and more electrons attached on the gas molecules and formed negative ions. At last, almost all of the charge carriers collected on the plate electrodes were negative ions.

In the CDSW, besides above process lots of highly charged droplets were produced. Because the water surface on discharge electrode accumulated lots of negative charges under electric field, the water droplets had to carry the charges and formed charged droplets when they left the water surface. The droplets can be charged further in the near-ionized region of corona discharges. In this region not only the strength of electric field was very strong, but also the concentration of both free electrons and negative ions were much higher. The droplets were further charged by ions according to mechanism of electric field charging and diffusion charging. Especially a large number of free electrons existed in the near-ionized region(Xu, 1997). The free electrons have higher energy than gas molecule ions. Therefore they not only charged bigger droplets effectively, but also charged smaller droplets continually, which could easily achieve their saturation charges in the process of ions charging(O'Hara, 1989; DuBard, 1983).

Under the same voltages, the current of negative CDSW was higher than that of dry negative corona discharges. But the corona current in corona discharge of flue gas contained gaseous steam was lower than that of dry negative corona discharges under the same voltages. The reason was that there were ions and a few free electrons in the current of dry corona discharge. In the negative CDSW, besides ions and free electrons there were a large amount of charged droplets in charging spacing. This was different from the experiments of corona discharge in the flue gas contained gaseous steam, in which corona current decreased because of higher electron attachment coefficient of the gaseous steam.

The highly charged droplets had high charge-mass ratio. Their migration velocity was about 30 m/s under electric field(Lear, 1975). They had efficient electrostatic and dynamic agglomeration for the dusts in flue gas(Kazimierz, 2001), which never occurred in the traditional electrostatic precipitators. Therefore the precipitation of CDSW had higher precipitation efficiency.

In the traditional electrostatic precipitators, it is difficult to form a large number of both highly charged and flying droplets. The injected droplets from outside of the electric field can not approach the near-ionized region, because there was strong electric wind near the discharge electrode. Generally, the injected droplets have no charges. They could not be highly charged by ions and free electrons in the near ionized region.

2.3 Cleaning of electrodes

In CDSW, the spraying of water on the surface of discharge electrode was produced continuously. So discharge electrode can be cleared during the operation period, which could not be realized in the traditional electrostatic precipitation.

In order to demonstrate the cleaning effects of the plate electrodes, a thin layer of adhesive wet fly ash was smeared on the plate electrode before the operation. The spacing between plate electrodes was 300 mm, water flow rate on the discharge wire was 464 ml/min for each meter of discharge electrode, positive high voltage was 55 kV and current was 530 μA. The results are shown in Fig. 4 after 3 minutes discharges. The dark area on plate electrode was thoroughly cleared by water. At the top of plate electrode there was a small area, which was not cleaned. The area would become smaller, if the spacing between two electrodes was shortened or discharge electrode was raised.

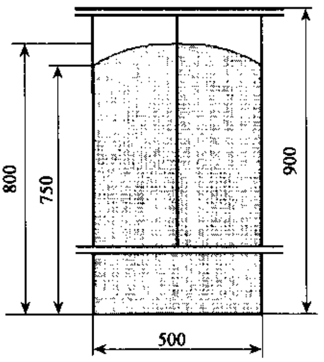

Fig. 4 Cleaning effects of plate electrode

In the CDSW, flying droplets bombed plate electrodes and formed water film on their surface. And the discharge electrode was covered by dropping water along wire. Both collecting electrodes and discharge electrode were covered by flowing evenly water film. Therefore, the adhesive liquid or solid particles in flue gas could not adhere to collecting electrodes and discharge electrode. They bumped water film of plate electrodes and were brought away by water film immediately. In this way, the contamination of electrodes was avoided. Moreover, we could observe original contamination on plate electrodes was removed by flying droplets in the experiments. Comparing with traditional wet electrostatic precipitators, the precipitation of the CDSW not only saves water, but also has higher effects for cleaning plate electrodes.

2.4 Influence of water temperature on the discharge

In the negative CDSW, when water temperature respectively was 22℃ and 64℃, influence of water temperature on discharges is shown in Fig.5. The discharge currents had no obvious increase under usual operating high voltages, when water temperature increased from 22℃ to 64℃.

In the usual corona discharges of heating electrode or high temperature flue gas, the influence of temperature on corona discharges was researched carefully (McDonald, 1980; Moon, 2000). There was no obvious change of discharge characteristic below 100℃. In the CDSW, sometimes the higher temperature was applied. If the water temperature is below the boiling temperature of the water, the obvious increase of discharge current also can not occur. This is because of that higher water temperature increases both the secondary electron emission coefficient on water surface and the electron attachment coefficient of flue gas. The former makes the current increasing, but the latter makes the current decreasing.

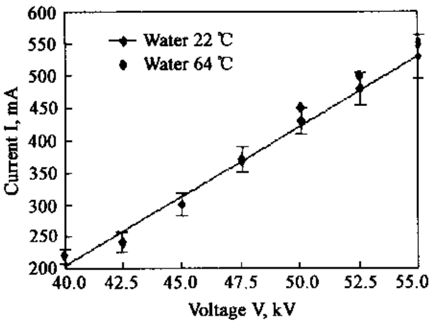

Fig. 5 Influence of water temperature on the discharges

2.5 Treatment of spraying water using the discharge

The corona discharge and EHD spray have function of decolorization and sterilization. The experiment on the decolorization of indigo solution was carried out by authors using CDSW (Wu, 2001). The initial concentration of aqueous solution of indigo carmine ($C_{16}H_8N_2Na_2O_8S_2$) was 5.0×10^{-5} mol/L. A spectrophotometer(1 cm path length) was used for measuring decolorization rate. When air gap was 30 mm and high voltage was 25 kV, the decolorization rate can get to 80.8% in 30 minutes.

The experiment of killing bacteria in water using EHD spraying has been reported(Lee, 2001). In the experimental apparatus, the inner diameter of nozzle was 0.2 mm and the inner diameter of ring electrode was 20 mm. The survivability of Wscherchia coli treated only once decreased to 2.8%, when high voltage was 5.4 kV.

The mechanism of decolorization and sterilization using the corona discharge or/and EHD spray is not very understandable. Many researches have been done on the $DeSO_2$ and the DeNOx from flue gas, the decolorization as well sterilization in water using the pulsed corona plasma(Masuda, 1990; Chang, 1989; Clements, 1989). The researches demonstrated that the active species are dominant factors for treating gases or water using the pulsed plasma. In the CDSW a certain number of energetic electrons also occur near discharge electrodes. It is reasonable to deduce that the decolorization in CDSW can attribute to the active species, such as OH, O, H_2O_2, O_3 and so on. The possible reactions for the generation of active species are as follow.

$$e + O_2 \rightarrow e + 2O, \qquad (3)$$

$$O + O_2 + M \rightarrow O_3 + M, \qquad (4)$$

$$O + H_2O \rightarrow 2OH, \qquad (5)$$

$$2OH \rightarrow H_2O_2. \qquad (6)$$

There the third body M is O_2, O_3, N_2, O and so on.

Although the average energy of electrons in the CDSW is lower and plasma region is smaller than those in pulsed corona discharges, the experiments have demonstrated that treating water is very effective. This can be attributed to the special shapes of treated water. In the CDSW, all the water has to form filament flows and droplets, which are surrounded by corona plasma region and active species during a short time. Therefore the reaction areas between plasma and treated water are significantly enlarged and the mass transfer of the active species into water is considerably improved.

The corona plasma region in CDSW is larger than that in usual corona discharges. The expanding plasma region was observed in corona discharge on water drops dripping from a conductor under DC high voltage(Hara, 1981). In the CDSW, corona plasma is produced by filament flows, which extend outwards and downwards from wire electrodes. Sometimes the droplets near discharge electrode are highly charged so that corona discharges occur on the droplets. All these expand the corona plasma region from wire electrodes, which improved efficiency of treating waster.

The CDSW has the potential for removing some harmful gases from flue gas. An experiment of DC corona discharge over water surface demonstrated that the DC corona with the presence of water with provides excellent effects for NOx removal processes(Tomio, 2001).

In the CDSW, water quantity for cleaning electrodes was much smaller than that of traditional wet electrostatic precipitation. So it is possible to frequently treat the water, when circulation water system is employed. The odor can be avoided, and the colors can be removed. Some microorganisms can be killed in order to prevent the equipment from corrosions and blockages. Even though the circulating water includes some harmful resolved compounds after a long time operation, its spraying could not add the pollution of flue gas. Most droplets have higher charges and bigger sizes of above 80 μm. They are easily removed by corona discharge from flue gas instead of mixing with atmosphere.

3 Conclusions

Based on theoretical and experimental researches, a new electrostatic precipitation method using

CDSW was proposed, in order to effectively remove the adhesive and fine dusts from flue gas.

In the CDSW, both the discharge electrodes and supplying water system were grounded according to the principle of electrostatic induction. Therefore the difficulty of high - voltage insulation in the supplied water system of discharge electrodes was avoided. The stable and safe operations of the precipitators were insured.

When the quantity of the supplied water was 464 ml/min for each meter of discharge electrodes, a large number of water droplets with a diameter of about 80 μm were produced from discharge electrodes according to the EHD spraying principle. The droplets bombarded water film of plate electrodes with the velocity of about 30 m/s. And the discharge electrode was covered by dropping water along wire. Therefore, both discharge electrodes and collecting electrodes were effectively cleaned.

Besides the precipitation mechanism of traditional wet electrostatic precipitation, the CDSW added some new precipitation mechanisms on the precipitators, such as the dynamic agglomeration of flying droplets, the electrostatic agglomeration of charged droplets and the electron charging of fine particles. Therefore higher precipitation efficiency for fine dust was achieved.

The spraying circulation water in the CDSW was treated by corona discharge plasma near the discharge electrodes. The color of some dye was removed and the some harmful bacterium can be killed in the water.

The water quantity employed in the CDSW was rather little. The circulating water can be repeatedly treated by corona discharge plasma in the precipitation process. The droplets are easy removed by corona discharge from flue gas instead of mixing with atmosphere. All above factors provided the convenient conditions for using the circulating water during a long period.

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