Experimental research on V-I characteristic of a novel cavity atomizing corona discharge device

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Abstract. In order to seek a new control method which can control the dust, SO₂, NOₓ and other pollutants comprehensively, a novel atomizing corona discharge device without external dynamic force was invented. The voltage-current (V-I) characteristics in different electrode structures were studied. In the cavity-wire type discharge structure, the voltage-current characteristics of de-ionized water, tap water and saturated solution of Ca(OH)₂ were compared and analyzed. The results showed that: the atomizing effect of cavity-wire type discharge structure was better than that of cavity-plate under the same electrode diameter and voltage. A better atomizing effect could be obtained when the curvature radius of the cavity atomizing electrode was reduced. Active ions in solution had damaging effect on hydrogen bond among water molecules, which is in favour of solution atomization. This work will provide theoretical basis and experimental supports for a new field that the electrostatic and the wet flue gas desulphurization (WFGD) are combined together at the same time.

1. Introduction

Atmosphere is our essential survival elements. In recent years, with the development of the living and producing standard of the people, the carrying capacity of environment is increasing. China is a coal production and coal-fired country. Coal accounts for 70% of the total energy consumption [1]. This situation will not improve in a short time. Therefore, a series of environmental problems caused by coal-fired can not be ignored. In the process of coal combustion, not only is the fly ash produced, but the harmful gases polluting the atmosphere environment are produced such as SOₓ and H₂S. SO₂ is the main material for the formation of acid rain. Acid rain affects human life and cause serious damage on the Earth’s environment. Therefore, coal-fired desulphurization is essential.

At present, as one of the desulphurization areas, atomized discharge technology has already made some progress. Binlin Dou and Y M Kang [2-3] studied SO₂ from the perspective of mass transfer and catalytic, respectively. J L Wen [4] used pressure nozzles to compare the desulphurization efficiency between water and lime slurry. It showed that the static gain is obvious. Z T Wang [5] analyzed the influence that the atomizing charged characteristic of two-fluid and various factors had on the charge - mass ratio of droplet. X L Zou [6] studied the velocity and particle size distribution of lime slurry droplet using pressure nozzles. However, there is rarely research on the atomized nozzles without external dynamic force at home and abroad.

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In the present, a new atomized discharge device without external dynamic force was used. The influence that the electrode matching and solution property have on the corona discharge was studied experimentally. This method will provide theoretical and experimental basis for the new area that the electrostatic and wet flue gas desulfurization (WF-GD) are combined together at the same time. After technological design is mature, this technology can join to the ESP to achieve dust removal and desulfurization process simultaneously. This also makes the flue gas purification process simplified, practical and effective.

2. Experimental devices, materials and methods
The experimental device was based on the atomized discharge device [7-8]. After being improved, the device is shown in figure 1. The grounding electrodes are plate structure and circular wire, respectively. They are shown in figure 3.

![Figure 1. Cavity atomizing device.](image1)

![Figure 2. Atomizing nozzle and Taylor cone.](image2)

![Figure 3. The experimental device of atomizing corona discharge system.](image3)

1-liquid storage pot, 2- blender, 3-atomizing nozzle

The grounding wire with 1.9 mm diameter was set in horizontal. The size of grounding plate electrode placed perpendicular to the ground was 1.0×0.6 m². The space between cavity atomizing electrode and ground electrode was set to 10 cm. 1# and 2# micro-cavity atomizing electrode of different diameters were used. The diameter of 1# is 1.26 mm and 2# is 0.5 mm. The length of cavity is 4.5 mm. Experiments were performed at room temperature. Atomized liquid are de-ionized water,
tap water and saturated solution of Ca(OH)$_2$. The solution of Ca(OH)$_2$ consisted of ionized water and analytically pure Ca(OH)$_2$ powder. The devices above were used to measure the V-I characteristics under different voltages. The influences that electrode structures and liquid property had on the atomizing discharge were studied.

3. Experimental results and analysis

3.1. The influences that the cavity diameter and electrode structure had on the atomizing discharge

In this experiment, the systems of cavity-line and cavity-plate and the cavity electrode of 1# and 2# were used. The atomizing liquid was de-ionized water. The discharge characteristics under different discharge conditions were investigated. The result is shown in figure 4.

![Figure 4. The V-I characteristics of different electrode matching and cavity diameter.](image)

![Figure 5. The V-I characteristics of solutions with different ion concentration.](image)

For two different discharge structures, if the wire electrode diameter and voltage were all the same, the cavity-line structure could obtain higher corona current. With the voltage increasing, the current difference between two types of discharge structure rise. The relation between the electric field strength and the electric fluxline can be written as follows:

$$E = \frac{dN}{dS}$$

(1)

Where $dS$ is cell area, $dN$ is the number that the electric fluxline through the cell area.

In the same voltage, the electric field strength between the electrodes of cavity-line structure is stronger. Correspondingly, the number of space charges increases. The space charges have higher velocity. Then the rate of droplet charged increases. The formula of critical droplet breakage charge is as follows:

$$q_0 = 8\pi (\epsilon \sigma r^{1.5})^{1/2}$$

(2)

Where $q_0$ is the droplet charge, $\epsilon$ the permittivity of liquid, $\sigma$ the surface tension of droplet, $r$ droplet diameter.

When the droplet charge is greater than $q_0$, the binding effect of surface tension will be less than the expansion of the electrostatic force [9], which makes the droplet break. Therefore, in the strong discharge conditions, the droplet can quickly reach the Rayleigh limit [10]. In the cavity-line structure, the spraying droplets can form an unstable jet even under a lower voltage. Besides, the raise of space
charges not only increases the possibility of the droplet charge, but increases the chance that the space charges strike the ground electrode due to air entrainment. These factors make the discharge current of cavity-line structure is much larger than that of cavity-plate structure in the same voltage.

For the same electrode structure, the cavity having small curvature radius (2#) could obtain larger current. There are two reasons for this phenomenon. The first reason is according to the electric field strength formula of the needle electrode [11]:

$$E = 2U \left( \frac{r + 2x}{r} \right) \ln \left( \frac{r + 2d}{r} \right)^{-1}$$

(3)

Where $E$ is the electric field strength in the vicinity of the corona electrode, $U$ the applied voltage, $r$ the curvature radius of needle, $d$ the space between the electrodes, $x$ the distance of a point to the needle tip in the electric field.

With the curvature radius of the tip decreasing, the electric field strength in the vicinity of the corona electrode increase under the same voltage. Then the cavity electrode having smaller diameter could generate stronger electric field strength. The number of space charges in this structure was larger. These increase the probability of droplets charged.

The other reason is when the Taylor cone forms, the ration of long axis and short axis of Taylor cone belonging the same liquid is constant, namely, $D/H=d/h$ (it is shown in figure 2). When the long axis of the Taylor cone is 1.9 times the short axis [12], the shape of droplet tends to unstable and breaks. Being restricted by the cavity electrode wall, different cavity electrodes form different short axis diameters of Taylor cone. This make the droplet volume formed in the tip of the cavity difference. After the Taylor cone breaks, the liquid forms initial spherical droplet due to the effect of the surface tension. Because of the electric field, droplets have collision charged with the space charges and the charges attach to the outer surface of the droplets. With the electric field strength increasing, the charges accumulating in the surface of the droplet are more and more and gradually reach saturation. Due to the electrostatic repulsion, the surface tension of the droplet can’t maintain its inherent form and the droplet breaks. When a single large droplet is broken into several small droplets, the specific surface of the droplet increases resulting in a single droplet charged unsaturated. Broken droplets will continue to be charged to the saturation and then broken again under the electric field. This process will be repeated until the electrostatic repulsion and surface tension reach to balance. When the droplets are no longer broken, the entire process of breaking charge is completed. If it is the same liquid to reach to the balance of breaking charge, the droplets size and charge basically the same. In the same voltage, the droplet having small initial diameter can quickly reach to the balance of breaking charge. The number of droplet and the total surface area increase, so that the amount of charge reaching to the ground plate increase rapidly.

These two aspects above (the electric field strength and the rate of droplets breaking) make the smaller diameter cavity generate larger current in the discharge process.

Basing on the analysis above, we can imagine that different properties of discharge liquid and different ion concentrations make the time reaching to the balance of breaking charge different. This will have influence on the atomizing corona discharge.

3.2. The influences that the ion concentration had on the atomizing discharge

Calcium-based desulphurization technology is one of the world’s most widely used and most mature desulphurization processes [13-14]. Then Ca(OH)$_2$ was selected as the experimental material.

According to the experiments above, the cavity-line atomizing system was selected and the 2# atomizing electrode was used. The solutions were de-ionized water, tap water and saturated solution of Ca(OH)$_2$. The V-I characteristics of these solutions are shown in figure 5.

The figure shows that in the same voltage, the order of the three solutions discharge current was saturated solution of Ca(OH)$_2$> tap water> de-ionized water. With the voltage increasing, the intensity of corona discharge increased. Therefore, the discharge current rose. Increasing the ion concentration
in liquid (i.e., the ionic number in the per unit volume of aqueous solution) had a positive impact on the liquid charge. Then the discharge growth trends of these three solutions were different.

There are two reasons for the difference of discharge current. The first one is water molecules have strong polarity. There is a strong hydrogen bond among molecules [15]. The ions added to the de-ionized water will damage the original hydrogen bond of water molecules. Different ion concentration has different damaging effect for hydrogen bond. This causes the reduced degree of the liquid viscosity and the surface tension different. Increasing the ion concentration will enhance the damaging rate of the hydrogen bond. Thus increases the possibility of droplets breaking.

The second reason is from the formula which is as follows:

$$E^2 = 77 \times \frac{\sigma}{2\pi \varepsilon_0 d} \quad (4)$$

Where $E$ is the electric field strength, $\sigma$ surface tension of the droplet, $d$ droplet diameter.

If the ion concentration increases, the droplets break into small droplets more easily. This will increase the total surface area of the droplets and the space electric field strength. Then the total droplets charges increase. Finally the current is larger in the same voltage. In the de-ionized water, tap water and saturated solution of Ca(OH)$_2$, the ion concentration is from small to big, so the discharge current will change with the change of ion concentration.

4. Conclusion
(a) In the same electrode diameter and same voltage, cavity-line electrode can get better atomizing effect than cavity-plate electrode. The cavity-line electrode can be selected as the electrode matching of flue gas desulphurization.

(b) The influence that solution properties and electrode shape of the cavity having on the particle size and surface tension of the atomizing droplets can make discharge current change. With the electrode radius of curvature decreasing and the number of ions in the solution increasing, the discharge current increases.

(c) The active ions in the solution can damage the hydrogen bonds among water molecules. Improving the concentration of active ions can enhance the ability of droplets breaking.

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