Investigations of dc corona and back discharge characteristics in various gases

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Abstract. The paper presents investigations of forward and back discharges occurring in air, carbon dioxide, and nitrogen, with plate electrode covered with fly ash. For the glow discharge, the back corona current is lower than for normal corona discharge, but for back-arc discharge, both currents are nearly the same. A dielectric layer covering the plate electrode causes that the arc discharge can start at higher voltages. In the arc discharge, the elements present in fly ash can volatilise due to electron bombardment of the layer.

1. Introduction
Corona discharge has been studied in detail in the literature [1] due to its many industrial applications, for example, for the charging of aerosol particles [2,3], or in plasma chemistry [2,4]. Back discharge is less known phenomenon, and has only limited practical use [5]. This type of discharge is known due to its harmful effects caused in electrostatic precipitators [6], decreasing their collection efficiency, or in surface coating technology, damaging the powder layer. Back discharge is a type of discharge, which occurs between point and plate electrodes, when the plate electrode is covered with a dielectric layer. The charge emitted by the point electrode accumulates on the surface of the dielectric layer and produces high electric field within it. The increasing electric field leads to a breakdown of the layer. The charge accumulated on the layer surface flows throughout small channels to the plate electrode, and faint, glowing spots can be visible on the layer. An increase of the voltage and discharge current lead to an increase in the current density in these channels that causes heating of the material of the layer. When sufficiently high current flows through one of such channels, it becomes conducting due to thermal ionisation of the layer material. This ionisation ignites a low-current back-arc discharge. The current in this type of discharge increases uncontrollable, and its magnitude is only limited by a series resistor (5 MΩ).

In the present paper, two types of direct current electrical discharges: corona discharge and back discharge generated in the needle-to-plate electrode configuration are investigated. The discharges were generated in N₂, and CO₂, as main components of flue gas, and in air for reference. The research is aimed at better understanding of the back-discharge processes which cause harmful effects in electrostatic precipitators. The current-voltage characteristics of the corona and back-discharges at normal temperature and pressure are discussed.

2. Experimental
The experiments were carried out in a discharge chamber of 0.75 dm³ made of plexi glass. The discharge needle was made of tungsten wire 1.5 mm in diameter, and the plate of nickel alloy. The
dimensions of the plate were 67×90 mm. The distance between the electrodes was 21 mm. For the investigations of back discharge a fly ash layer of thickness of 6 mm was deposited on the plate. The discharge electrodes were supplied from the high voltage DC source SPELLMAN HV SL 300. The voltage was changed from +2 kV up to +30 kV. The discharge current was measured with a moving-coil ammeter. Both polarities of the voltage to the discharge electrode, positive and negative were tested. The positive and negative corona and back-discharges refer to the positive and negative voltage on the discharge electrode, respectively. The pressure in the discharge chamber was slightly above the atmospheric to allow the chamber to be smoothly washed-out with the gas flowing with the flow rate of about 5 l/min. In order to remove absorbed water, the fly ash was dried at a temperature of 200°C for a period of 2 hours before the measurements.

3. Results

The current-voltage characteristics of corona and back discharges are presented in Figure 2, and arc discharges in Figure 3. The characteristics show the dependence of the discharge current on supply voltage. The characteristics with supply voltage, instead of voltage between the electrodes, at abscissa were chosen due to a monotonic increase of the current in the plots. In all these plots, three main regions can be roughly distinguished: the glow, streamers and arc discharges. The regimes of the discharge modes are schematically labelled in each figure.

Initially, for low voltage of positive polarity, the current was lower than 1 μA. With the voltage increasing, the current increased to tens of microamps, for N₂ and CO₂, and hundreds of microamps for air. The glow discharge was generated in this case. For negative polarity, the current of the glow discharge can increase up to 1 mA with the voltage increasing, except in air in which it is not higher than 100 μA. From the photographs of the discharge of positive polarity (not shown in the paper), a faint glow plumes originating from the discharge electrode could be noticed in air and nitrogen. The plumes became longer with the voltage increasing, finally bridging the entire interelectrode space. For the same discharge current, the discharge in carbon dioxide was, however, invisible. For negative polarity, the glowing regions were confined close to the discharge electrode only, independently of the gas used.

In the back discharge, the bright regions could be equally observed near the needle tip and on the dielectric layer surface. Many faint breakdown points on this layer could be observed. From these points, ions of polarity opposite to that of the discharge electrode are emitted. These bright spots indicate that ionisation and recombination processes take place in both regions: in the vicinity of the needle tip and on the layer surface. The discharges on dielectric layer were called by Masuda and Mizuno [7] as surface-glow discharge. The current in the back-glow discharge was usually lower than the current in the discharge without dielectric layer. It was caused by lower electric field in the interelectrode space due to the charge accumulated on the dielectric layer. The glow discharges developed into the interelectrode space with the supply voltage increasing, and finally the dark space between them disappeared.
For higher voltages, when energy of electrons was sufficiently high, the breakdown streamers could be generated, and the discharge current could sharply increase above 1mA. For the discharge without dielectric layer, the streamers moved spontaneously over the plate, probably due to the space charge remaining after the previous discharge. In the case of back-discharge, when the electrode is covered with fly ash layer, the streamers concentrated only in a few distinguished points on the layer. Streamer discharges did not differ much for both polarities. In the case when the plate is covered with dielectric layer, the time averaged streamer current is lower than for uncovered electrode. Due to high ballast resistance used, the voltage interval of the streamer discharge was very narrow, and these discharges were easily converted to a stable low-current arc discharge (Fig.3).

Figure 2. Current-voltage characteristics of forward and back discharges in air (a, b), CO$_2$ (c, d), and N$_2$ (d, e), for positive (a, c, e) and negative (b, d, f) polarities. The plate electrode covered with fly ash layer.
Air - positive arc discharge

U=29 kV, i=5.23 mA
exp. 1/100 s

Air - negative arc discharge

U=29 kV, i=4.2 mA
exp. 1/100 s

Air - positive back-arc discharge

U=29 kV, i=4.65 mA
exp. 1/100 s

Air - negative back-arc discharge

Arc was not obtained in this range of voltage.

CO₂ - positive arc discharge

U=30 kV, i=5.1 mA
exp. 1/10 s

CO₂ - negative arc discharge

U=30 kV, i=5.1 mA
exp. 1/10 s

CO₂ - positive back-arc discharge

U=30 kV, i=5.1 mA
exp. 1/50 s

CO₂ - negative back-arc discharge

U=30 kV, i=3.3 mA
exp. 1/50 s

N₂ - positive arc discharge

U=19 kV, i=2.4 mA
exp. 1/100 s

N₂ - negative arc discharge

U=30 kV, i=4.5 mA
exp. 1/100 s

N₂ - positive back-arc discharge

U=28 kV, i=4.8 mA
exp. 1/50 s

N₂ - negative back-arc discharge

U=28 kV, i=4.65 mA
exp. 1/50 s

Figure 3. Photographs of low-current arc and back-arc discharges in various gases.
In arc discharge in the electrode system without dielectric layer, the plasma column bridges entire interelectrode space. The exception is that for lower voltages, a dark space was formed between two separated plasma columns that indicate lack of ionisation processes in this region. In air, for negative polarity of the discharge electrode, no arc discharge was generated in the voltage range tested.

The colour of emitted light is different for each gas, depending on energy levels during the recombination and de-excitation. The light emitted by the discharge in air is dominated by the second positive system of the emission spectrum of nitrogen. The light emitted by CO$_2$ is bluish-white, indicating that probably ionisation processes are more intense than excitation of CO$_2$ molecules. An effect of back discharge is an intense heating of the crater formed during the ion bombardment of the layer. For positive polarity, the light emitted by the plasma column is the same as in the case when no dielectric layer is deposited on the electrode. For negative polarity, elements present in the fly ash are volatilising during the discharge, changing the luminosity of the plasma column. The colour of the column is yellow, and is the same for all gases tested. This phenomenon indicates that volatilisation is mainly due to electron bombardment of the layer and not due to thermal vaporisation or ion bombardment.

Comparing the current-voltage characteristics of the discharges in different gases it can be noticed that the transition from glow discharge to streamer and arc in back discharges takes place for higher supply voltages (Table 1). This rule is broken in air in which the transition voltage is lower.

| Gas | Discharge | Polarity / Supply voltage range [kV] |
|-----|-----------|-----------------------------------|
|     |           | Glow     | Streamers | Arc     |
| Air | forward   | + 7 ÷22  | + 22 ÷27 | + 27 ÷30|
|     |           | - 6 ÷30  | –         | – ÷30   |
|     | back      | + 5 ÷22  | + 22 ÷24 | + 24 ÷30|
|     |           | - 5 ÷20  | - 13.5 ÷24 | - 24 ÷30|
| CO$_2$ | forward | +10 ÷22.5 | +22.5 ÷25 | + 25 ÷30|
|      |           | - 6 ÷20  | - 22 ÷24 | - 24 ÷30|
|      | back      | + 8 ÷28  | + 28 ÷30 | + ÷30   |
|      |           | - 5 ÷18  | -18 ÷21  | - 21 ÷30|
| N$_2$ | forward   | + 5 ÷9   | 9 ÷17   | + 17 ÷30|
|      |           | - 3.5 ÷30 | –        | - ÷30   |
|      | back      | + 5 ÷18  | 18 ÷20  | + 20 ÷30|
|      |           | - 5 ÷24  | –        | -24 ÷30 |

4. Conclusions
It can be concluded from this research that in back-discharge, the ionisation processes can equally take place near the corona electrode (needle) and within the crater in the dielectric layer. Ions of opposite polarity to those emitted by the needle are ejected to the discharge channel that causes a decrease in collection efficiency of an electrostatic precipitator. In the glow mode, the back-discharge current is lower than for normal corona discharge, but for back-arc discharge, both currents are nearly the same. For the experimental conditions presented in this paper, the discharge current in the back-arc discharge was between 2 and 6 mA. A dielectric layer covering the plate electrode causes that the arc discharge can start at higher voltages. For negative polarity, the elements present in fly ash volatilise during the discharge, probably due to electron bombardment of the layer.
5. References
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