Characteristics of sliding discharge in a multi-rod reactor

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Abstract. This paper is aimed at investigating the characteristics of a sliding discharge (SD) including the onset voltage ($V_O$), spark voltage ($V_S$), and current-voltage (I-V) relationship in a multi-rod reactor stressed by sinusoidal AC or pulse voltage. The effects of various parameters (the voltage amplitude, frequency, gas flow rate, and voltage type) on the characteristics of the reactor sliding discharge ($V_O$, $V_S$ and I-V relationship) have been studied experimentally. It has been found that the DC onset and spark voltages increase with the increase of the gas flow rate, while the effect of the frequency on them is not pronounced. The onset and spark voltages of the stressed reactor for sinusoidal AC voltage are lower than those obtained under a pulse voltage of the same peak value. Subsequently, the sliding current increases with the increase of the sinusoidal AC high voltage, the frequency, and the negative DC voltage, while, it decreases with the increase of the flow rate. It is observed that stressing the reactor with sinusoidal AC voltage gives higher values of sliding current than those obtained using a pulse at the same peak voltage. Stressing the reactor with sinusoidal AC voltage gives higher values of the NO removal efficiency than those obtained using pulse voltage.

1. Introduction
Dielectric barrier discharges (DBD) are characterized by the presence of at least one insulating layer (dielectric barrier) between the electrodes. The dielectric barrier limits the discharge current, preventing the transition to an arc. This stable discharge that can be generated under atmospheric pressure is suitable for ozone generation [1], NOx removal [2, 3] and SO₂ removal [4].

The sliding discharge is a discharge generated on a dielectric surface by a combination of AC or pulse and DC stresses in three-electrode geometry [5, 6]. The resulting DBD with the AC or pulse stress slides along the dielectric surface by the effect of the DC stress applied to a third electrode. The sliding discharge was generated on flat dielectric surfaces [5] or along the inner surface of glass capillaries [6]. The present study is aimed -for the first time- to propose a new design of DBD reactor for NO removal seeking improved efficiency using sliding discharges. The effects of the voltage amplitude, frequency, gas flow rate and the voltage type on the characteristics of a sliding discharge ($V_O$, $V_S$ and I-V relationship) are examined with experimental confirmation of NO removal efficiency.

2. Experimental setup
The details of the multi-rod DBD reactor used in the present study are illustrated in figure 1. It consists of an internal cylindrical glass tube (inner diameter: 19.5 mm, outer diameter: 22.7 mm, length: 87 mm) and an external cylindrical glass tube (inner diameter: 34.8 mm, outer diameter: 40 mm, length: 270 mm) which was used as the dielectric material. Stainless tubes (diameter: 6 mm, length: 66 mm)
were inserted between the two glass tubes as discharge rods. Two grounded stainless meshes were wrapped outside the external glass tube and inside the internal glass tube. To generate the sliding discharge, high sinusoidal AC or pulse voltage with high frequencies and high negative DC voltage are applied to the discharge rods alternately. At a given high sinusoidal AC or pulse voltage, the onset voltage of the sliding discharge is defined as the minimum value of DC voltage where the sliding current starts to flow, while the spark voltage is the corresponding DC voltage leading to spark conditions.

Figure 2 shows a schematic diagram of the experimental setup. A sinusoidal AC high voltage power supply (Function generator (KENWOOD AG-204D) + high voltage amplifier (TREK Model 20/20C)) with variable frequency was used. The net output high voltage applied directly to the DBD reactor was measured using a 1000:1 high voltage probe (Tektronix P6015A). A 0.1 µF capacitor was connected in series with the plasma reactor to measure the discharge power using Lissajous figures [3]. The waveform of the discharge current was recorded using a 1 kΩ resistor. All waveforms were displayed on a digital oscilloscope (Tektronix TDS 1012B). To generate the sliding discharge, a high voltage DC power supply (Matsusada Precision Inc.) was used and the sliding current was measured using a digital multi-meter (CDM-12D, Custom Co., Ltd.) with a limiting resistor of 5 MΩ.

A pulse generator (ECG-KOKUSAI model PPS-5000) with variable frequency was used for applying the pulsed voltage and the discharge current was measured using a Pearson current monitor (model 2877), which was located in the return current path to the ground.

The experimental measurements were carried out at room temperature under normal pressures with a constant relative humidity (8%). Simulated gas (dry air + NO, N₂ base) was fed through the plasma reactor with the NO initial concentration of 200 ppm. FTIR (Fourier Transform Infra-Red) spectroscope gas analyzer (model SESAM 3-N) was inserted to measure the concentrations of NO.

3. Results and discussion

3.1. Sliding discharge characteristics

3.1.1 Effect of AC high voltage amplitude. Figure 3 shows the relation between the sliding current and the negative DC voltage for various sinusoidal AC peak voltages (5.5, 6, 6.5 kV) at a frequency of 3 kHz and flow rate of 5 L/min. It is clear that the sliding current increases with increasing DC voltage for all cases and the sliding current increases with the AC high voltage.

3.1.2 Effect of the frequency. It is observed that the onset and spark voltages decrease with increasing sinusoidal AC peak voltage irrespective of the frequency, while the effect of the frequency on Vo and
Vs is not clear. Figure 4 shows the sliding current as a function of the negative DC voltage for various frequencies (2, 3, 4 kHz) at a sinusoidal AC peak voltage of 6 kV and flow rate of 5 L/min. It is clear that the sliding current increases with increasing the frequency.

![Figure 3](image1.png) ![Figure 4](image2.png)

**Figure 3.** Sliding current as a function of the negative DC voltage for various sinusoidal AC peak voltages at 3 kHz and 5 L/min.

**Figure 4.** Sliding current as a function of the negative DC voltage for various frequencies at 6 kV and 5 L/min.

3.1.3 Effect of the gas flow rate. It is observed that the onset and spark voltages increase with increasing flow rate due to the retarding effect of the gas flow on the discharge ion motion. Subsequently, the sliding current decreases with increasing gas flow rate as shown in figure 5, which shows the relation between the sliding current and the negative DC voltage for various gas flow rates (2, 5, 10 L/min) for a sinusoidal AC peak voltage of 6 kV and frequency of 4 kHz.

![Figure 5](image3.png)

**Figure 5.** Sliding current as a function of the negative DC voltage for various flow rates and voltage types at 6 kV, and 4 kHz.

3.1.4 Effect of the voltage type. Figure 6 shows the relationship between negative DC voltage and peak voltage at onset and spark conditions for various voltage types (sinusoidal AC and oscillatory pulse) at frequency of 4 kHz and flow rate of 5 L/min. The first oscillation of the applied pulse has a rise time of about 235 ns and tail time (time up to 50% of the peak value) of 1550 ns. The duty cycle being defined as the ratio between on-time of positive-going of the first oscillation and the pulse period (1/4000= 0.25 ms) is 0.014. It is clear that the onset and spark voltages decrease with the peak voltage irrespective of the voltage type. The AC voltage gives lower onset and spark voltages when compared with the pulse voltage at the same voltage due to the shorter stress time with the application of pulse voltage compared with AC voltage.

![Figure 6](image4.png)

**Figure 6.** Relationship between DC voltage and peak voltage for various voltage types at 4 kHz, and 5 L/min.
Subsequently, stressing the reactor with AC voltage gives higher values of sliding current when compared with the pulse voltage at the same peak voltage as shown in figure 5, which shows the relation between the sliding current and the negative DC voltage for various voltage types at peak voltage of 6 kV, frequency of 4 kHz and flow rate of 5 L/min.

3.2. Removal of Nitric Oxide (NO)

Figure 7 shows the temporal variation of the NO concentration in ppm at sinusoidal AC peak voltage of 6.5 kV, frequency of 3 kHz, flow rate of 5 L/min and DC voltage of -2.275 kV. It is clear that using SD with DBD reduces the concentration more than by using DBD only due to the increased current.

Figure 8 shows the NO removal efficiency \(\text{NO removal efficiency} = \left(\frac{\text{NO}_i - \text{NO}_f}{\text{NO}_i}\right) \times 100\), where \(\text{NO}_i\) and \(\text{NO}_f\) are the initial and final concentrations of NO in ppm, respectively) as a function of the energy density \(\left(\frac{P_d \times 60}{Q}\right)\), where \(E_d\), \(P_d\), and \(Q\) are the energy density (J/L), discharge power (W) and gas flow rate (L/min), respectively) for various voltage types (AC and pulse) at a peak voltage of 6.5 kV, frequency of 3 kHz, flow rate of 5 L/min and variable negative DC values. The NO removal efficiency increases with the increase of energy density irrespective of the voltage type. However, stressing the reactor with sinusoidal AC voltage gives higher values of removal efficiency as compared with the pulse voltage. The removal efficiency expressed as a percentage of the energy density is high at first but decreases with increasing energy density irrespective of the voltage type as shown in figure 8.

4. Conclusion

The generation of sliding discharges inside the multi-rod DBD reactor by a combination of AC or pulse and DC stresses was investigated. The sinusoidal AC high voltage and corresponding DC high voltage at sliding-discharge onset and spark condition in the DBD reactor were measured. From the electrical measurements, it has been shown that the sliding discharge generation depends on the voltage amplitude, frequency, gas flow rate and the voltage type (sinusoidal AC or pulse). Preliminary results showed the effectiveness of the sliding discharge generated in the DBD reactor for removing NO but further investigation is necessary to develop more effective NO and NO\(_x\) removal reactors.

References
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