DC Discharges in Atmospheric Air and Their Transitions

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***Abstract*—We present images and basic characteristics and describe transition mechanisms between three dc discharges in atmospheric air point-to-plane or point-to-water gap. With increasing applied voltage, a streamer corona transits to a transient spark: a repetitive spark with very short (∼100-ns) current pulses (∼1 A) of very limited energy. With an appropriate ballast resistor, this transient regime evolves into a pulseless glow discharge. These three discharges generate nonequilibrium plasmas of high chemical activity interesting for environmental and biomedical applications.**

***Index Terms*—Atmospheric pressure, corona, DC discharges, non-equilibrium plasma, streamer, water electrode.**

THREE TYPES of direct-current (dc) electrical discharges generating nonthermal plasmas in atmospheric air were investigated: a well known streamer corona (SC) and a relatively novel transient spark (TS) and glow discharge (GD). We studied these discharges between two metal electrodes of positive point-to-plane configuration or with the plane cathode submerged 2 mm in tap water ∼2 mm, which simulates water treatment or biodecontamination. SC and TS are pulsed discharges despite the dc applied voltage; GD is pulseless.

A simplified electrical scheme is shown in Fig. 1. A dc high voltage (HV) was applied through the ballast resistor $R(\sim\mathrm{M}\Omega)$ and through the HV cable on the needle electrode. The discharge voltage U was measured by the HV probe (Tektronix P6015A). The current I was measured on a 50-Ω resistor or by a Rogowski current monitor (Pearson Electronics 2877). The U and I signals were processed by a 200-MHz oscilloscope Tektronix TDS 2024.

The discharge photographs with a 6 mm separation between the needle HV anode and water level, and their typical voltage and current waveforms are shown in Fig. 2. When a few kilovolts is applied to the point electrode, SC appears. SC has small current pulses (∼10 mA) with a repetitive frequency of 10–30 kHz, during which the discharge voltage remains fairly constant [1]. As the voltage is further increased (to ∼8 kV in a 6-mm gap), the streamers establish a conductive channel

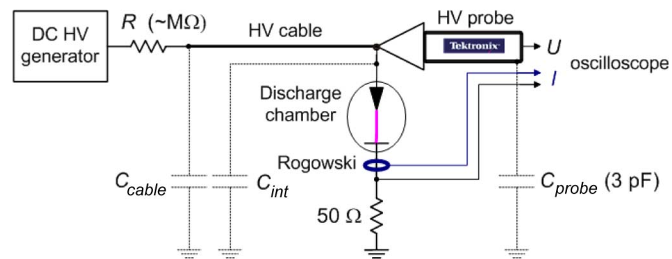

Fig. 1. Schematic of the electrical circuit of dc discharges.

that leads to a spark formation. During the streamer-to-spark transition, local gas heating in the streamer-induced channel decreases the gas density N, thus enhancing the reduced electric field E/N. Because E/N is the main parameter controlling the rate of electron-impact reactions, particularly ionization, this leads to enhanced ionization, resulting in a spark breakdown with an excessive current pulse [2]. Other mechanisms related to the accumulation of active particles changing the balance between the rates of generation and loss of electrons due to enhancement of detachment, stepwise and associative ionization, can take place as well [3]. In our case, the spark pulse current is limited by the following: 1) the ballast resistor R that drops voltage as the current increases and 2) the capacitance C between the electrodes that is small (on the order of 10 pF). Thus, even if a spark forms, it is only transient because the discharged energy is small (∼0.1–1 mJ). [C is a sum of the internal capacity of the discharge gap ($C_{\mathrm{int}} \sim 1$ pF) and the capacities of the HV cable ($C_{\mathrm{cable}} \approx 20$ pF) and the probe ($C_{\mathrm{probe}} = 3$ pF)]. After the pulse, C is recharged by a growing potential on the stressed electrode. As soon as C is recharged, it triggers a new pulse. This TS then becomes a repetitive streamer-to-spark transition discharge, with each spark pulse (∼1 A) being preceded by one or a sequence of streamer pulses [3]. The frequency of pulses is 0.5–5 kHz and increases with increasing applied voltage. Due to the very short pulse duration (∼100 ns) given by the small C and a limiting R, the plasma does not reach local thermal equilibrium conditions.

By setting the values of R and C (C can be set by the length of the HV cable or by filtering $C_{\mathrm{cable}} + C_{\mathrm{probe}}$ by a small resistor that is put very near the HV electrode), we can either obtain TS pulses and control their amplitude and frequency or attain a continuous discharge. This pulseless discharges typically appear after the spark pulse if $R \leq 2$ MΩ and $f > 5$ kHz. The voltage drops to a certain small value, which is high enough though to sustain a small current (approximately in milliamperes). It has the character of a GD, with constant voltage and current (∼1–10 mA), a cathode fall

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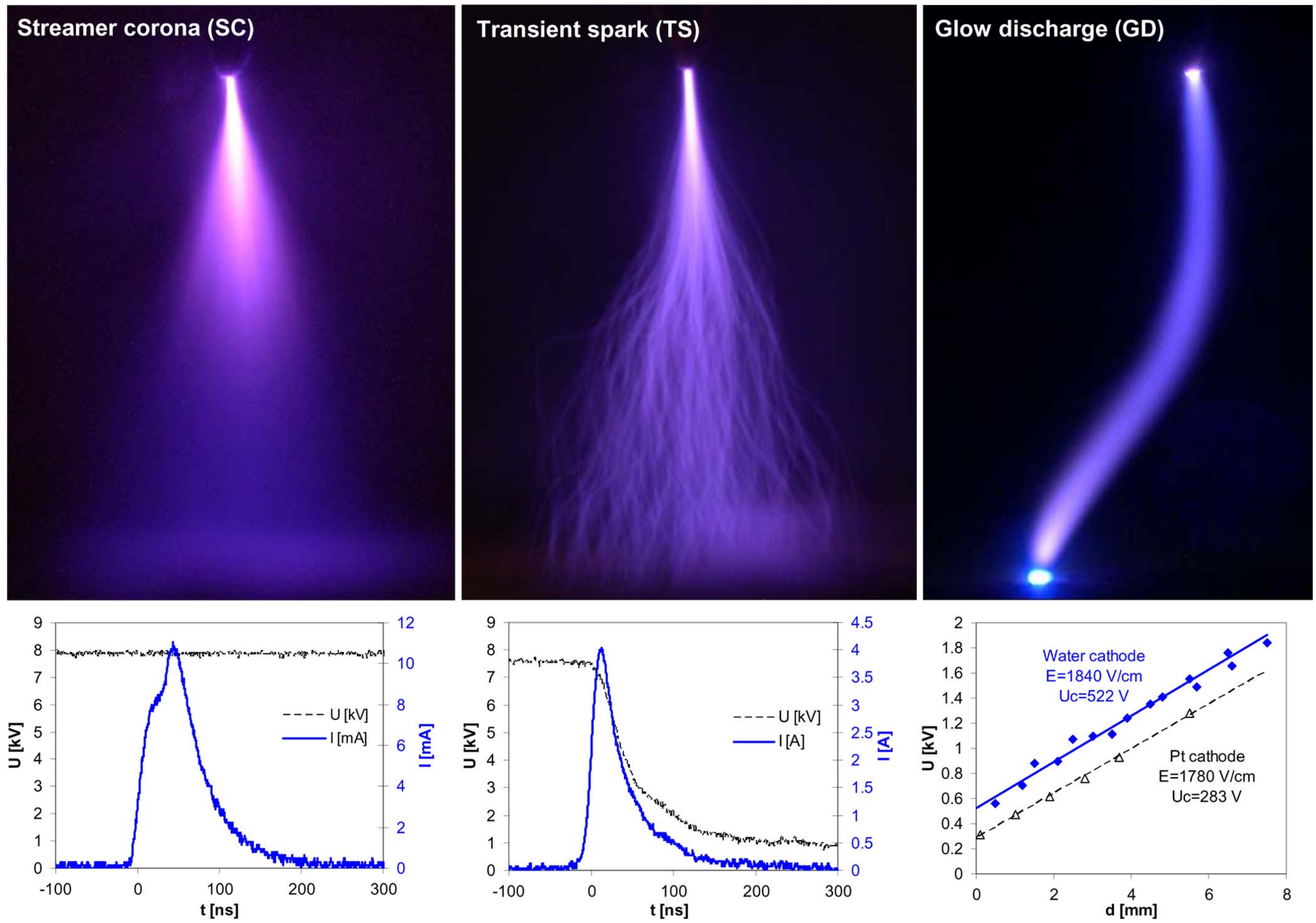

Fig. 2. Photographs of SC, TS, and GD discharges in positive needle–water gap of 6 mm, cathode ∼2 mm below the water level, and aperture f/4.8. SC: 14 kHz, $I_{\max} = 12$ mA, $U = 8$ kV, $R = 3.5$ MΩ, exposure: 4 s, and ISO 100. TS: 1.2 kHz, $I_{\max} = 4$ A, $U = 7.5$ kV, $R = 3.5$ MΩ, exposure: 1/4 s, and ISO 200. GD: $I = 6$ mA, $U = 1.2$ kV, $R = 590$ kΩ, exposure: 1/30 s, and ISO 400. Typical U and I waveforms of SC and TS, and voltage-on-gap distance dependence of GD (5 mA) in needle–water versus needle–Pt gap. Corresponding electric fields E and cathode falls U_C are indicated.

of several hundreds of volts, and a luminous positive column that occupies most of the gap space. Its current–voltage characteristic is descending. GD is described in more detail in [4]. Its current is determined by the applied voltage and the value of R that prevents its transition back to TS but allows a small current. When its current is progressively increased to ∼100–1000 mA, the GD smoothly transitions towards a continuous arc.

Optical emission spectroscopy was used to determine rotational (i.e., gas) and vibrational temperatures and to identify the excited species. Details on this technique, the optical system used, and the temperature measurements from emission spectra can be found in [5]. The gas temperatures measured in SC, TS, and GD with the plane electrode submerged in water were 350 ± 50 K, 550 ± 100 K, and 1900 ± 100 K, respectively. Without water, the same discharges at the same parameters gave slightly higher temperatures, particularly in GD. With water, a portion of thermal energy was probably spent for its evaporation and dissociation, and so the plasma was colder. The electrical discharge parameters of SC and TS with or without water were very similar. In GD, the voltage was higher with a water cathode than with metal cathodes due to the higher cathode fall U_C (∼500 versus ∼300 V) for the same I and gap length (Fig. 2, right). The resistance of the water layer causes only a ∼10 V drop, so the high U_C is probably due to water vapor increasing the electron attachment in the cathode region.

The measured temperatures and emission spectra indicate that the discharges generate nonequilibrium plasmas with various excited species and molecular and atomic radicals such as N_2(C), N_2(B), N_2(A), N_2^+(B), OH(A), H, O, and N. Such plasmas induce chemical and biological effects that are important for applications, such as volatile organic compound abatement from flue gases and water or biodecontamination [5].

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