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Impedance-stabilized positive corona discharge and its decontamination properties

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Abstract. The point-to-plane DC corona discharge in air at atmospheric pressure was stabilized by a serially connected ballast impedance. The ballast impedance was implemented by a resistor–capacitor group connected in parallel. In the case of connecting the serial impedance into the electric circuit of a negative corona, the transition into a spark takes place at parameters similar to those of a non-stabilized discharge. In contrast, in the case of a positive corona, the discharge does not undergo a transition into a spark, but rather into a mode of periodic streamers. We measured the bactericidal effect of the stabilized discharge. The experiments showed that after a 2-minute exposure the quantity of surviving bacteria decreased from 95% for a non-stabilized discharge down to 5% for a stabilized one.

1. Introduction

Non-thermal plasma decontamination is among the intensively studied techniques described in a large number of publications, e.g. [1, 2]. The advantage of using non-thermal plasma for decontamination purposes is that most of the energy introduced into the system is used mainly for ionization, dissociation, excitation, creation of charged or reactive species, etc. Therefore, non-thermal plasma decontamination is useful on heat sensitive surfaces since it does not degrade the material and no energy is wasted for heating. The operation expenses are thus much lower in comparison with the classic means of thermal decontamination, such as autoclaving. Due to its easy implementation, the corona discharge is a very suitable source of non-thermal plasma. Even though the mechanisms of positive and negative corona discharge formation are different, increasing the discharge voltage leads in both cases inevitably to a transition into a spark, which is the basic limitation of the corona discharge [3]. This breakdown occurs at a very low discharge currents (up to hundreds µA depending on the gap width and discharge polarity). Stabilization is, therefore, required in order to achieve higher current and power values thereby increasing the efficiency of future applications.

This article deals with the stabilization by means of an in-series impedance implemented by the parallel connection of a resistor and a capacitor.

We achieved a streamer mode of operation by choosing a proper impedance value. This mode is called “flashing corona” in the literature [5] (even though it has not been thoroughly described) and

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consists of periodical current pulses – streamer channels. These thin weakly-ionized plasma channels [5, 6] grow in the gap between the electrodes thus making a conductive connection. This connection may increase the electric current significantly and cause a streamer-to-spark transition. In comparison with the spark, the streamer channel provides a relatively low current of about 10 mA [5], while a current of $10^3 – 10^5$ A with current density $j = 10^4$ A·cm$^{-2}$ flows through the spark channel [5,6]. This is sufficient to heat up significantly the surrounding gas so that the spark discharge tends to generate thermal plasma while the streamer remains almost at room temperature [4].

In order to find a suitable combination, several capacitance-resistance values were tested and the current, power and discharge stability achievable were measured. In the second part of this work, the decontamination properties of the discharges investigated were compared; finally, the optimal parameters of the discharge and of the ballast impedance are presented with respect to the decontamination energy yield and efficiency.

2. Experimental arrangement

The experimental setup is shown in figure 1. The corona discharge in ambient air was formed by using a DC high-voltage power source (DC HVPS) (current range 0 – 350 μA, voltage range 0 – 25 kV). The point electrode consisted of a hypodermic needle (N). It was fixed into a micrometric screw and placed over the plane electrode - water surface (W). The stabilizing impedance consisting of a parallel R–C combination was connected serially into the circuit. The resistance values were varied between 4 and 10 MΩ, those of the capacitance, between 0 and 100 pF. The voltage drop on the stabilizing impedance $U_z$ and its time dependence were measured using a voltmeter and an oscilloscope connected through a high-voltage probe (HVP) (HVP–40, 1:1000, max. 40 kV DC). The DC HVPS was equipped by built-in volt- and ammeters. To minimize the parasitic capacitance and inductance in the circuit, the cables were shortened to the smallest possible lengths. The discharge stabilization by the in-series impedance was tested for positive as well as negative point electrode polarity. During all experiments, the distance between the tip of the needle and the water surface was set at $d = 4$ mm. The decontamination properties of stabilized and of non-stabilized discharges were tested on cultures of the Escherichia coli bacteria. One ml of water suspension of these bacteria was placed into a dish with diameter of 2 cm and depth of 1 cm thus forming a plane electrode as in the previous experiments. The suspension samples were exposed to a positive or negative corona discharge and, after appropriate dilution, were cultivated overnight on the surface of a Mueller-Hilton cultivation medium. Finally, the number of colonies grown was counted.

3. Experimental results and discussion

3.1. Discharge stabilization

In the case of a positive corona, the inclusion of a suitable impedance increased the discharge current by an order of magnitude without a transition into a spark taking place. Furthermore, this discharge did not undergo a transition into a spark, but rather into a periodic streamer mode. In contrast, in the case of a negative corona, the in-series impedance did not affect significantly the discharge current or the discharge mode. Examples of V-A characteristics of non-stabilized and stabilized positive and negative corona discharges for one typical stabilizing impedance are shown in figure 2.

It can be seen that for a non-stabilized positive discharge the current slowly increases with the discharge voltage. A transition into spark occurs at values of approximately $U = 6.2$ kV and $I = 25$ μA.
In contrast, for a stabilized discharge, the current increases with the discharge voltage rapidly up to values of $U = 5 \text{kV}$ and $I = 80 \mu\text{A}$. At this point, a qualitative change occurs of the discharge mode. The discharge transits into a pulsed streamer mode (values of around $U = 4 \text{kV}$, slowly decreasing, and $I$ between 210 and 340 $\mu\text{A}$) and does not change into a spark. The streamer frequency as measured by the oscilloscope was in the range from 800 to 2500 Hz and increased with the current. Current values over $I = 350 \mu\text{A}$ could not be measured due to the voltage and current limits of the high-voltage supply used.

In the case of negative corona discharges, the V-A characteristics were similar. The stabilized corona underwent a transition into a spark at slightly higher values. It is interesting to note that the plateau measured in the case of a non-stabilized discharge at current values near $I = 110 \mu\text{A}$ was shifted to the higher values. This is probably related to a change in the discharge mechanism. However, studying the origin of this phenomenon was not among the aims of this work.

3.2. Decontamination

Typical time dependencies of the decontamination efficiency $\eta$ (amount of inactivated bacteria divided by amount of bacteria before exposition) are shown in figure 3. Due to the very similar electrical properties of the stabilized and non-stabilized negative discharges, the efficiency is almost the same and after 3 minutes of exposure increases up to around 60%. In contrast, the decontamination efficiencies of the stabilized and non-stabilized positive discharges differ as markedly as their electrical properties. The stabilized corona efficiency increases up to almost 100% after 3 minutes.
exposition, while in the case of non-stabilized one the efficiency after 3 minutes is immeasurable or is lower than 10 %. The decontamination efficiency slightly increases with the ballast impedance capacitance and unexpectedly decreases with the discharge power (figure 3). This may be explained by the voltage waveforms as seen on the oscilloscope (figure 4). Assuming that the waveform of the voltage across the impedance correlates with the waveform of the current in the discharge, one could conclude that the frequency decreases as the capacitance of the ballast impedance is raised; thus, the current pulse width increases. The decontamination efficiency as a function of the capacitance is shown in figure 5. The decontamination efficiency increases with the capacitance; it is higher, almost 100%, for the value of $C = 75 \, \text{pF}$ and is and does not depend on the resistance used.

**Figure 5.** Decontamination efficiencies for stabilized positive corona as a function of the capacitance included in the ballast impedance. $I = 300 \, \mu\text{A}$, $t = 45 \, \text{s}$.

**Figure 6.** Energy yield of decontamination for $t = 3 \, \text{min}$.

It is clear that the positive corona discharge is more efficient than the negative one. This proposition is supported by the following calculations. Figure 6 presents the energy yields of decontamination for several discharges. These are calculated as the ratio of the percentage of inactivated bacteria to the total energy delivered by the power supply for 3 minutes (necessary to inactivate almost all bacteria). The discharge current was set at 0.2 mA; in the case of negative corona there was no need to use ballast impedance, while the ballast impedance parameters in the case of positive polarity are shown in the figure 6. Although in the case of positive polarity some part of energy is lost in the ballast impedance, it is clear that the energy yield is almost twice as high as that of the negative corona.

4. **Conclusions**

By inserting a suitable in-series impedance, implemented by an R-C group connected in parallel, into the electrical circuit of a positive corona discharge we were able to prevent the discharge from undergoing a transition into a spark and obtained a periodic streamer mode. The discharge current was thus increased by a factor of nearly 13, with the further increase of the current being limited by the high-voltage power supply used only. This change in the discharge mode is illustrated by the V-A characteristics presented. For negative corona, the effect of the impedance on the current and power increase was not significant. However, a shift was observed of the plateau in the V-A characteristics in comparison with the non-stabilized case, which will be investigated in future studies.

By using suitable ballast impedance, the decontamination efficiency of the positive corona discharge reached almost 100 % after 3 minutes of exposure; in contrast, the negative corona discharge efficiency for the same exposure time was 60 % only. We found that the suitable ballast
impedance from the viewpoint of decontamination efficiency was capacitance $C = 75 \, \text{pF}$ and resistance $R = 6–10 \, \text{M} \Omega$. Moreover, the energy yield of the positive corona discharge was almost twice as high compared with the negative one. For the negative corona, the decontamination efficiency at the particular current was the same as that in the non-stabilized case.

References