Plasma based sterilization using new multipoint ignition accessory

Kiril Ivanov, Ivo Iliev, Serafim Tabakov

This article discusses the physical phenomenon of plasma and its basic principles. The processes of the plasma generation as well as the various particles that are produced with it are described. An overview of the effects of each generated during plasma particle on the processes of sterilization and disinfection is made. A solution for the mechanical part of plasma sterilizer accessory is presented. It is suggested a possible operating principle of such a sterilizer, how to control the mechanical part of the shown sterilizer. The main topic of the article is based on a series of experiments. The results of these experiments will evaluate the effect of each RF signal parameter on the plasma generated by the same signal.

Keywords – Accessory, Disinfection, Plasma, Sterilization.

Плазмена стерилизация, чрез нов многоточков аксесоар (Кирил Иванов, Иво Илиев, Серафим Табаков). *В настоящата статия е разгледано физичното явление плазма и неговите основни принципи. Описани са процеса на генериране на плазмата и различните частици, които се получават при него. Направен е кратък обзор на въздействието на плазмата, върху процесите на стерилизация и дезинфекция. Показано е примерно решение за механичен накрайник за плазмен стерилизатор. Предложен е възможен принцип на работа и управление на механичната част от показания стерилизатор. Представени са редица експерименти, чиято цел е да се оцени въздействието на различните параметри на изходен високо-честотен сигнал върху плазмата генерирана с негова помощ.*

Disinfection and sterilization are both decontamination processes. While disinfection is the process of eliminating or reducing harmful microorganisms from inanimate objects and surfaces, sterilization is the process of killing all microorganisms. Sterilization also destroys the spores of various organisms present on surfaces, in liquids, in medication or in compounds such as biological culture media. Such "extreme" forms of decontamination are needed during surgery or in environments like industrial, laboratory or hospital. In everyday life it is more practical to use disinfection [12].

One newly used methods for sterilization and disinfection is based on the use of plasma and plasma products. Plasma is often called the "Fourth State of Matter". Although found in virtually every home and business, gas plasma is not well known. The term plasma was first introduced by chemist Irving Langmuir in the 1920s. He proposed the following description: “A plasma is a quasi-neutral gas consisting of positively and negatively charged particles (usually ions and electrons) which are subject to electric, magnetic and other forces, and which exhibit collective behavior”.

Plasma can be simply considered as a gas of charged particles. These charged particles are negatively charged electrons and highly charged positive ions, being created by heating a gas or by subjecting gas to a strong electromagnetic field. However, true plasma production is from the distinct separation of these ions and electrons that produces an electric field, which in turn, produces electric currents and magnetic fields [2].

A significant number of highly charged particles together make plasma electrically conductive so that it responds strongly to electromagnetic fields [3].

Depending of the temperature, there are two types of plasma – high and low temperature plasma. High temperature plasma is more often on the Earth, most often as a lightning [10], [11].

Low temperature plasma is used for surface etching, disinfection, sterilization etc. It is mostly created by ionization of gases in vacuum or low pressure environment, inside chambers with controlled environment in them – atmospheric gases are absent or have very low concentration.

Brief overview of recent research plasma-based sterilization/decontamination methods is given [1], [4].

Plasma-based sterilization/decontamination.

Biological materials can be exposed to plasma in two different methods: (1) "direct exposure" and (2) "remote exposure". "Direct exposure" is when the sample to be treated is in direct contact with the plasma [13]. All plasma-generated agents, including charged particles, are in contact with the sample. In the "remote exposure" method, the sample is placed at a distance from the plasma volume or in an adjacent chamber. In this configuration, the amount of heat transmitted to the sample is reduced. Charged particles do not play a role since they recombine before reaching the sample, and many of the short-lived neutral reactive species also do not reach the sample. In the following section contribution of the four main inactivation factors of a non-equilibrium high-pressure air plasma are reviewed.

Heat: Heat-based sterilization methods use either moist heat or dry heat. In the case of moist heat, such as autoclave, a high temperature and high pressure is used. Dry heat sterilization requires temperatures close to 170˜ and treatment times of about 1h.

UV Radiation: UV radiation in the 200-300nm wavelength range with doses of several mW·s/cm^2 causes lethal damage to cells. This effect is strongest for UV light at 285nm wavelength. Amongst UV effects on cells of bacteria is the dimerization of thymine bases in their DNA strands. This inhibits the ability of the bacteria to replicate properly [6], [8].

Charged particles: Charged particles play a very significant role in the rupture of the outer membrane of bacterial cells. Electrostatic force caused by charge accumulation of the outer surface of the cell membrane could overcome the tensile strength of the membrane and cause its rupture.

When charged, a body of the size of a bacterial cell (in the µm range) experiences an outward electrostatic force because each charge is subjected to the repulsive forces of all the similar changes accumulated on the cell surface. This force is proportional to the square of the charging potential, Φ, and inversely proportional to the square of the radius of the curvature of the surface, ***r***. Therefore, the smaller the radius of curvature the stronger the electrostatic force. The charging potential Φ depends on the ratio of the ion mass to the electron mass. So gases with larger atomic mass lead to higher electrostatic forces [7]. Based on this the condition for membrane disruption is:

$$(1)\quad |\Phi| > 0.2 \cdot (r \cdot \Delta)^{1/2} \cdot F_t^{1/2}$$

where r is the radius of the curvature, Δ is the thickness of the membrane, and F_t its tensile strength [5], [9].

Reactive Species: In high-pressure non-equilibrium plasma discharges, reactive species are generated through various collisional pathways, such as electron impact excitation and dissociation. Reactive species play an important role in all plasma-surface interactions. Air plasmas, for example, are excellent sources of reactive oxygen-based and nitrogen-based species, such as O, O_2, O_3, OH, NO, NO_2, etc.

Disinfection/Sterilization accessory proposal

Based on the information above a new disinfection/sterilization accessory could be designed. For the accessory is important to define whether the plasma is in direct contact to the treated surface or not (direct exposure or remote exposure method). Since the sterilization/disinfection effect of the heat is proven, the appropriate method should be with direct exposure. Considering the relation between plasma spot, energy consumption and generated temperature, we propose a conception for accessory (*Fig. 1*) including many small plasmas that will be ignited in series to form one big plasma spot.

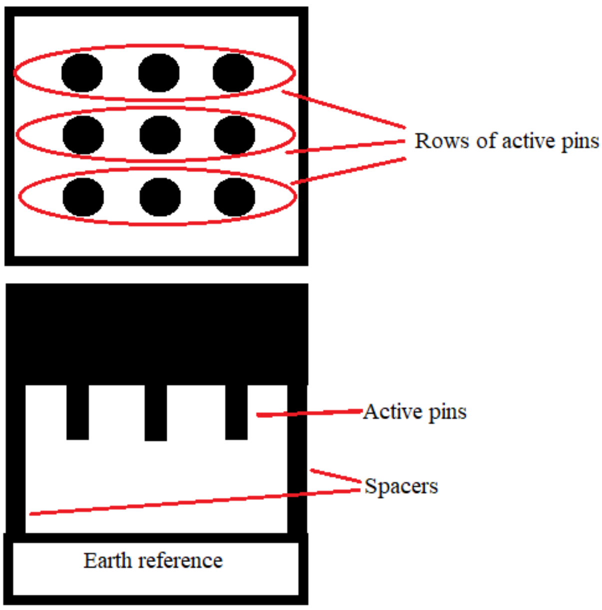

Fig. 1. Example structure for Plasma based sterilization accessory.

Structure like this should have as much as possible active electrodes (pins). Each electrode will create plasma to the treated surface. This surface could be referenced to earth or isolated. Electrodes should be activated in some series to create "moving" plasma along the accessory. This ignition sequence could be electrically or mechanically controlled. The so called spacer guarantees the stable (not changing) distance between active pins and surface. If the distance is always same, the energy delivered by the plasma for 1s (or for some other predefined period) will be constant. This means that the heat, the UV light and the charged particles generated for the respective period will be constant. This way the device will guarantee the same behavior during every procedure. To determine the length of the spacer the ignition distance in various conditions should be measured.

Ignition distance measurements

Ignition distance is the distance between the active and return electrodes, when the plasma is stable. In addition, one more parameter should be taken into consideration – strimmer length. This is the minimum distance between the active electrode and the treated surface when the ionization of the medium gas medium for the plasma is visible.

To perform the tests described below in the article, a special device is used. It is based on existing RF technology used in electrosurgical equipment. Important feature of this device is the capability to deliver controlled gas flow to the working area. Any type of gas, stored in a tank under pressure, could be used. The combination of RF output signal and delivered gas is the foundation for plasma generation. Test setup used for the next experiments is shown on *Fig. 2*.

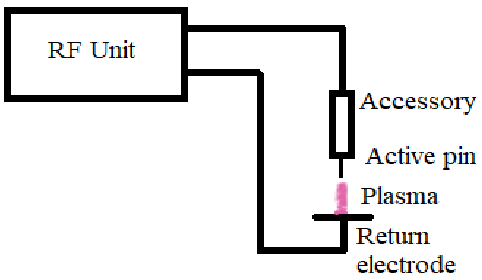

Fig. 2. Test set-up used for performing following experiments.

The device (RF Unit) has built in sensors for measuring real time RMS (Root Mean Square) Voltage and RMS Current. Based on the measurements of these sensors and on the internal schematic of the device, following parameters are controlled:

- Maximum RMS Voltage – output voltage can be controlled from 0V to 1200V;
- Maximum RMS Current – output current can be controlled from 0A to 1.6A;
- Output power – calculated based on the voltage and current measurements. Module could deliver up to 100W output power;
- Frequency – output signal frequency can be selected in the range from 320kHz to 500kHz;
- Gas flow – gas delivered to the working area can be adjusted in the range from 1slpm to 5slpm ("slpm"- Standard Liter Per Minute). Here should be noted that the gas used in the following experiments is helium.

Special software developed for this module controls all output signal parameters during the tests.

Maximum output RMS Current: Purpose of the first test was to evaluate the effect of the maximum output RMS current on the ignition distance and strimmer length. In this test all other parameters were constant:

- Maximum RMS Voltage – 600V;
- Frequency – 336.13kHz;
- Duty cycle – 4 ON pulses, 12 OFF pulses;
- Gas flow – 4slpm.

Results from the experiment are shown on *Fig. 3*.

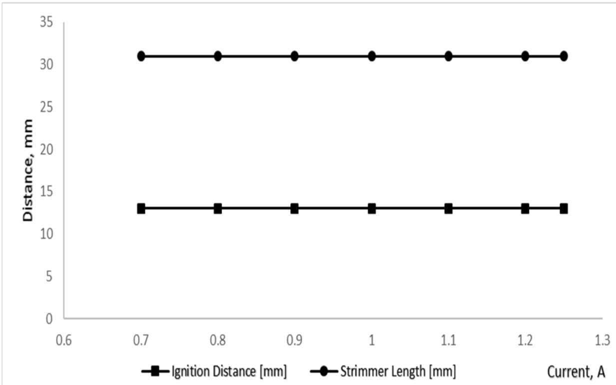

Fig. 3. Ignition distance and strimmer length depending on the maximum output RMS current.

In the focus of next experiment was the evaluation of interdependency between RMS current and plasma impedance when the ignition distance and the strimmer length are constant. Results are shown on *Fig. 4*.

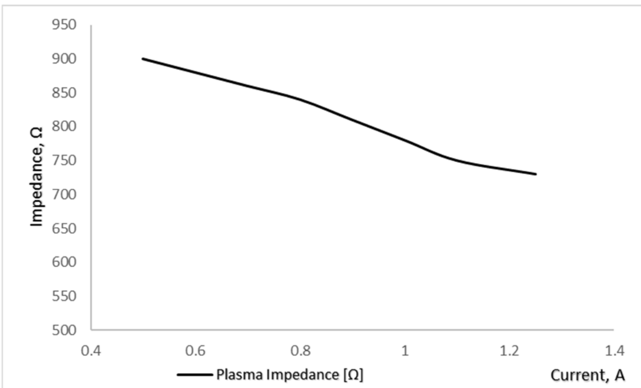

Fig. 4. Plasma impedance depending on the maximum output RMS current.

Maximum output RMS Voltage: To evaluate the effect of the maximum output RMS voltage on the ignition distance and strimmer length the next test was performed. In this test, other parameters are:

- Maximum RMS Current – 1.25A;
- Frequency – 336.13kHz;
- Duty cycle – 4 ON pulses, 12 OFF pulses;
- Gas flow – 5slpm.

Results are shown on *Fig. 5*.

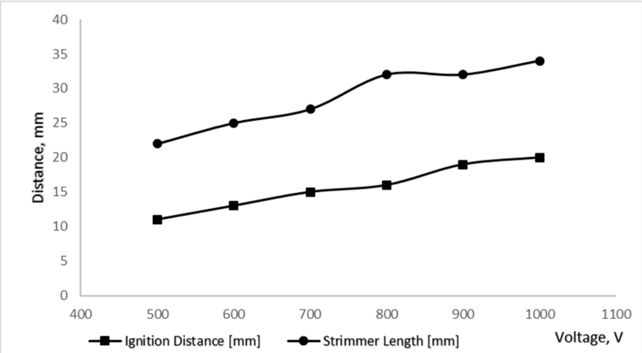

Fig. 5. Ignition distance and strimmer length depending on the maximum output RMS voltage.

Gas flow rate: Subject of the next test was the evaluation of ignition distance and strimmer length depending on the gas flow rate. In this test, other parameters are:

- Maximum RMS Current – 1.25A;
- Maximum RMS Voltage – 600V;
- Frequency – 336.13kHz;
- Duty cycle – 4 ON pulses, 12 OFF pulses.

Results are shown on *Fig. 6*.

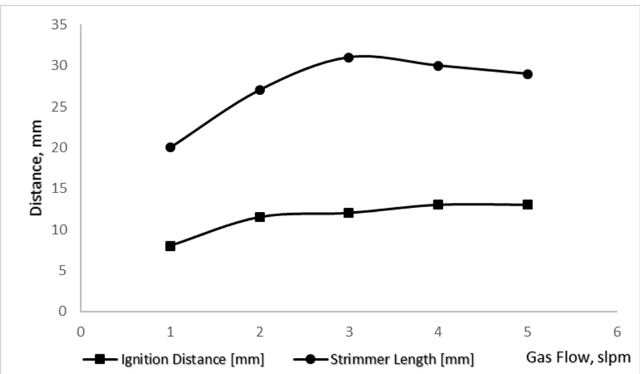

Fig. 6. Ignition distance and strimmer length depending on the gas flow rate.

Duty cycle: Subject of the next test was the evaluation of ignition distance and strimmer length depending on the duty cycle. In this test, other parameters are:

- Maximum RMS Current – 1.25A;
- Maximum RMS Voltage – 600V;
- Frequency – 336.13kHz;
- Gas Flow – 4slpm.

Results are shown on *Fig. 7*.

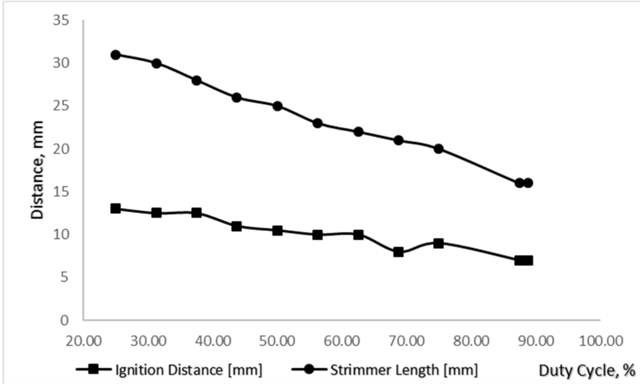

Fig. 7. Ignition distance and strimmer length depending on the duty cycle.

Frequency: For the next test the focus is on the evaluation of ignition distance and strimmer length depending on the output signal frequency. In this test, other parameters are:

- Maximum RMS Current – 1.25A;
- Maximum RMS Voltage – 600V;
- Duty cycle – 4 ON pulses, 12 OFF pulses;
- Gas Flow – 4slpm.

Results are shown on *Fig. 8*.

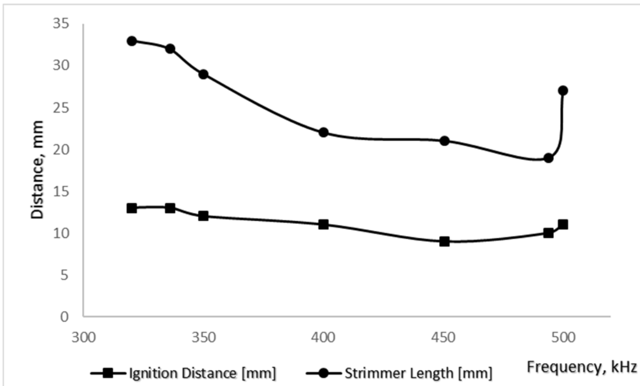

Fig. 8. Ignition distance and strimmer length depending on the output signal frequency.

To better understand the relation between the plasma parameters and the output signal frequency additional experiment is performed. In this experiment measurements on the plasma impedance depending on the output signal frequency are performed. Results are shown on *Fig. 9*.

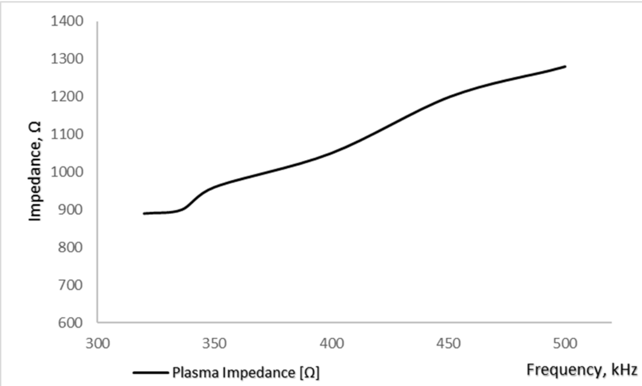

Fig. 9. Impedance of the plasma depending on the output signal frequency.

For further evaluation of the influence of the output signal frequency on the characteristics of the unit, output signal waveform is observed. This experiment is performed with disabled feedback control of the unit and over 2000Ω non-inductive load. This value is selected based on the measured impedance of the plasma at 10mm distance. This is the typical distance between the active electrode and the treated surface allowing to have enough visibility. First experiment is performed at set for approximately 20W output power. Second one is performed at set for approximately 40W.

Results from this test provides information about the correlation between the CF of the output signal and output power set and output signal frequency. Other parameters are:

- Duty cycle – 4 ON pulses, 12 OFF pulses;
- Gas Flow – 4slpm.

Crest factor is calculated using the formula:

$$CF = \frac{I_{PEAK}}{I_{RMS}},$$

where: I_{PEAK} is the maximum value of the current and I_{RMS} is the RMS value of the current.

Results are shown on *Fig. 10*.

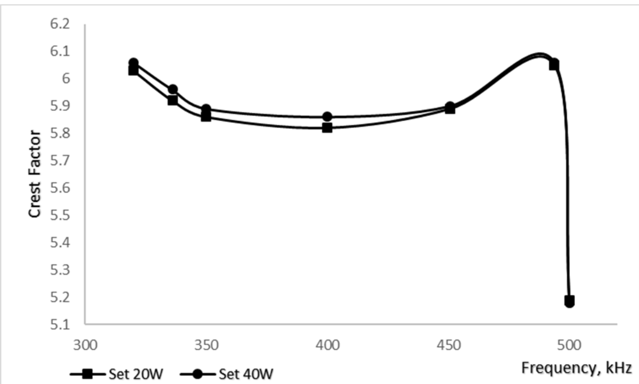

Fig. 10. Calculated CF (crest factor) of the output signal depending on the frequency.

Above results proves that the CF depends on the frequency and doesn't depend on the output power.

To evaluate only the influence of the frequency (not the crest factor) on the ignition distance and the strimmer length, additional two tests are conducted. The RF device is set to deliver output signal with peak-to-peak voltage approx. V_{PP}=5.00kV and for the second test with RMS voltage approx. V_{RMS}=700V. Other set parameters are:

- Duty cycle – 4 ON pulses, 12 OFF pulses;
- Gas Flow – 4slpm;
- OPEN LOOP – ON;
- SMPS Range – ON;
- V_{PP} – 5.00kV;
- V_{RMS} – 700V.

Results are shown on *Fig. 11* and *Fig. 12.*

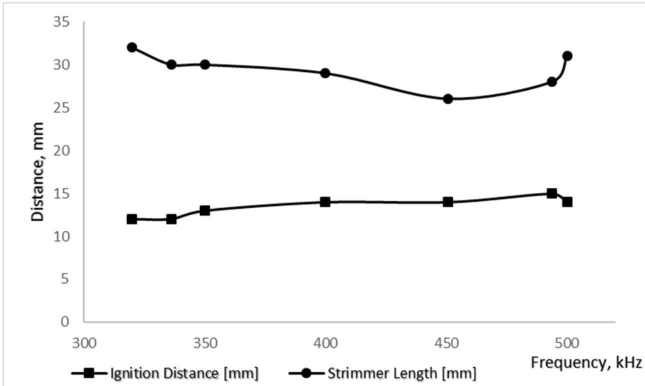

Fig. 11. Ignition distance and strimmer length depending on the frequency at V_{PP} 5kV.

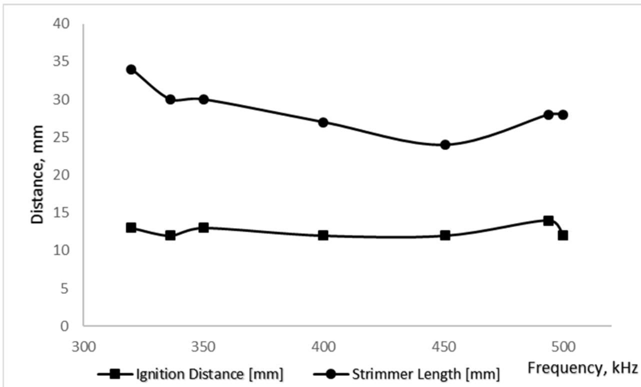

Fig. 12. Ignition distance and strimmer length depending on the frequency at V_{RMS} 700V.

Results interpretation

Based on all of the data presented in previous section (Ignition distance and Strimmer length) some conclusions are obtained:

- Increasing the maximum RMS current does not affect the ignition distance and strimmer length.

This was expected result because these two parameters are mostly affected by the ionization of the medium gas, which depends mostly on the peak-to-peak voltage of the output RF signal. However increasing the RMS current flowing thru the plasma reduces the impedance of the plasma beam. The higher the RMS current is the more charged particles are induced in the plasma beam.

- Increasing the maximum RMS voltage of the output RF signal increases both the ignition distance and the strimmer length of the plasma. This is caused by the better ionization of the medium gas, because of the increased peak-to-peak voltage of the output signal.
- Increasing the duty cycle of the output signal is leading to decrease of both the ignition distance and strimmer length. The increase of the duty cycle (while the RMS of the voltage is the same) leads to decrease of the peak-to-peak. As already proven a decrease in the peak-to-peak value is decreasing in both ignition distance and strimmer length.
- Gas Flow is the first parameter of the plasma that shows some irregularity in the test results. As visible from the results the increase of the gas flow is leading to increase of the ignition distance and strimmer length until some a specific point. After that, the quantity of the medium gas molecules become too high to be ionized and the flow is able to cool down the ionized gas, leading to reduced ignition distance and strimmer length.

All results from the tests performed by changing the output signal frequency are not consistent. It could be conclude that the frequency of the output signal has very strong influence over the parameters of the plasma. In addition, the frequency is affecting the parameters of the final output stage of the RF signal generator. These effects should be subject to other experiments.

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[13] PJ - bench top plasma unit, http://www.astp.com/plasma-pj

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