Surface-wave-sustained plasma torch for water treatment

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Abstract. In this study the effects of water treatment by surface-wave-sustained plasma torch at 2.45 GHz are studied. Changes in two directions are obtained: (i) changes of the plasma characteristics during the interaction with the water; (ii) water physical and chemical characteristics modification as a result of the plasma treatment. In addition, deactivation of Gram positive and Gram negative bacteria in suspension are registered. A number of charged and excited particles from the plasma interact with the water. As a result the water chemical and physical characteristics such as the water conductivity, pH, H₂O₂ concentration are modified. It is observed that the effect depends on the treatment time, wave power, and volume of the treated liquid. At specific discharge conditions determined by the wave power, gas flow, discharge tube radius, thickness and permittivity, the surface-wave-sustained discharge (SWD) operating at atmospheric pressure in argon is strongly non-equilibrium with electron temperature Tₑ much higher than the temperature of the heavy particles (gas temperature T₉). It has been observed that SWD argon plasma with Tₑ close to the room temperature is able to produce H₂O₂ in the water with high efficiency at short exposure times (less than 60 sec). The H₂O₂ decomposition is strongly dependant on the temperature thus the low operating gas temperature is crucial for the H₂O₂ production efficiency. After scaling up the device, the observed effects can be applied for the waste water treatment in different facilities. The innovation will be useful especially for the treatment of waters and materials for medical application.

1. Introduction
Management of unacceptable bacterial presence and growth in different media, products and water can be ineffective, expensive, time consuming and not always applicable even by the contemporary control methods [1, 2]. Novel methods as plasma treatment of bacteria would be useful in such cases. The low temperature non-equilibrium plasmas have lots of advantages for such applications. Their active components are: electrons, ions, chemically active radicals and excited atoms, electric fields, UV radiation, heating (figure 1).
The plasma source for these investigations is surface-wave-sustained discharge produced in Argon at atmospheric pressure by surfatron type electromagnetic wave launcher operating at 2.45 GHz (plasma torch). A picture of the plasma torch device used in this pilot study is shown in figure 2.

This plasma is strongly non-equilibrium: the electron energy distribution function (EEDF) is non-Maxwellian and the temperature of the heavy particles (so called gas temperature \( T_g \)) is much lower than the electron temperature \( T_e \) defined as \( T_e = \frac{2}{3} <u> \) (\(<u>\) being the mean electron energy obtained by the actual EEDF):

\[
T_g \ll T_e.
\]

Usually for these plasmas \( T_g \approx 1\text{–}2 \text{ eV} \), and \( T_g \approx 1000\text{–}4000 \text{ K} \). In our case we have produced Argon plasma torch with \( T_g \) close to the room temperature. In this way the heating effect of the plasma is eliminated so that the plasma torch can be touched (figure 3) and can be used for treatment of temperature sensitive materials and even of living tissues.

2. Experimental investigation and results

2.1. Physicochemical plasma characteristics of plasma torch in contact with water

Two aspects of the plasma–liquid interaction have been investigated – on one hand the changes of the plasma characteristics and on the other the modification of the water properties. The plasma torch is
considered as plasma–air configuration. Working gas is Argon at atmospheric pressure. Discharge conditions are: plasma radius 0.05 cm, 0.1 cm and 0.15 cm sustained by surface wave of frequency 2.45 GHz; gas flow rate varying from 0.1 l/min up to 1 l/min. Treatment time during all the investigations is significantly short – less than a minute and the input wave power is in the range of 12 W to 40 W. The low gas temperature allows plasma to be in close contact to the treated water.

In the presence of water placed below the discharge the geometrical dimensions of the plasma change. They have been measured and compared to those without water at the same discharge conditions (wave power, gas flow and plasma radius).

![Image](image_url)

**Figure 4.** Plasma column length at internal tube diameter 3 mm and various input powers. Upper row – without water; lower row – with water below the torch.

In figure 4 the discharge in air without water at different input power (upper row) is put together with the same discharge when water is present at a fixed distance at the end of the discharge tube (lower row). In figure 5 the dependence of the plasma column length on the wave power is presented. This experiment confirms the well-known almost linear dependence of the SWD length on the wave power. New and surprising result is that when the water is present below the plasma torch its length is higher. For the tube with diameter 3 mm for all the discharge configurations the plasma torch is longer especially at higher power when water is placed below the plasma.

![Image](image_url)

**Figure 5.** Plasma column length as a function of the wave power at tube diameter 3 mm and different discharge conditions with and without water below the torch.

Estimation of the changes in the characteristic concentration of hydrogen peroxide in plasma treated liquids is done. The hydrogen peroxide concentrations have been measured in distilled water being in direct contact with the plasma. The surface-wave Argon plasma torch is produced in discharge tube with radius of 0.15 cm with gas flow 1 l/min. The characteristic concentration of hydrogen peroxide for different input power and different volume of treated liquid is measured immediately after the plasma treatment and 10 minutes after that in order to determine the time dependence of the presence of hydrogen peroxide. The H$_2$O$_2$ concentration at two treatment times (30
s and 60 s) and different wave power is presented in figure 6. As one can expect at higher wave power the H$_2$O$_2$ production is much higher even at shorter time (30 s) than at smaller wave power (figure 6, left). One can see that at smaller treated water volume the H$_2$O$_2$ concentration is higher (figure 6, right). This can be due to the fact that the water is not mixed during the treatment process but only the water surface is in contact with the plasma.

![Figure 6](image)

**Figure 6.** Concentration of H$_2$O$_2$ at different wave power, treatment time and water volume.

The hydrogen peroxide plays an important role in various biological, biomedical, environmental and wastewater treatments. It is one of the most powerful oxidizers, able to destroy organic contaminates which are ordinarily difficult to destroy, as well as inactivating cells of living organisms. This is the reason why its creation and concentration determination is so important.

### 2.2. SWD for bio-medical applications

We have experimentally tested the efficiency of nonthermal atmospheric pressure plasma torch in treatment of bacterial suspensions. The experimental set-up is shown in figure 7.

![Figure 7](image)

**Figure 7.** SWD treatment of bacterial suspension.

Only the surface of the suspension is treated by the plasma since at the low power used the plasma cannot penetrate inside the liquid and the liquid is not mixed during the treatment. The discharge conditions and the types of bacteria in the suspension are shown in the scheme in figure 8. The wave power is 20 W and the treatment time does not exceed 1 min.
Figure 8. Design of bio experiments.

Two model bacterial strains *Pseudomonas aureofaciens* AP-9 and *Brevibacillus laterosporus* BT-271 were used in experiments. *P. aureofaciens* AP-9 (current classification and phylogenetic affiliation – *P. chlororaphis*) is aerobic, Gram-negative, motile, polar-flagellated, rod-shaped bacterium. *Brevibacillus laterosporus* BT-271 is a rod-shaped, Gram-positive, endospore-forming bacterium. Gram-negative bacteria are considered to be more susceptible to plasma treatment than Gram-positive bacteria because of specific cell structure and composition [3–5]. Formation of endospores as extreme survival strategy of bacteria is another factor that can affect the end results at plasma treatment. The both strains were isolated from contaminated soils and had high proven potential for biodegradation of aromatic compounds [6]. This implies their possible application as special preparations for improvement of wastewater treatment processes.

Freeze-dried bacterial cultures were rehydrated and enriched in Nutrient Broth for achievement of average initial cell concentration of 10^8–10^9 cells/ml. The cell concentration was estimated by direct microscopic counting of bacterial cells in Bürker chamber (simple manual method for enumeration of average cell number by counting of cells in 80 squares – each with area 1/400 mm^2 and volume of sample 1/4 000 000 cm^3).

Plasma treatments are carried out in 35 ml volume of bacterial suspensions with different exposure time. Then bacterial suspensions were serially diluted and dispersed into the Nutrient agar in Petri dishes. The percentage of kill and log reductions were quantified by count of surviving colony forming units (CFU) after incubation at 37°C for 24 h. Each treatment and microbial analysis was repeated two or three times for reproducibility.

The results show a decreasing number of surviving cells with increase of treatment duration (figure 9). Figure 10 presents the logarithmic cell number reduction of the two bacterial strains as a function of plasma treatment time. A clear bactericidal effect of plasma treatment is observed. This effect depends on the treatment time but the type of bacteria also plays a specific role. For *Pseudomonas aureofaciens* AP-9 the inactivation effect is significant for short treatment time but the increasing of treatment time does not change it (the red columns in figure 10). The inactivation of the *Brevibacillus laterosporus* BT-271 depends stronger on the treatment time (the blue columns in figure 10). At this large treated volume (35 ml), short treatment times, and bacterial suspension with high cell density of 10^8–10^9 cells/ml only partial disinfection was registered, equal to 92-99 % inactivation of bacteria.
Figure 9. Survived colonies *Brevibacillus laterosporus* BT-271 at 10, 30 and 60 sec treatment of bacterial suspension with average initial number of 7.6×10^8 cells/ml.

Figure 10. CFU reduction curves for *Pseudomonas aureofaciens* AP-9 and *Brevibacillus laterosporus* BT 271 at 10, 30 and 60 sec treatment.

Results from SEM micrographs provide a proof for plasma treatment effect on the cell level (figure 11). The morphology of pseudomonad cells before and after plasma treatment is shown in the SEM micrographs, 15 000 magnification. The untreated cells of *Pseudomonas aureofaciens* AP-9 are ellipsoidal with average dimensions of 2 µm × 0.4 µm. At the 40 sec treatment, some cells are deformed; the cell surfaces are damaged and ruptured. With increase of plasma treatment duration, the deformations and damages of cells became more serious, a mass of debris and leakage is observed.

Figure 11. SEM pictures (scanning electron microscope JEOL JSM 5510) of: control of *Pseudomonas aureofaciens* AP-9 without plasma treatment (left), with 40 s treatment (middle) and with 50 s treatment (right).
3. Conclusion
In this study it has been observed that SWD plasma is able to efficiently inactivate bacteria at short exposure time less than 60 sec. The effect depends on the treatment time, volume of treated suspension and cell concentration. Although the suspension was not mixed during the treatment, the effect is noticeable. For Pseudomonas aureofaciens AP-9 the inactivation effect is significant for short treatment time but the increasing of treatment time does not change it. The inactivation of the Brevibacillus laterosporus BT-271 depends stronger on the treatment time.

After further investigations the effects of plasma on liquids can be applied for the water treatment in different facilities as a sufficient method for bacteria inactivation. The wide use of different microbial inoculants with expressed special characteristics (for example high biodegradation potential) as amendments in treatment of waters is a factor for increase of risk level from their survival in water. The plasma presents new opportunities for the better control of this unacceptable bacterial survival. The innovation also will be especially useful for the treatment of waters and materials for medical application. SWD plasma has the potential to be a cost effective, convenient and efficient method of sterilization.

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