

SIMULATION OF LONG-LIVED PLASMA PROCESS, CREATED BY THE IMPULSE DISCHARGE IN DROPLET ENVIRONMENT

Serge Olszewski¹, Waldemar Wójcik²

¹Taras Shevchenko National University of Kyiv, Radio Physics Faculty, ²Lublin University of Technology, Faculty of Electrical Engineering and Computer Science

Abstract. It was found that during the electric impulse discharge in droplet environment, created by ultrasound sputtering of water, the systems' volume process had different observable properties in comparison with simple impulse discharge. The hypothesis was proposed that this process is distributed correlated spark discharge between charged and uncharged fog drops during their approaching. According to physical model in hypothesis frame, 3D computer model was developed. The results of long-lived process simulation confirmed the proposed hypothesis.

Keywords: spark, droplet, plasma, ultrasound sputtering

SYMULACJA PROCESU PLAZMY DŁUGOTRWAŁEJ WYTWORZONEJ PRZEZ WYŁADOWANIE IMPULSOWE W OTOCZENIU MGŁY

Streszczenie. Stwierdzono, że w czasie wyładowania elektrycznego w środowisku utworzonym przez kropelki wody uzyskane w procesie rozpylania ultradźwiękowego, proces posiada inne obserwowalne właściwości, w porównaniu z prostym wyładowaniem. Zaproponowano hipotezę, że proces ten jest skorelowanym rozłożonym wyładowaniem między naładowanymi i obojętnymi kroplami mgły podczas ich zbliżania. Został opracowany komputerowy model 3D według modelu fizycznego w ramach hipotezy. Wyniki symulacji procesu potwierdzają proponowaną hipotezę.

Słowa kluczowe: iskra, kropla, plazma, napyłanie ultradźwiękowe

Introduction

Water is a valuable natural resource. With metabolic processes forming the base of human living, water plays an exclusive role in every aspect. The everyday human need for it is known to all. At the UN World Economic Forum (January 2008) held in Switzerland, has been claimed that the population of more than half of the world population will experience a shortage of clean water by 2025, and 75% by 2050. Methods based on plasma-chemical processes in the liquid-gas environments for water treatment and purification of highly polluted wastewater is among the most promising.

The one of methods of water treatment by plasma was investigated in experiments with spark discharge in droplet environment. It was found that during the electric impulse discharge in droplet environment, created by ultrasound sputtering of water, the systems' volume process had different observable properties in comparison with simple impulse discharge. The computer simulation model was used for more detail research of this system specificity.

The traditional modeling scheme of physical systems with multiple components is the using of physical model as the adapted to computer calculation system of equations. As a rule, this equations system describes the every standalone component of physical system and used for modeling of total system iteratively. When the property interval of these is large the physical model is built as the universal for all property intervals. But the traditional paradigm of modeling is kept. However when the conditions of validity are changed the many physical models are degenerated to more trivial model in mathematical aspect. If the system of equations is correct it will transformed to new more trivial system, because part of equations component will be zero. However the calculation time for this degenerated model don't changed practically. For modeling of a large ensemble of particles, for example to burning processes, it can be substantial unproductive timetable. As a rule the model with decreasing particles count and unavoidable loss of accuracy is used for this case. But the intellectual systems of decision-making can be alternative modeling method that gives an opportunity of simulation of systems with multiple components without of particle count decrease and loss of accuracy. This system saves time of calculation owing to the fact that oneself select optimal calculation scheme on the predefining criterion basis. The computer model with elements of systems of decision-making is attempted to use for simulation of experimentally detected long-lived plasma process in this work.

1. Experiment

The scheme of experimental setup and photo of researched effect are represented on fig 1. In this setup the distilled water – 4 where sprayed by ultrasound field and transform to mono-disperse fog – 10. The ultrasound field was created by quartz crystal – 8. The friction of ultrasound field was 800 Hz and acoustic power ~ 60 W. For initiate spark discharge between electrodes – 1, into it was inputted high voltage ~ 7 kV. The current of spark was measured by Rogowski loop. The value of current was ~ 1 kA.

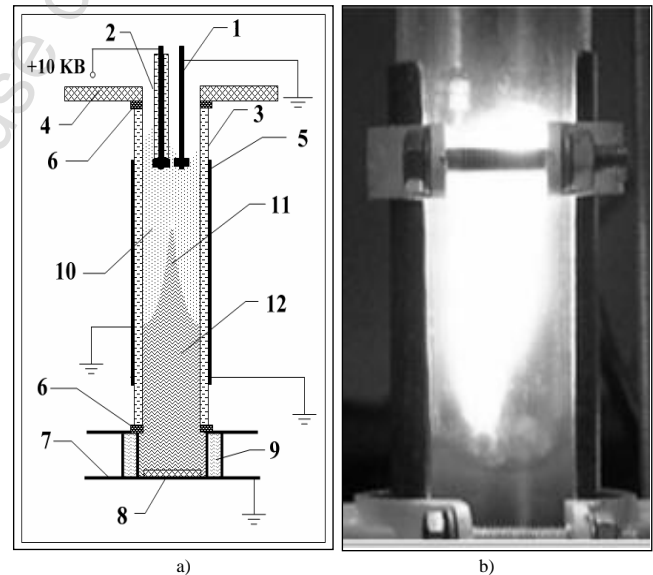


Fig. 1. Experimental setup: a) Long-lived volumes plasma process; b) 1 – metal electrodes, 2 – quartz insulator, 3 – quartz vessel, 4 – up flanges, 5 – side metal walls, 6 – rubber seals, 7 – ultrasonic sprayer, 8 – quartz piezocrystal, 9 – water cooler, 10 – ultrasonic fog, 11 – ultrasonic fountain, 12 – work liquid

It was found that during the electric impulse discharge in droplet environment, created by water sputtering, the systems' volume process is accompanied by the radiation with different spectral contents in comparison with simple impulse discharge. The characteristic time of this process is varied between 120 ÷ 533 ms for the length of impulse discharge current about ~ 10 μs.

The emission spectra of spark discharge and long-lived plasma process are shown in the fig. 2, 3 – appropriately.

The molecular spectral bands of hydroxyl are absent in the emission spectra of discharge, while intensive atomic lines of electrodes' material are present. On the contrary, emission spectral bands of hydroxyl are intensive, while atomic lines of electrodes' material are practically absent in case of long-lived process. Estimated electric current, which is flowing in system during the long-lived process, is about in 3 orders of magnitude smaller than discharge current. Estimated rate of radiation area boarder spreading is $\sim 0,5$ m/s. The comparative evaluation of impulse discharge and long-lived volumes process was represented in table 1.

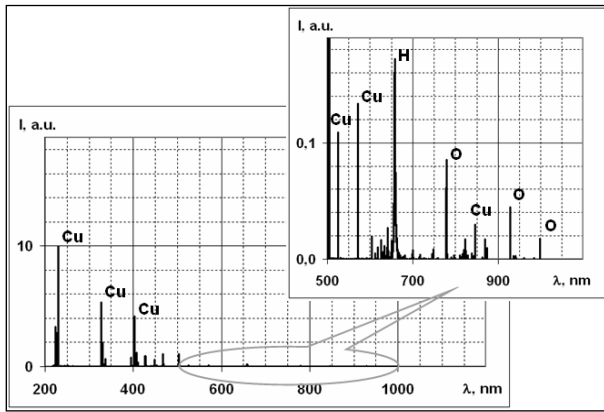


Fig. 2. Emission spectra of spark discharge

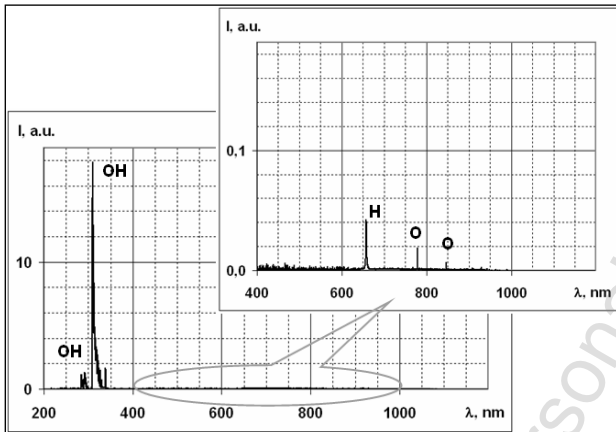


Fig. 3. Emission spectra of long-lived plasma process

Table 1. Comparative evaluation of impulse discharge and long-lived process

	Spark discharge	Gliding discharge	Long-lived process
Voltage	~ 7 kV	~ 7 kV	–
Current	$0,4 \div 1,5$ kA	$0,4 \div 1,5$ kA	< 150 mA
Glow duration	< 10 μ s	< 10 μ s	$120 \div 533$ ms
Localization	Near-electrode area	Inner surface of quartz vessel	Full volume
Characteristic dimension, mm	$1 \times 1 \times 7$	$1 \times 1 \times 50$	

2. Physical model

Statistical analysis of experimental data shows that the necessary condition of durable process appearing is obligatory presence water fog in the volume with discharge. The hypothesis was proposed, that durable process for given conditions is distributed correlated spark (**DCS**) discharge between charged and uncharged fog drops during their approaching. To verify this hypothesis, the approximate model of durable process was created. According to the model, fog drops localized in the area impulse discharge channel gain an electric charge due to their contact with

plasma. Due to the Brownian motion they are mixed in the volume with the uncharged fog drops. Chaotic motion of aerosol particles leads to the approaching of single drops on the lengths in order of magnitude of their radii. In the case of such approaching between the fog particles with different charges, or between charged and uncharged particles, the electric field appears with the magnitude that can be much larger (according to [3, 5]) than the one calculated using the Coulomb's law. Electric fields' value between the single particles is also related with self-consistent electric field, formed by the ensemble of charged drop, chaotically distributed in the working space. Spatial redistribution of charged particles in time is defined by the Langevin equation with the additional determinate force, which has an electrostatic nature:

$$\zeta_{tr}^x \frac{dx}{dt} = f_x(t) + F_x \quad (1)$$

where ζ_{tr}^x – drag coefficient for a ellipsoidal droplet, $f_x(t)$ – random force, F_x – external electrostatic force.

Evolution of electro conductive liquids' drops in strong electric fields can be realized in the following competitive ways:

- coagulation of particles with keeping of their charge with the increasing of characteristic size;
- break-up of particles into smaller particles with redistribution of a charge between them;
- electric charge loss as a result of corona discharge without changing of characteristic size;
- charge loss as a result of spark discharge between the neighboring particles.

More complicated evolution processes of the drops were not considered. An artificial incompleteness of presented set of processes is one of the approximate models' limitations.

According to [5], the drop can be split into the parts as a result of Rayleigh or Taylor instability. As far as Taylor instability depends on the outer electric field and can be developed even for the electro neutral drops, - in case of charged aerosol drops ensemble it is more probable. According to [6], charged liquid drop always acquires an ellipsoidal form. An instability criterion for ellipsoid drops is given by the inequality:

$$\frac{\epsilon_0 E_s^2 R}{4\alpha_s} \geq 1.54 \quad (2)$$

according to Taylor [4], where R – is the drops' radius, α_s – is coefficient of surface tension, E_s – is the value of outer electric field, ϵ_0 – absolute dielectric permittivity. The conditions of spark discharge ignition between the drops, according to [2], are defined by the electric field value in kV/cm:

$$E_s = 27.2(1 + 0.54/\sqrt{R}) \quad (3)$$

where R – radius of drops.

The conditions of spark breakdown require more intensity of the electric field, comparing to the case of drops' break-up according to the capillary surface instability of Taylors' criterion. In cases of quasi-static systems, spark breakdown between micro-drops of electro conductive liquid is low- probable. But according to [1] the characteristic time of cappilar instability development can be estimated as

$$\tau \sim R^2 \rho^{1/2} \alpha_s^{1/2} \quad (4)$$

where ρ – is liquids' density. This time range is more than in 6 orders of magnitude greater than the time range of spark discharge.

Hence, in dynamic systems the conditions can be realized when the electric field between neighbor drops can increase to the value enough for spark discharge ignition during period of time less then characteristic time of instability development. Such an increasing of the electric field can be provided either by rate of charged and uncharged drops approaching, or by the superposition of charged aerosol drops' self-consistent field and vortex electric field produced by the alternating current of spark discharge between neighbor pair of drops. The later mechanism is also a discharges' correlation factor between the approaching drops' pairs, because it relieve the breakdowns' conditions due to the photoelectric effect and charges' diffusion, and leads to the impulse increasing of the electric fields' value.

3. Simulation, results and discussion

According to presented physical model, 3D computer model was also developed. Due to the orbital symmetry of ellipsoidal drops, the number of dimensions can be reduced to 2D, so the working space was chosen more like the experiment only for two coordinates, and the third dimension was contracted in two orders of magnitude: $0,02 \times 2 \times 10$ cm. Fogs' density was $5 \times 10^3 \text{ cm}^{-3}$.

On the first step of calculation the ensemble of fog drops was created, with Gamma-distributed characteristic sizes and random coordinates inside the working space

$$n(a) = \frac{\mu^{\mu+1}}{\Gamma(\mu+1)} \frac{a^\mu}{r_m^{\mu+1}} \exp\left(-\mu \frac{a}{r_m}\right) \quad (5)$$

where $\Gamma(\mu+1)$ – gama-function, r_m – most probable drops radius, μ – half-width of distribution.

Initial velocities of particles were generated according to the Maxwellian distribution. For each N-th particle random charge was specified, where value $1/N$ was distributed in space according to Gaussian law. The fig. 4. illustrate the initial state of charged drops cloud.

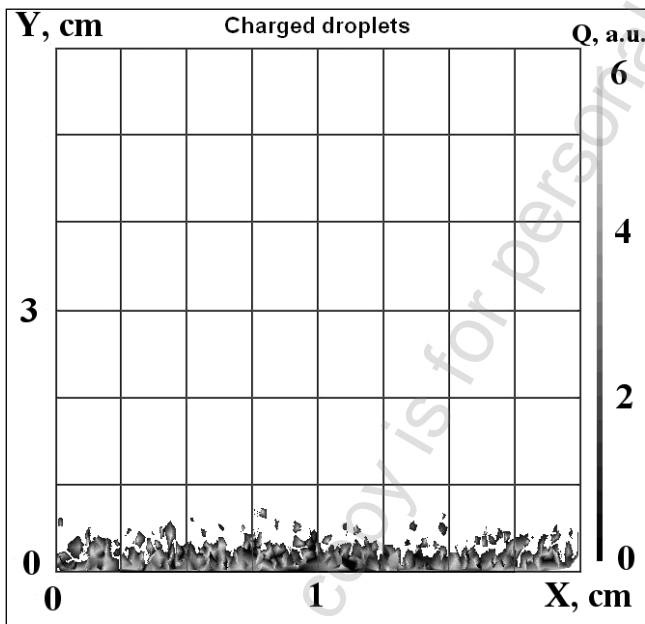


Fig. 4. Emission spectra of long-lived plasma process

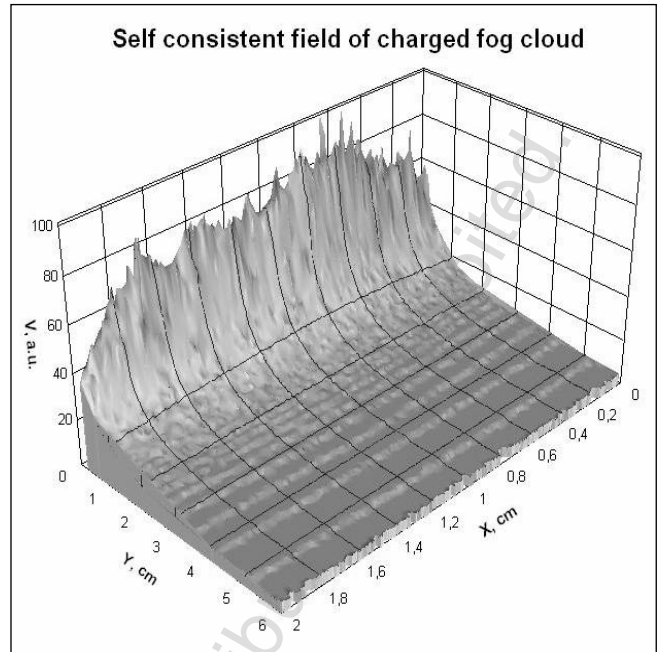


Fig. 5. Space distribution of potential of self-consistent field charged water fog cloud

On the next step self-consistent electric field in instant coordinate of each particle was calculated. The initial space distribution of potential of self-consistent field is shown in the fig. 5.

Then, for each pair of particles were calculated the correction to the electric fields' intensity [3, 6], criterion of electrical breakdown (3), and particles' break-up criterion (2). For the pairs of particles, which conform to the breakdown criterion, the breakdown impulse discharge was calculated. For the particles conform to the break-up criteria, the initial time point of instability development was fixated. If in the process of further evolution integral time, during which the break-up criteria is fulfilled, exceeded the time of instability development, such pair of particles was replaced by the ensemble of particles with characteristic sizes and integral charge according to [4]. For the particles conform to the criterion of corona discharge:

$$\begin{cases} \tau_{approach} \leq R^2 \rho^{1/2} \alpha_s^{1/2} \\ E_s \geq 50kV \\ r \geq 10R \end{cases} \quad (6)$$

where, the losses of charge due to the discharge current during the time step were calculated. The pair of particles, approached at the distance equal to the sum of their radii, was replaced by the one particle with the integral volume and charge. On the next step, the Langevin equation (1) was numerically solved for each particle, and the next step of particles ensemble spatial evolution was obtained. After that, iteration was repeated. Calculations stopped when the linear velocity of glow boundary of DCS-discharges area was formed.

As simulation result it was calculated how the areas that contained multiple spark discharges between drops are propagated in space. The evolution of simulated DCS-discharge is shown in the fig. 6.

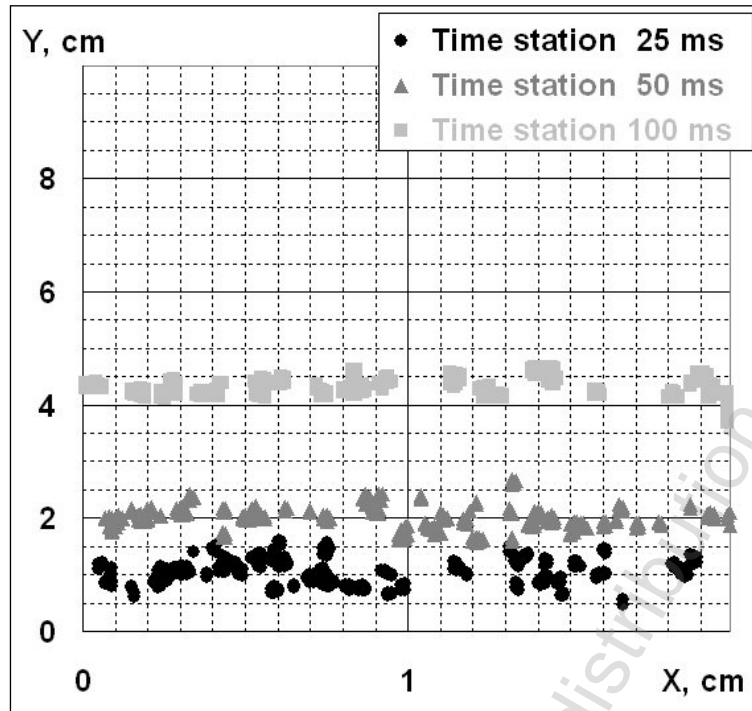


Fig. 6. Space distribution of areas that contained pairs of drops with spark discharges between them

This evolution is represented by space distribution of spark current in different time stations. The black points correspond to **DCS**-discharge state after 25 ms from charged cloud created. The dark grey points correspond to time station 50 ms and light-grey points – 100 ms. Calculated rate of **DCS**-discharge area boundary spreading is $\sim 0,4 \text{ m/s}^{-1}$. This result is conformed to experimental measured values. The mean radius of drops that support **DCS**-discharge is $\sim 0.8\text{--}1\mu\text{m}$. For drops size $\geq 10 \mu\text{m}$ the atomization probability is greater than probability of spark breakdown, because for this case drops has smaller mean velocity and capillary instability have time to progress. For drops size $\leq 0.5 \mu\text{m}$ the probability of lost charge in corona discharge is greater than probabilities of remainder elementary acts of the drops state transform.

The increase of self-consistent field value reduce the probability of spark breakdown, because enhance a conditions of capillary instability. However the field gradient enhances conditions of spark breakdown for sufficiently rapid drops. On periphery of charged fog cloud the gradient of self-consistent field is opposite mainly to electrical field increase during drops approach. It is right for charged drops that are moved from charged cloud to periphery. But chaotic pattern of drops move provides a grate drops ensemble with velocity that oriented to self-consistent field gradient increase. It is this ensemble is main source of **DCS**-discharge existence.

4. Conclusions

Comparison of calculation results with the results of previous experiments gives the following conclusions:

- In the frame of proposed model, durable plasma process created by the impulse discharge in droplet environment can be presented as distributed correlated spark discharge between pairs of charged and uncharged fog drops.
- Self-consistent electric field of drops ensemble leads to less probability of **DCS** discharge in comparison with probability of drops break-up and charge loss in coronal discharge on charge localization zones' periphery area.

- As the result of charged drops ensemble self-consistent electric field presence, drops Brownian motion and local heating in the accumulating area of drops, charged by the current of impulse charge, multiply-connected area can exist outside the charge localization zone. In this area probability of **DCS** discharge exceeds the probability of drops' coagulation and break-up.

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Ph.D. Serge Olszewski
e-mail: olszewski.serge@gmail.com

Serge Olszewski was born in Kremenchug, Ukraine, in 1965. He received the Ph.D. degree in plasma physics from Kyiv National Taras Shevchenko University, Ukraine, in 2000. He is currently a Senior Research Scientist of Faculty of Radiophysics, Kyiv National Taras Shevchenko University. His research interests include experimental study of electric discharge in plasma-liquid systems and their applications. He has authored more than 130 publications.



Prof. Waldemar Wójcik
e-mail: waldemar.wojcik@pollub.pl

Prof. Waldemar Wójcik - Director of Institute of Electronics and Information Technology at Lublin University of Technology. His research interests include electronics, automatics, advanced control techniques and the optimization of the industrial processes. He is an author or coauthor more than 400 publications.

