Frequency-dependent transition from homogeneous to constricted shape in surface dielectric barrier discharge and its impact on biological target

To cite this article: A V Lazukin et al 2018 J. Phys.: Conf. Ser. 946 012140

View the article online for updates and enhancements.
Frequency-dependent transition from homogeneous to constricted shape in surface dielectric barrier discharge and its impact on biological target

A V Lazukin\textsuperscript{1,2}, Y A Serdukov\textsuperscript{1}, M E Pinchuk\textsuperscript{3,4,5}, O M Stepanova\textsuperscript{5,3}, S A Krivov\textsuperscript{2} and O I Grabelnykh\textsuperscript{6,7}

\textsuperscript{1} Timiryazev Institute of Plant Physiology of the Russian Academy of Sciences, Botanicheskaya 35, Moscow 127276, Russia
\textsuperscript{2} National Research University Moscow Power Engineering Institute, Krasnokazarmennaya 14, Moscow 111250, Russia
\textsuperscript{3} Institute for Electrophysics and Electrical Power of the Russian Academy of Sciences, Dvortsova Naberezhnaya 18, Saint-Petersburg 191186, Russia
\textsuperscript{4} Peter the Great Saint-Petersburg Polytechnic University, Polytechnicheskaya 29, Saint-Petersburg 195251, Russia
\textsuperscript{5} Saint-Petersburg State University, Universitetskaya Naberezhnaya 7/9, Saint-Petersburg 199034, Russia
\textsuperscript{6} Siberian Institute of Plant Physiology and Biochemistry of the Siberian Branch of the Russian Academy of Sciences, Lermontova Street 132, Irkutsk 664033, Russia
\textsuperscript{7} Irkutsk State University, Karl Marx Street 1, Irkutsk 664003, Russia

E-mail: lazukin_av@mail.ru

Abstract. The results of an experimental research of influence the surface dielectric discharge products excited by alternating sinusoidal voltage with RMS of 3.5 kV across the barrier of aluminum nitride with frequency of 50 Hz–100 kHz on a germination of soft winter wheat (\textit{Triticum aestivum} L.) are presented. The stimulation effect on seedling morphological characteristics (sprout length and total length of roots) was observed but its reproducibility with combining the same processing conditions and subsequent germination is insignificant.

1. Introduction

Surface dielectric barrier discharge (SDBD) is a basis for several modern technologies. Advanced technological solutions using SDBD can be divided into two main groups: biomedical [1] and gasdynamic [2] applications.

Developments and researches on disinfecting of surfaces [3], foodstuff [4, 5] and water [6] (destruction of microorganisms, including a resistive microflora), sterilizations of wounds [7] and stimulation of their treatment [8], modification of textile and materials [9], processing of cancer tissue and application in dermatology [10], action on seeds of cultural plants with their modification and stimulation of germination [11,12] belong to biomedical applications of SDBD.

Various ways of gas flow control are a gasdynamic application of SDBD. Among these are deposition of aerosols [13], manipulation with a wing section flow [14] or a helicopter propeller blade adjustment [15], suppression of noise at a flow of various bodies (for example, chassis racks) [16].
Increase in frequency of voltage attached to an electrode configuration for fixed voltage value leads to transition from the homogeneous discharge form (visually it look like the uniform luminescence along an electrode edge) into constricted form (the discharge structure is characterized by bright stretched channel cords). From the point of view for gas flow control systems the similar transition is extremely undesirable as it is accompanied by effect of volume force saturation [17,18]. Channel appearance at particular combination of frequency and voltage leads to increase energy input to discharge and trust saturation. It is known that the similar effect not only restricts thrust, but also creates the substantial increase of temperature in discharge area [19]. Energetic characteristics of the discharge are increased under similar transition [20].

From considerations given above it is clear for what reasons the SDBD voltage frequency is limited for actuators. However, there is no understanding about significance of this transition into the constricted form of impact on biological targets. In particular, vegetable systems in a status of nondeep physiological dormancy are very practical for using them as a model object for verification of influence of SDBD in restricted and homogeneous forms. The research results in a wide frequency range are presented in the paper.

2. Experiments

2.1. Experimental set-up

The electrode configuration used in experiments is presented in a figure 1. Three disk electrodes with a diameter of 16 mm (aluminum foil, 100 microns) are located by centers in peaks of an equilateral triangle with 40 mm sides. A dielectric barrier of 110 by 80 mm in size is aluminum nitride 1 mm thick. The opposite electrode occupies all space of a barrier.

Seeds are set down on the grounded plane located at 10 mm distance from the barrier plane. The electrode system does not assume relocation of seeds during processing. This allows clarifying effect of influence of the discharge created by voltages with different frequencies on the seeds locating on different line from the electrode edge. Zone projections of layout of sowing material on grounded electrodes (which is detached from a barrier on 10 mm by cylindrical insulator) are shown in figure 1 by dash line:

(i) diameter is 28 mm—an internal zone (a ring is limited by diameters of 16 and 28 mm);
(ii) diameter is 40 mm—an external zone (a ring is limited by diameters of 28 and 40 mm).

![Figure 1. Electrode configuration scheme.](image-url)
Zone demarcations were selected based on results of the researches conducted earlier. It had been shown that the length of positive streamer changes ranging from 3.5 to 7 mm at a RMS voltage of 3.5 kV in configuration of single disk with a diameter of 16 mm depending on frequency [21]. Data had been obtained with high-speed ICCD camera Andor iStar DH-720 for SDBD frequencies of 5, 20 and 100 kHz. The external border with diameter of 40 mm was defined by calculation of electric field strength on a surface of the electrode intended for seed layout. Calculation is carried out for the voltage amplitude about of 4.9 kV for axial symmetry and the radius of 5 mm is taken for a zero point.

2.2. Plasma characteristics
The technique of electric measurements was similar with earlier performed works [20,21]. SDBD energetic characteristics was determined by Volt–Coulomb Characteristic (VCC) method [22]. A measuring capacitor of 8.3 nF was set between the opposite electrode and ground wire. High-voltage divider P6015A (Tektronix) and oscilloscope TDS3054 (Tektronix) were used. The registered cyclograms were averaged by 32 measurements.

2.3. Biological target
High-quality soft winter wheat (Triticum aestivum L.) of “Irkutskaya” variety harvested in 2015 was used as a model object. All morphological tests were executed in the fourth quarter of 2016.

Seeds were exhibited by SDBD plasma within 1 minute. In this case it is supposed that there is a proportional response between the target and plasma source action: the embedded energy would be equal for increase in frequency to proportional extension time of action with low frequency.

The processed seeds were put on two layers of the filter paper moisturized with distilled water at temperature 20 ± 1 °C in the dark.

Morphological tests on length of a sprout and the total length of roots were done on third day of germination (day of loading and day of removing is considered as one day).

2.4. Statistical analysis
Four independent experiments were carried out. In each experiment 50 seeds were put in the isolated volume in three repetitions in each case. Calculation of plants on third day allows estimating of seedling vigor; however, development of the wheat germs at this period goes intensively and it is possible to expect increase in lengths by 1–2 mm/h. It distorts result of the morphological test and is critical as, for example, the average length of a sprout makes 8–12 mm. To stop growth processes during an initial stage of the account the technique of electric strike was used: the sprouts on the wetted filter paper were exposed five times by aperiodic voltage impulse of 85 kV. It caused death of 95% of plants and, as a result, stopped their growth.

The normality of distribution of data in selection was confirmed by means of Anderson Darling test. Dispersion in each case did not exceed dispersion between variants. The importance of distinctions between options was estimated by means of the test of multiple comparisons of Tukey Honestly Significant Difference Test. Calculations and graphics were made by means of language of statistical programming R.

3. Results and discussion
3.1. Plasma state
In paper [20] the assumption was made that transition to the constricted form for SDBD is connected to growth of energy and it is well viewed in dependence of energy versus frequencies. Dependence of energy for SDBD versus sine wave voltage frequency (RMS voltage of 3.5 kV) for the electrode configuration (figure 1) counting on one disk is given in figure 2. With frequencies
Figure 2. Embedded SDBD energy vs frequency.

over 50 kHz the transition to the constricted form is clearly viewed not only as growth of embedded energy, but also by appearance of a bright stretched channel in the discharge structure. At the same time with growth of frequency over 70 kHz the electrode system noticeably gets warm working 1 minute, even in case of using of aluminum nitride with high heat-transfer capacity. Therefore the frequency was limited a value of 66 kHz. The lower bound was of 50 Hz.

3.2. Biological target response without the control of seed position

Three-day seedling vigor is defined as the ratio of a number of normally germinated seeds to all loaded seeds in the experiment to the third day. Normally germinated seed is a plant with a sprout length more than half of the seed and with at least two roots. Control germination is 98 ± 2%. We observed no significant changes in germination at any of the experimental sets. The first series of experiments was carried out without the control of seed position on the grounded electrode. The results of the morphological tests on sprout length and the total length of the roots, taking into account the scatter of the data for each of three independent experiments, are shown in figures 3 and 4 correspondingly. A significant differences between the experimental groups are shown in the graphs by a letters. Identical letters marked groups that do not have statistically reliable differences.

First of all, it should be noted that none of the set of experiments had shown negative impact of the transition to the constricted form of SDBD on the seed germination. However, the presence of significant stimulatory or inhibitory effect on seed development in relation to the control groups in the separate experiments did not reveal a tendency to reproduce these results in full experimental data set. This suggests that factors influencing the biological target response on the impact by SDBD plasma products on seed germination were not revealed in this experimental approach.

3.3. Biological target response with the control of seed position

The experiments with the control of seed position were carried out at frequencies of 725 Hz, 4.5 kHz and 61 kHz.
Figure 3. Sprout length: (a)—experiment 1; (b)—2; (c)—3. Scale in mm.

Figure 4. Total length of roots: (a)—experiment 1; (b)—2; (c)—3. Scale in mm.

Also an experiment was made on testing of the influence by only electric field with frequency of 61 kHz only (without grounding of opposite electrode on barrier). In this variant there was no surface discharge plasma, and the seeds were exposed solely to an electric field of high frequency.

To control the position of the seed the grounded electrode surface was appropriately marked on internal and external areas (figures 1). The electrode system was adjusted above the grounded electrode by these marks.
The results of the morphological test are shown in figures 5 and 6. From these results it is clear that with increasing frequency of the supply voltage differences between the seeds in the external and internal zone location also increase. In this case there is no difference between the exposure of seeds in the outer zone of the surface discharge and exposure of seeds in an electrostatic field (shown for 61 kHz). The absence of germination inhibition in the interior discharge zone is probably due to the fact that the discharge plasma screens seeds from the effects of the electric field for a significant time of the exposure. In [21] had been shown that the SDBD plasma density is sufficient for this shielding.

3.4. Discussion
Seeds are a biological object with minimal physiological activity. Before the emergence of germination trigger (in the case of wheat dormant seed that is humidity) exchange energy with the environment is reduced to the minimum breathing process (CO$_2$ for wheat $225 \times 10^{-6}$ ml/(h per g dry weight)). Presowing exposing of seeds under the influence of SDBD plasma products is aimed on modulating the development of the plant, not only at an early stage of ontogeny, which is most often studied, but also on the stability of young crops to adverse weather conditions and phytopathogenic load, volume and quality of the harvest.

The results obtained in this study indicate that even in the presence of very optimistic results in the individual experiments, the reproducibility of these results is not at the proper level. The effect of treatment is associated with strategies of subsequent actions. There are a lot of elements of these post-actions though: waiting time between treatment and sowing, germination temperature gradients, humidity, processing season, the moisture content, contamination, electromagnetic environment, etc.

Parameters such as seed germination, morphology, phytohormone content and activity of enzymes in seedlings do not have a direct connection with the peculiarities of starting plasma treatment.

4. Conclusion
The morphological characteristics and germination ability of high quality seeds after treatment does not changed with the transition to the constricted form of SDBD. The best frequency was not found for preplant seed treatment by products of the SDBD plasma. The stimulation
effect on seedlings morphological characteristics (sprout length and total length of roots) was observed but its reproducibility with combining the same processing conditions and subsequent germination is insignificant.

Acknowledgments
The reported study was partially supported by the Fund of Assistance to Development of Small Forms of the Enterprises in the Scientific and Technical Sphere in framework of program UMNIK under agreement No. 10593GU2/2016 of 13.10.2016. The research was done using the collections of the Core Facilities Center “Bioresource Center” at the Siberian Institute of Plant Physiology and Biochemistry SB RAS (Irkutsk, Russia).

References
[1] Weltmann K D, Polak M, Masur K, von Woedtke T, Winter J and Reuter S 2012 Contrib. Plasma Phys. 52 644–54
[2] Moreau E 2007 J. Phys. D: Appl. Phys. 40 605–36
[3] Mastanahah N, Johnson J A and Roy S 2013 PLoS ONE 8 1–14
[4] Schütter O, Ehlbeck J, Hertel C, Habermeyer M, Roth A, Engel K H, Holzhauser T, Knorr D and Eisenbrand G 2013 Mol. Nutr. Food Res. 57 920–7
[5] Grabowski M, Holub M, Balcerak M, Kalisiak S and Dabrowski W 2014 Decontamination of black pepper powder using dielectric barrier discharge systems in atmospheric pressure Book of Contributions of HAKONE XIV—14th Int. Symp. High Pressure Low Temperature Plasma Chemistry (Zinnowitz, Germany) pp 1–4
[6] Sláma J and Kríha V 2014 Acta Polytech. 54 290–4
[7] Dobrynin D, Wasko K, Friedman G, Fridman A A and Fridman G 2011 Plasma Medicine 1 109–14
[8] Dobrynin D, Wasko K, Friedman G, Fridman A A and Fridman G 2011 Plasma Medicine 1 241–7
[9] Lux C, Szalay Z, Beikircher W, Kováčik D and Pulker H K 2013 Eur. J. Wood Wood Prod. 71 539–49
[10] von Woedtke T, Reuter S, Masur K and Weltmann K D 2013 Phys. Rep. 530 291–320
[11] Dobrin D, Magureanu M, Mandache N B and Ionita M D 2015 Innovative Food Sci. Emerging Technol. 29 255–60
[12] Zahoránová A, Henselova M, Hudecova D, Kaliňáková B, Kováčik D, Medvecka V and Černák M 2016 Plasma Chem. Plasma Process. 36 397–414
[13] Masuda S, Washizú M, Mizuno A and Akutsu K 1978 Boxer charger—a novel charging device for high resistivity powders Conf. Electrostatic Precipitation vol 21 (Leura, Australia) p 24
[14] Roth J R and Dai X 2006 Optimization of the aerodynamic plasma actuator as an electrohydrodynamic (EHD) electrical device 44th AIAA Aerospace Sciences Meeting and Exhibit p 1203
[15] Bityurin V A, Efimov A V, Kazanskiy P N, Klimov A I and Moralev I A 2014 High Temp. 52 483–9
[16] Kopiev V F, Bolyaev I V, Zaytsev M Yu, Kazansky P N, Kopiev V A and Moralev I A 2015 Acoust. Phys. 61 178–80
[17] Fortov V E et al (eds) 2007 Encyclopedia of the Low-Temperature Plasma. Plasma Aerodynamics vol IX-4 (Moscow: FIZMATLIT)
[18] Thomas F O, Corke T C, Iqbal M, Kozlov A and Schatzman D 2009 AIAA J. 47 2169–78
[19] Tirumala R, Benard N, Moreau E, Fenot M, Lalizel G and Dorignac E 2014 J. Phys. D: Appl. Phys. 47 255203
[20] Lazukin A V, Gundareva S V, Krylov S A, Nikitin A M, Kavyrshin D and Fedorovich S D 2016 J. Phys.: Conf. Ser. 774 012195
[21] Lazukin A V, Pinchuk M E, Stepanova O M and Krylov S A 2016 Izv. Vyssh. Uchebn. Zaved., Fiz. 59(9/3) 257–60
[22] Manley T 1943 Trans. Electrochem. Soc. 84 83–96