Effect of the surface dielectric barrier discharge plasmas on winter rye seeds germination

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Abstract. Results of experimental studies of the effect of surface dielectric barrier discharge plasma products on the seeds of winter rye (\textit{Secale cereale} L., “Chulpan” variety, 2013 harvest, treatment in the 1st–2nd quarters of 2017) located at a distance of 8–10 mm from the surface of the barrier are presented. The electrode system consists of parallel strips 1 mm wide, located 5 mm apart. A sinusoidal voltage of 25 kHz 2.5 kV is applied to the strips. The seeds are determined by the action of the electric field strength (1–1.6 kV/cm), the chemical active particles and the ion wind induced towards the seed layer (the ion wind velocity is 0.2–0.5 m/s, measured by the particle image velocimetry system). Optimal processing mode is achieved by changing the exposure time of seeds by the action of surface discharge products (from 15 to 120 s). It is shown that when the system is actively cooled (temperature 23–24 °C), the length of the shoot is proportional to the exposure time. In this treatment mode, the root system at all exposures is stimulated significantly. When the system operates without cooling, the maximum length response of the seedling is observed at 60 s (at 60 s the temperature reaches 54 °C).

1. Introduction
Barrier discharges of atmospheric pressure, both in volume and surface configurations, exists as a sequence of individual microdischarges, more intense for a positive half-cycle of alternating voltage and noticeably weaker for a negative half-cycle. The microdischarge duration and power deposition are limited by charging of the dielectric layer that allows the discharge to be operated across a relatively wide surfaces without additional decoupling of separate sections. Barrier discharges work as a source of low temperature plasmas, requiring relatively small energy consumption for their operation. These properties make the dielectric barrier discharges ideal for large-scale treatment of biological objects, for example, in agrotechnical applications.

Current studies considering the surface and volume barrier discharge for seed stimulation, although mainly limited to laboratory tests, show the high efficiency of this method. Efficiency (meaning a significant effect of the discharge at optimal treatment mode) is shown for seeds of wheat, radish and a number of other crops [1–6]. Key mechanisms considered by various independent authors, responsible for the effect of discharge plasma on the qualitative characteristics of germination are following: etching (microdamages, microcracks) of the seed
surface, reducing the phytopathogenic load on the germinating seed and changing the water status, including the wetting characteristics of the seed surface. At the same time, methodically the studies vary significantly. The key difference seems to be the position of the seed material—the seeds can be placed on the surface of the dielectric barrier in the plasma layer [1–3], or at a short distance [4–6]. In the second case the seeds are not located immediately on the dielectric barrier, that makes it possible to exclude several treatment factors from the consideration. First of all, in this configuration microdischarges does not directly contact with the seed, transfer the charge to its surface. The temperature loading in also seems to be not so hard as neither high-temperature electrode spots are formed on the seed surface, nor the barrier transfers the heat to the seeds. The general electrical field at the treated target positions seems to be much smaller in comparison to “direct” treatment schemes.

Significant ways of interaction between the discharge plasma and the remote (8–10 mm) layer of seeds include at least three factors. First, the effect of the “accompanying” electric field (the average electric field in the gap between the high voltage strip electrode and the grounded plane on which the seeds are located) is 1–2 kV/cm. Secondly, the seeds can be affected by relatively long-lived chemical agents. The chemical activity of the surface discharge in air from the point of view of action on the remote target is well modeled [7]. The third factor is the ion wind directed to the seed layer.

From the point of view of choosing the electrode configuration, a group of parallel strips is considered as a promising one since it allows the formation of an intense convective ion flux from the barrier to the seed layer “synthetic jet” configuration.

The choice of a culture for research is also an important methodological issue, not less significant than the control of discharge characteristics and the description of operating factors. Many authors work with wheat, since it is cultivated in significant areas, has high productivity, food and social value. However, the stability of wheat is varies significantly, the phytopathogenic load has a disastrous effect on it. Winter rye is less dependent on environmental conditions. For rye extensive laboratory studies have shown a significant effect of magnetic fields [8] (presumably electrically and magnetic fields have similar bioreceptors in resting seed). Rye is more resistant to stress, even under a noticeable strain of phytopathogens, less demanding on water availability. Rye, in comparison with wheat, has a more developed root system, which is also an indicator of resistance. A study on the reaction of winter rye and winter wheat, distributed over Eastern Siberia (the variety of winter soft wheat “Irkutskaya”, a variety of winter rye “Chulpan”), on cold stress showed greater resistance of winter rye, both to simulated stress, and to the modification of the germination properties after surface etching [9]. It should be kept in mind that the etchant has an equivalent efficiency in suppressing the activity of phytopathogens on the surface of the seed coat.

The purpose of this study is to identify the optimal treatment mode for winter rye seeds under the action of a remote surface barrier plasma discharge. The second goal of the work is to test the hypothesis about the leading role of microdamages of the seed coat under the influence of microdischarges and the role of the integral temperature of the electrode configuration.

2. Experimental setup and measurement system

2.1. Geometry of the electrode system

The cross section of the electrode configuration is shown in figure 1.

The electrode configuration of the surface dielectric barrier discharge (SDBD) consists of five strip electrodes with a length of 50 mm and a width of 1 mm, made of aluminum foil (50 µm thick). The distance between the electrodes is 5 mm. The total length of the electrode edge is 350 mm. The electrodes are located on the surface of an aluminum oxide dielectric plate (96% with additions of titanium and silicon oxides, dielectric permittivity 9). The thickness of the plate is 1 mm. On the other side a second (grounded) electrode is located. Sinusoidal voltage is
applied to the strip electrodes. At a distance of 10 mm from the surface of the barrier the metal ground plate is placed, on which the treated seeds are located.

2.2. Control of ion wind
The velocity and direction of the ion wind in the gap between the dielectric barrier and the grounded plane was determined by the particle image velocimetry (PIV) system. The restoration of the velocity field was carried out without seeds on the target plane, assuming that seed layer has no significant effect on the flow structure.

Application of PIV method to the electrohydrodynamic flows may introduce measurement errors, associated with particle charging. For the small particles used with \( d = 0.1–1 \) \( \mu \)m the diffusive charging mechanism seems to be the dominant one. One can estimate [10] that the typical charge obtained by such a particle in 10 ms (characteristic gasdynamic time for the system) in the ionic cloud with \( n_i = 10^8 \) cm\(^{-3}\), should be on the order of 10–1000 elementary
Figure 3. (a) Distribution of the electric field strength near the plane of the grounded electrode. (b) Dependence of the discharge energy on the applied voltage (root mean square value of voltage).

charges. Taking the upper estimate, we can calculate the force, encountered by particle in the electric field of 1 kV/cm, to be on the order of $10^{-12}$ H. To obtain the estimate of the systematic bias, introduced into PIV data due to particles drift, we should compare this value to Stokes force: $V = \frac{F_{\text{el}}}{6\pi a \eta}$, providing the typical error to be within 0.02 m/s.

2.3. Electric field
Regardless of the sinusoidal-voltage frequency, the strip electrodes create an inhomogeneous electric field near the barrier surface and a relatively uniform electric field in the gap between the dielectric surface of the conductive surface on which the seeds are located, provided that the surface is grounded. The field distribution in the absence of the discharge is presented in figure 2.

The electric field strength becomes uniform at a distance comparable with the distance between the strips (5 mm). The electric field was calculated by the finite element method in the BetaFields software package [11].

Given the field structure near the grounded electrode, the seeds are located only under the discharge zone within 10 mm of the central band [the boundaries of 20 and 40 mm in figure 3(a)] to ensure the uniform treatment.

2.4. Energy of discharge
To ensure equal impact on the seed material, SDBD was operated below the to the constriction threshold, thus limiting amplitude and frequency of the supply voltage.

On the other hand, the SDBD should relatively evenly cover the barrier between the strip electrodes, i.e. the ignition voltage of the discharge should be noticeably exceeded. To select the operating voltage, the dependence of the energy consumption of the discharge on the voltage at a supply voltage frequency of 25 kHz was obtained. The measurement was carried out by the method of voltage coulomb curves integration [12] (measuring capacitor 8 nF, high voltage probe P6015A Tektronix, oscilloscope TDS 3054 Tektronix). The dependence of the energy consumption on the voltage amplitude is shown in figure 3(b).
Figure 4. Dependence of the temperature of the electrode system (the plane of the return electrode or the radiator installed on it) from the exposure time of the system under discharge (25 kHz, 2.5 kV of the current one): PC—passive cooling system radiator; AC—active cooling of the system by air flow; WOC—without cooling.

In figure 3(b), in addition to the experimental points, approximation lines and squares of the approximation reliability coefficients are given. The approximated dependence, with a sufficient level of reliability, can be divided into two sections. Relatively linear E1, which continues up to a voltage of 1.2 kV and a dependence of the type E2, to which the experimental points are approximated with a high degree of reliability at voltages above 1.2 kV. It can be assumed that 1.2 kV is the ignition voltage for used electrode configuration. A double excess of the ignition voltage is sufficient to ensure a uniform operating of the discharge in the electrode configuration (visually) and makes it possible to realize several options for heating the electrode system without provoking thermal damage in the seeds layer.

2.5. Electrode configuration temperature
The temperature of the electrode system can have a significant effect on the results of the treatment. Discharge was powered by a sinusoidal voltage of 2.5 kV in amplitude with a frequency of 25 kHz. The system can be cooled passively through a massive radiator, placed besides the grounded electrode, and actively cooled through the radiator equipped with a fan or not cooled at all. Temperature dynamics of the electrode system for different cooling options are shown in figure 4. The temperature measurement is carried out on the grounded electrode using the ir-thermometer Condtrol IR-CAM 2 (accuracy of measurement is $\pm 2 ^\circ C$).

2.6. Seed material
As a model object, the seeds of the winter rye (*Secale cereale* L.) of the variety “Chulpan” of the 2013 harvest obtained from the collections of the Bioresource Center of the Siberian Institute of Plant Physiology and Biochemistry of the SB RAS (Irkutsk) were used. After the treatment seeds were aged for 1–2 days, then germinated for three days in the dark at
a stabilized temperature (24 °C) on two layers of filter paper moistened with distilled water (10 ml). Seeds were laid out in plastic containers in 50 pieces per container at a distance of about 1 cm from each other. The paper was additionally moistened daily with 2 ml of distilled water, the containers were vented and rearranged. For each experiment, three variants were laid (150 seeds per option). After 30 days, the experiment was repeated. Data on the seeds response to the action of plasma treatment were obtained on the basis of a generalization of the data of 3 experiments. Morphological characteristics (length of the sprout and total length of the roots) and 3x daily germination were monitored (the ratio of the number of seeds normally germinated on the third day to the total number of seeds). Histograms indicate average values with 95% confidence intervals. The reliability of the differences between the various sets was confirmed by the Tukey’s multiple comparisons test. Variants that do not have significant differences are identified by the same letters. Statistical processing of data was carried out using the R [13] programming language.

All experiments on germination were carried out in the 1st–2nd quarters of 2017.

3. Results and discussion
The response of the qualitative characteristics of germination to the seeds treatment with SDBD plasma products without cooling the electrode system and with cooling of the electrode system is shown in figures 5 and 6.

Figure 5. Summary results of morphological tests: (a) sprout length; (b) total root length; (c) seed vigor (3-days germination). Electrode system is without cooling.

Figure 6. Summary results of morphological tests: (a) sprout length; (b) total root length; (c) seed vigor (3-days germination). Electrode system is with cooling.
The difference in the observed response is associated not only with the treatment time, but also with the cooling intensity. Thus, in the presence of active cooling, an almost proportional response of the sprout length to the treatment time is observed. If the system does not cooled (the temperature is saturated), there is a reliable maximum response of the seedling at an exposure time of 60 s. Still, no reliable differences in the germination of treated and control seeds are observed. The response of the length of the root system to processing is ambiguous; it is likely that a more detailed statistical study is needed for this indicator. The temperature (or cooling rate) of the system determines the moisture loss of the seed in the layer, intensified by the accompanying electric field and the convection induced by ion wind. It is known that at a flow velocity of 0.3 m/s in an electric field of 400 kV/m, a noticeable difference in moisture loss in wheat seeds is observed in less than 1000 s [14]. One should note that temperature surely has a significant effect on the drying rate. When the temperature rises from 20 to 50 °C in an equally stressed electric field, the loss of moisture in seeds increases by 15% in tens s of treatment [15].

The results of reconstructing the averaged velocity field averaged across 70 instantaneous frames are shown in figure 7. Regions of upward-directed flow correspond to the position of the exposed electrodes.

The velocity of the ion wind induced toward the seed layer is 0.2–0.5 m/s. Thus, the situation develops when the SDBD system creates an ion wind that carries both charged particles to the seed layer and short-lived active complexes. One can expect that the intensity of the alternating electric field also acts on the seeds. Probably, the total effect of these factors is sufficient to change the water status of the exposed seeds, which in turn leads to a change in the features of germination. Increasing the temperature of the electrode system leads to an intensification of moisture loss. The passage of the optimum moisture content point in the seeds leads to a maximum in the curve of the seedling length relative to the treatment time.

The moisture content in seeds and the moisture loss of seeds in this study were not investigated by direct methods. These relationships will be established in future work.

4. Conclusions
The following conclusions can be drawn from the studies:

- For winter rye seeds, variation of the treatment time, at the constant discharge parameters (fixed frequency and voltage) allows to select an optimum stimulation mode, both based on the length of the roots and on the length of the sprout.
• The nature of the stimulation directly depends on the temperature mode of the electrode configuration of the SDBD. At relatively high barrier temperatures, a maximum in treatment time is observed. If the barrier temperature is not high, the response of the seedlings is proportional to the treatment time.

• The effect of plasma products of SDBD can change the morphological characteristics of seedlings, but does not affect the germination of winter rye seeds.

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