The effect of applied voltage frequency on surface dielectric barrier discharge energy

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Abstract. Results of the experimental investigation of surface dielectric barrier discharge’s energy dependence on frequency of applied sinusoidal voltage varying from 0.6 to 40 kHz at atmospheric pressure are presented in the paper for disk electrodes of 20, 50 and 150 µm thick. It is shown that surface dielectric barrier discharge’s energy dependence on applied voltage frequency represents an U-shaped curve with a distinct minimum. The value and position of energy minimum are related with thickness of the generating plasma electrode, the barrier material and supply voltage. Increase of plasma heat dissipation owing to selection of the dielectric barrier material changes significantly a trend of the U-shaped curve.

1. Introduction
A surface dielectric barrier discharge (SDBD) is used for various electrotechnologies such as agriculture [1], food industry [2], ozone synthesis [3], disinfection of materials and pollution control [4], air flow control [5]. Whether an extended high-energy discharge with significant current and temperature or a low-energy low-temperature discharge can be obtained in the same electrode configuration for different purposes. Transition from one form of discharge to another is primarily related with applied voltage or its frequency increase [6].

On the one hand, such transition from the low-energy form of discharge to the high-energy form is mostly undesirable due to ambient temperature increase. This fact is especially important for the treatment of polymeric materials (destruction of the surface layer) and biological objects (heat shock, necrosis). On the other hand, increase of supply voltage and frequency promotes increase of SDBD’s plasma products yield (for example, ozone yield [3]). Therefore, there may be an optimal combination between discharge energy and applied voltage frequency for used electrode configuration.

2. The experimental setup
2.1. The electrode system
The typical flat SDBD’s electrode system has been chosen for studying discharge power and energy dependence on applied voltage frequency. It was carried out the first run of experiments with the dielectric barrier consisted of a 60 × 48 mm flat Al₂O₃ plate (94% aluminum oxide...
with silicon oxide, chromium oxide and manganese oxide addition), 1 mm thick, and the second run of experiments with the AlN dielectric barrier (100% purity) of the same linear dimensions. In both cases two electrodes were placed on each side of the dielectric. The electrode which generates plasma was an aluminum foil disk 16 mm in diameter pasted on the center of the dielectric plate. The thickness of the disc was different and equals 20, 50 and 150 µm. On the other side of the dielectric barrier it was placed the opposite electrode occupying the same space within the dielectric plate. The capacitance of this system, without plasma, was 16 pF (digital LCR meter E7-22, frequency 1 kHz). For experiment realization several high voltage supplies were employed for different frequency ranges: 0.6–5 kHz, 5–12 kHz, 12–28 kHz, 28–40 kHz.

Figure 1 shows the disk electrode placed on the dielectric barrier and two plasma generation processes at applied voltage of 3.5 kV (RMS) and different frequencies of 5 and 30 kHz. The images were obtained with digital camera EOS 600D, shutter speed 1/25 sec, ISO 12800, aperture f/5.6.

Voltage was applied to the central part of the disc that enabled to avoid discharge distortion due to the edge effect. The opposite flat electrode was grounded through the charge-probe capacitor of 37.6 nF. The experimental setup used in this investigation is sketched in figure 2. Supply voltage was measured by the voltage divider C1/C2 (P6015A, Tektronix). Signals from the low voltage divider arm and the charge-probe capacitor were used for determination of the Volt–Coulomb characteristic (oscilloscope TDS 3054, Tektronix). The consumption energy of discharge unit (SDBD’s energy) was defined as an area in a centre of the hysteresis loop of the Volt–Coulomb characteristic [7].

2.2. Recording of SDBD’s spectral characteristics
Visual evaluation of the surface discharge is unreliable source of information about low-temperature plasma transition to higher temperatures of discharge. More accurate data about this process can be obtained by spectral characteristics analysis. It determines vibrational and rotational temperatures which change considerably with intensity of plasma discharge [8]. For recording the SDBD’s emission spectrum a three-channel fiber-optic diffraction spectrometer “AvaSpec-ULS2048x16” was used. The spectrometer “AvaSpec-ULS2048x16” (Avantes company) enables to take accurate spectroradiometric measurements which require rather high resolution in a wide spectral range (200–1100 nm). The ultra-violet, visible and infra-red channel resolutions are no worse than 0.18 nm, 0.12 nm and 0.3 nm respectively.

Input section of the spectrometer’s fiber-optic cable was allocated at a distance of a few centimeters from the investigated discharge process to minimize effects related with absorption
of plasma radiation in the air. The described optical system was used for recording the emission spectrum of discharge and subsequent determination of vibrational and rotational temperatures.

3. Results and discussion

SDBD’s power dependence on applied voltage frequency and the thickness of the disc electrode is shown in figure 3 for the $\text{Al}_2\text{O}_3$ barrier and applied voltage of 3.5 kV (RMS). This dependence is almost linear for the thickness of 20 and 50 $\mu$m but for the 150 $\mu$m thick disk electrode at high frequency there is significant deviation from linear character of the curve.

SDBD’s energy dependence on applied voltage frequency is more significant (figure 4). It represents an U-shaped curve with a distinct minimum that indicates two competitive processes.

It is known that the dielectric barrier collects charges within every half-cycle of supply voltage during SDBD’s plasma existence [9]. A deposited surface charge is neutralized during the reverse discharge. There are two possible explanations of the barrier charging process: in [10] it is assumed that electron avalanches propagating from the electrode edge towards the dielectric barrier gradually charge its surface. The electron avalanches length and the amount of settled charge rise with applied voltage increase. In [11] the barrier charging is presented like charge distribution in the RC circuit. The charge transfer between the previous and the next surface
elements begins with achievements of a definite voltage drop value between them, which ensures
the occurrence of local breakdown.

In both models of the barrier charging the amount of settled charge is related with the period
time during which applied voltage rises from the moment of inception of the first electron
avalanches to the moment of voltage maximum. The energy consumption is caused by both the
barrier charging and subsequent charge neutralization during the reverse discharge.

Thus discharge energy decreasing with frequency on a left part of the U-shaped curve is
related with reduction of the cycle duration of plasma existence and therefore with charging
rate reduction of the dielectric barrier.

Smoothing of the U-shaped curve deflection with the change from the 150 to 50 µm
and then to 20 µm thick electrode generating plasma is related with decrease of discharge
initiation voltage from 1.4 to 1.2 kV. During elementary companion processes of dielectric barrier
charging and discharging plasma releases heat which is absorbed by the dielectric barrier and
an ambient air. Vibrational and rotational temperatures which were determined by spectrum
of N₂ molecular bands (figure 5) equal to $T_v = 3200$ K and $T_r = 400$ K respectively and
low depend on high voltage supply parameters under considered conditions (the rotational and
vibrational temperatures were calculated assuming a Boltzmann energy distribution of molecules
in vibrational and rotational levels).

The amount of absorbed heat is limited by a finite thermal conductivity of the barrier and
environment. After passing the minimum of the obtained U-shaped curve, thermal conductivities
of the barrier and environment are found to be insufficient for complete heat dissipation with
consequent temperature increase in the discharge area. Further rise of applied voltage frequency
and the number of dielectric barrier recharging cycles lead to a rise of discharge energy (a
right part of the U-shaped curve). Hence a right part of the U-shaped curve could be aligned
by plasma temperature decrease (supply voltage decrease) or increase of the ambient thermal
conductivity.

The Al₂O₃ barrier can be replaced with the barrier of more heat conducting material and
the same electrical characteristics—the AlN. Thermal conductivity of aluminium oxide ceramics

![Figure 4. SDBD’s energy dependence on applied voltage frequency for the different thickness
of the disc electrode.](image)

Figure 4. SDBD’s energy dependence on applied voltage frequency for the different thickness
of the disc electrode.
Figure 5. Molecular bands of the N$_2$ system recorded with the discharge at 3 kV and 20 kHz.

Figure 6. SDBD’s energy dependence on applied voltage frequency for the AlN barrier.

is about 20 W/(m K) while thermal conductivity of aluminium nitride ceramics is by order of magnitude greater and close to 200 W/(m K). As it is shown in figure 6, the change of the dielectric barrier material allows to align the right part of the U-shaped curve. At frequencies higher than the frequency of energy minimum the value of consumption energy remains almost steady.

4. Conclusions
The obtained experimental results can be widely used for designing of advanced electrical equipment which key working element is SDBD. First of all determination of the U-shaped curve and its minimum energy is a simple and reliable method of detecting critical operating conditions of discharge plasma and the dielectric barrier related with barrier surface heating and
thermal conductivity of the whole system. The passing of the minimum energy value signals about significant recession of heat to the discharge area. Also there is definite supply voltage frequency for low-energy systems with which discharge energy becomes minimal and remains steady with subsequent frequency increase that is interesting for equipment power choice.

The existence of minimum on the energy-frequency curve indicates the possibility of the streamer to leader transition and for low-energy discharges—the avalanche to streamer transition. We are going to investigate these physical facts in further work by means of detailed vibrational and rotational discharge temperatures measuring.

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