Proceedings of 20th International Congress on Acoustics, ICA 2010

23-27 August 2010, Sydney, Australia

Stabilization of Multi-needle-to-Plate Electrical Discharges in a High-intensity Sound Field

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PACS: 43.20.Ks, 43.25.Vt, 43.35.Kp, 52.35.Dn

ABSTRACT

Environmental applications, such as pollution control, utilize different chemical reactions. Their efficiency can be improved by the application of a power sound field. Many reactions can be enhanced by ionization of the reactant medium, which is most frequently performed by electrical discharges. One of the most reliable ways to meet these requirements utilizes the combination of an acoustic resonator with non-thermal electrical discharges. The important factors in the industrial applications are discharge power and volume. In order to increase the discharge volume and to prevent a discharge transition into sparks, we designed a new stabilization of multi-needle-to-plate electrode system, which is situated in the sound pressure node of the acoustic resonator. Factors which contribute to the stabilization are: first, the gas particles that are swung on the pressure node plane; and second, the sound pressure gradient, which strongly influences breakdown conditions. With the abatement of sound pressure, the reduced electric field is increased, and suitable conditions for streamer tracing are established. The streamers are easily swung into place over the estimated maximal amplitude of sound displacement and discharge is strongly spread. The discharges are stabilized at all needles even if they are connected to the same potential. The needle tips are effectively cooled by the sound wave. The stabilization may be applied to different regimes of discharges; e.g. corona, glow and streamer.

1. INTRODUCTION

Environmental applications, such as pollution control techniques, volatile organic compounds (VOCs) removal, car exhaust emission control, polymer surface treatment (to promote wettability, adhesion) or ozone generation, utilize different chemical reactions. The efficiency of these reactions depends, among other things, on the temperature, on the residence time (mixing of reactant medium) and also on the pressure in the reaction volume. Increase of the residence time and pressure in the reaction volume can be achieved by the application of a power sound field. At the same time, many reactions can be enhanced by ionization of the reactant medium, which is most frequently performed by electrical discharges. The synergy of power ultrasound with electrical discharges therefore opens new and unique perspectives for many applications. One of the most reliable techniques to meet these requirements utilizes the combination of an acoustic resonator with non-thermal electrical discharges.

The discharge power and volume belong among the most important factors in industrial applications. To increase the discharge volume and the discharge current-voltage range, and at the same time, prevent discharge transition into spark, a stabilized system of multi-needle electrodes situated against the plane electrode is often used. Application of cooling airflow through all of the needles and individual ballast resistors for each needle stabilizes and electrically separates the individual discharges at needle-to-plane electrode channels. This arrangement requires sufficient space and good insulation of the feed wiring. In addition, cool air flowing through the needles dilutes processed gas, and can substantially influence e.g. VOC decomposition efficiency.

Reference [1] describes the discharge volume enhancement with one needle, which is perpendicular to an ultrasonic vibrating piston. The variants with one needle placed in the resonator's pressure node plane, with both discharges stabilized, are in [2, 3].

In this paper, we describe a new resonator setup with the negative needle multi-electrode and one positive plate electrode placed in the node of sound pressure of the acoustic standing wave. The great advantage of this arrangement is that only one shared resistor for all the needles is required. The discharge is stabilized in all the channels even without airflow through the needles: it becomes more uniform and the discharge volume is substantially increased.

2. EXPERIMENTAL ARRANGEMENT

The experimental arrangement of the acoustic resonator with a multi-needle-to-plate electrode system is shown in Figure 1. The resonator - discharge chamber 10 is made from an acrylic glass tube. The loudspeaker 7 is attached at the chamber from one side. A movable reflector 2 is placed at the other side of the resonator chamber. There is a hole in the middle of this reflector, which serves as the output of the treated gas 1. The movable reflector is connected with a mechanism 11, which enables its arbitrary positioning along the whole length of the chamber. The center of the grounded plate-conducting electrode 3 is situated at the distance of $\lambda/4$ from the movable reflector in the node of sound pressure. The other electrode is formed by the multi-needle configuration 4, which is situated symmetrically towards the center of the plate electrode and consists of a set of needles located along the plane, which intersects the axis of the chamber and which is perpendicular to the sound pressure node plane. All the needles are electrically connected with one common resistor 5 to the negative terminal of a high voltage power supply 6. The positive terminal of the power supply is grounded. Processed gas is introduced into the tube 8 below the electrode's system. It is very useful, in case of low gas flow, to replace the needle electrodes with hollow needles and to supply gas directly into the discharge volume 9 through them.

In the specific arrangements the distance d between the tips of the needles and the surface of the plate electrode was 10 mm and the needle axes spacing was 4mm. The hypodermic needles (Terumo) of the outer and inner diameters of 1.2 and 0.7 mm respectively were used. The radius of the tip curvature is 17 µm. The loadspeaker BMS 4591 (maximum electrical input 100 W) was driven by an Agilent 33250A generator and a Mackie M 1400 power amplifier. A DC power supply (Module 30C24-N12, Ultravolt) provided voltage up to 30 kV. The needle electrode was ballasted by an R=6.6 MΩ resistor. The terminal voltage is labeled U_S, and discharge voltage U_D. Acoustic pressure was measured by means of a 1/8'' type 40DP pressure microphone, a 1/8'' to 1/4'' type RA0063 adaptor, and a 26AC amplifier type and a type 12AK power module; all are components produced by G.R.A.S. The microphone was temporarily pushed into the output gas hole to fit with the reflector position.

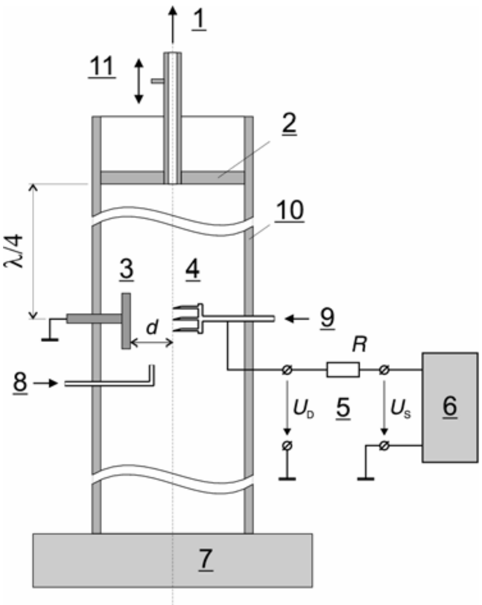
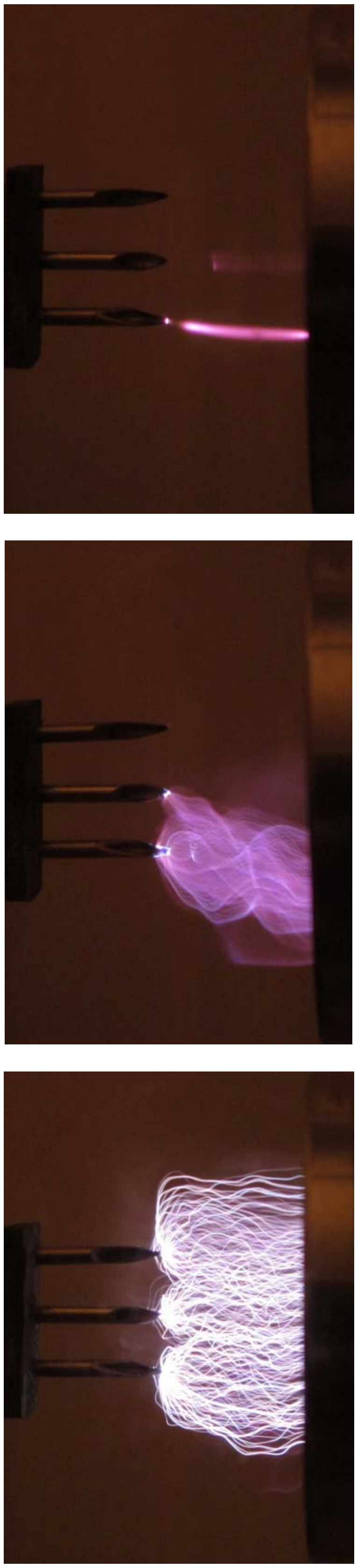


Figure 1. Schematic sketch of the experimental arrangement.

3. RESULTS AND DISCUSSION

All the experiments were undertaken at normal atmospheric pressure conditions. The air filled resonator, whose frequency was set to 500 Hz, was excited up to a sound pressure of P=5637 Pa. Slight nonlinear distortion of the acoustic wave was observed at this pressure level. The resonator quality factor Q=5.2-5.4, was slightly dependent on acoustic pressure. Maximum acoustic displacement U=4.3 mm and acoustic sound velocity V=13.6 m/s were calculated using the acoustic pressure measured at the reflector. The temperature in the chamber during the experiments was 28±2 °C and relative humidity was 19%.

Three-needle-to-plate electrical discharge regimes were formed in the resonator with a frequency of 500 Hz, by increasing the sound pressure level measured at the resonator reflector wall, at constant DC voltage U_S = –25 kV. Photographs are shown in Figure 2.



a)

b)

c)

Figure 2. Photographs of 3-needle-to-plate electrical discharge regimes formed in the resonator by increasing the sound pressure level with a frequency of 500 Hz and constant DC voltage U_S= –25 kV; a) P=0 Pa, U_D= –2 kV; b) P=1210 Pa, U_D= –4 kV; c) P=5380 Pa, U_D= –7.2 kV. Exposure time is 1/30 s.

In the case of no sound wave irradiations, Figure 2a, a single intermittent spark discharge appears in one specific interelectrode channel, the one with the best breakdown conditions (highest electric field intensity at the top of the needle).

By increasing the sound pressure, the discharge regime changes and the discharge volume is increased, Figure 2b, c. It is evident from the pictures that the discharge widens from 1 mm diameter in the case of no sound wave to about 20 mm of broadness if the resonator is excited to P=5380 Pa, Figure 2c. The filamentary discharges, Figure 2c, are well stabilized in all channels and are well cooled without threat of burning the tips of the needles. A similar stabilization effect can be observed in other possible discharge regimes induced by means of lower applied DC voltage.

We explain the mechanism of the synchronous multi-channel discharge stabilization phenomenon in acoustic standing wave field as follows: First, the discharge volume is homogenized because the neutral and charged gas particles are moved by the sound wave in the direction that is perpendicular to the needle axes and parallel with the needle axes plane. In other words, particles swing on the pressure node plane with a velocity in the node that reaches maximal value once through the wave half-period. During the other half-period the direction changes and the phenomenon is repeated. Second, the pressure gradient in the direction perpendicular to the pressure node also changes magnitude and direction. The maximum discharge spread displayed in the Figure 2c is substantially greater than would correspond to the sound displacement amplitude in the pressure node (U=4.35 mm). To clarify this effect, we add some basic characteristics of discharges related to the sound field.

When the applied electric field near the tip of negatively charged needles reaches the threshold value for ionization of air molecules by electron collision, an electron avalanche develops along the direction away from the needle. With the growth of the avalanche through the ionization zone around the needle tip, more electrons are developed at the avalanche head, more photons are emitted in all directions and more positive ions are left in the avalanche wake. Cascade ionizations may continue. Based on the intensity of the electric field, electrode geometry and air property, different discharge regimes are generated. The discharge current may be significantly increased from the small self sustained one to form the spark. The spark forming mechanism is based on the concept of a streamer – a thin ionized channel, growing fast between electrodes.

It is apparent that electric field non-uniformity has a strong influence on breakdown conditions and the avalanche transformation into a streamer [4]. Therefore, we refer to Figure 3, which shows the electric field distribution between the needle and the infinite electrode (on the right side). The field lines (arrows) represent the possible streamer directions. But it is not only non-uniformity of the electric field but also a reduced electric field non-uniformity that decreases the breakdown voltage for a given distance between the electrodes [5]. Reduced electric field E/N is inversely proportional to concentration of the neutral air particles N. With the sound pressure drop in the direction of the pressure node, the reduced electric field increases as a result of the standing sound wave. Suitable conditions for streamer tracing are created. The steamers are easily swung into place over the estimated maximum amplitude of displacement.

The conclusion is fully compatible with Meek's criterion, which represents a further restriction of streamer formation and whose validity is limited to a stationary state of the gas [5]: $\alpha(E/p)\bullet d \approx 20$, where α is the first Townsend ionization coefficient, E is the electric field strength, p is local pressure

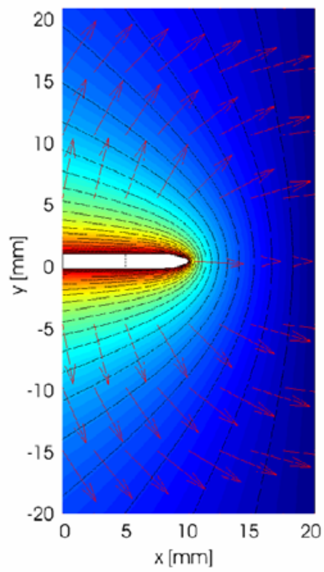


Figure 3. The electric field distribution between the needle and the infinite plate electrode on the right side of the picture. Arrows represent electric field lines.

and d is the distance between electrodes. As the electric field in the vicinity of the plate electrode does not substantially change, the fundamental quantity in Meek´s criterion for streamer formation is the local pressure. From the point of view of one streamer, the sound field, with the frequency of 500 Hz, constitutes the stationary state.

We tried to prove the share of sound pressure to the discharge spread by means of an experiment in which only one needle-to-plate electrode was used. The plate electrode was electrically separated at the pressure node plane into two parts, set side-by-side at a distance of 2 mm. The discharge with this electrode arrangement, excited to acoustic pressure P=5380 Pa, is shown in Figure 4.

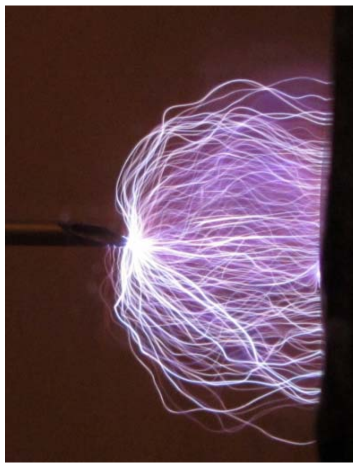


Figure 4. Discharge at 1-needle to 2-electrically separated plate electrode arrangement.

The time course of acoustic pressure at the reflector surface and the current waveforms through either part of the plate electrode (separated at node pressure plane) are shown in Figure 5. Trace (C1) displays the pressure progression, (C2) current impulses through the part of the plate electrode that is closer to the reflector and (C3) current impulses through the electrode further-out from the reflector.

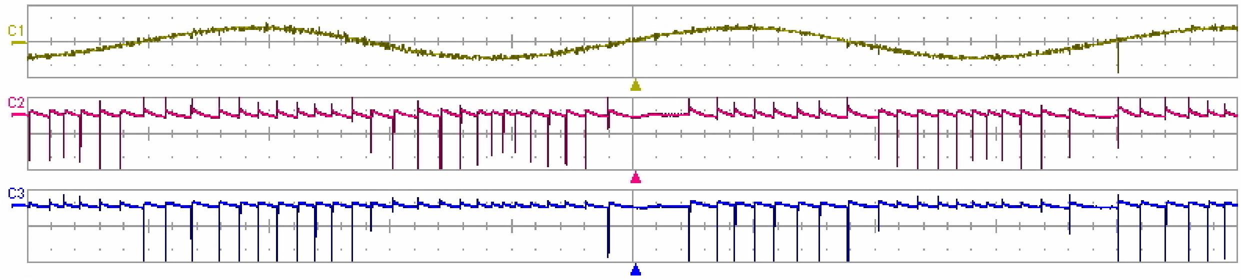


Figure 5. The time course of acoustic pressure amplitude at the reflector surface C1, and the current waveforms through either part (separated at nod pressure plane) of plate electrode: C2 - closer to the reflector, C3 - further-out from the reflector.

It is obvious from Figure 5, that current streamers from 1-needle are vibrated toward both sides of separated plate electrodes but flow only through that plate part which resides in the region with lower sound pressure.

4. CONCLUSION

The stabilization of the discharge which is placed in the pressure node of the acoustic resonator is based on homogenization, cooling and spread of the discharge volume in front of each needle of the multi-needle electrode by means of an acoustic standing wave field. The gas particles are swung on the pressure node plane, with the half-time period of sound frequency. Also, the sound pressure gradient changes its magnitude and direction upright to pressure node plane. Generated compression and rarefaction strongly influence breakdown conditions and different regimes of discharges may be created. With the abatement of sound pressure the reduced electric field is increased and suitable conditions for streamer tracing are established. The streamers are easily swung into place over the estimated maximal amplitude of acoustic displacement and discharge is strongly spread.

It is very convenient that acoustic waves in this arrangement stabilize discharges and cool the discharge electrodes without any threat that the tips of the needles would be burned and without any dilution of the possible processed gas. The stabilization may be applied to different regimes of discharges, e.g. corona, glow and streamer.

Suitably arranged acoustic resonators with electrical discharges offer the synergy effect of power sound with the discharge volume enhancement and discharge stabilization at all needles even if they are connected to the same electric potential. It opens new perspectives in many practical environmental applications.

ACKNOWLEDGMENT

This research has been supported by the research program No. MSM6840770015 "Research of Methods and Systems for Measurement of Physical Quantities and Measured Data Processing" of the CTU in Prague sponsored by the Ministry of Education, Youth and Sports of the Czech Republic.

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