69. SHOCK WAVES GENERATED BY CREEPING ELECTRIC DISCHARGE IN AIR

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Abstract. The dynamic of shock wave creation by initiation of creeping charge moving in form of plasma contact along semiconductor rod surface and shortening the electrodes with powerful electric arc was investigated. The hydrodynamics flow of plasma cord propagation in the spark gaps was visualized with the optical system on the base of the shadow device IAB-458 and the interferometric suplement RP-452.

The current measurements and frame recording of the process have shown the time development of electric arc discharge could be subdivided into two successive processes. The first is the initiation and propagation of plasma contact from one electrode to another. The second is the shortening of the spark gap then the plasma contact reach the second electrode and the development of arc discharge.

The frame recording have shown the coupled shock wave created in air in front of the plasma contact propagating with approximately constant velocity at the first stage of electric discharge evolution. The powerful shock wave in air is created due to electric discharge produced after the spark gap shortening by the plasma cord at the second stage of the electric discharge.

The shock waves generated in air by creeping discharge apparently can be used for modification of the hydrodynamical flow past a surface and thus to control the aircraft movement.

Introduction

Creeping electric discharges are used in various electrophysical devices such are laser pumping [1, 2] or effective UV sources [3].

The results of investigation of arc discharge initiation with plasma contact moving form one electrode to another along semiconductor carbon thread are available [1, 2]. This discharge is called creeping arc discharge analogously to the discharge on the surface of insulator covering the electrode. The studies of discharge dynamic have shown the velocity of discharge front is more than the sound in some conditions and is accompanied with generation of shock waves both in the beginning stage of electric arc development during plasma contact propagation form one electrode to another and after the electrodes shortening by the plasma cord and creation of the arc.

According to estimates the shock waves generated in air by creeping electric discharge are intense enough to change the flow of gases past an aircraft surface. Hence the creeping arc discharge could be used to control the aerodynamics of supersonic flow and hereby to steer the aircraft.

In this context it appears to be important to investigate the dynamics of shock waves generation at all stages of electric arc discharge evolution including both initiation of the creeping electric discharge propagating in form of plasma contact along the semiconductor rod surface and during the shortening of the electrodes by the powerful arc discharge.

The shock wave in form of coupled wave emerges already at the beginning stage of discharge during the plasma canal (leader) propagation in the spark gap. The stage of the creeping discharge evolution before the arc discharge is concluded by the gap shortening with the plasma canal. Then the much more powerful extended shock wave is created in the second stage while the plasma canal shortens the electrodes and becomes an arc in the spark gap.

Thus this work studies the results of investigation of shock waves forming in air in both the stage of pulse discharge before the arc [4] then the leader is initiated and propagating along the semiconductor rod surface from one electrode to another and the later stage of electric discharge evolution during the spark gap shortening by the arc.

The electric scheme of the experimental setup

Excitation of the spark was performed by discharging the gap between the electrode (usually anode) and the rod surface.

The electric scheme of the experimental setup is shown on Fig.1. The capacitor C with capacity of 100 μF is charged to the voltage U₀. The voltage was varied in range U₀ = 1–3,5 kV. The electric circuit was shortened by the spark gap. The capacitar was hereby discharged on the semiconductor surface of the rod situated in between the electrodes. The discharge current was measured by the Rogovski belt with the integrator. The spark gap span between the initiating electrode
and the rod was around 0.5 mm. The initial field intensity $E_0$ was calculated by the formula $E_0 = U_0 / L_0$ and ranged from the $12 \times 10^3$ to $91 \times 10^3$ V/m there the $L_0$ is the interelectrode span.

The typical oscilloscope recordings of current and voltage on the spark gap is shown at Fig. 2.

![Fig.1. The electric scheme of the experimental setup.](image)

The study aims are the shock waves generated in air at the early stage of the electric discharge evolution during the leader propagation over the semiconductor rod surface and at the terminating stage then the spark gap is shortened by the electric arc.

The optical system

The hydrodynamics flow of plasma cord propagation in the spark gaps was visualized with the optical system built atop the shadow device IAB-458 [5] and the interferometric suplement RP-452. The light source was an updated ruby laser OGM-20 there the Cerr's cell was replaced with the passive liquid shutter [6].

The laser produced series of flashes with the each 100ns long. The interferograms corresponding to the discrete flashes were recorded by the JFR photochronograph of the waiting type with dismounted ingress slot. The shot number in experiment was varied in range $10^1$ to $15$ with the range interval from 5 mks to 35 mks; the shot dimension was $12 \times 22$ mm.

The creeping discharge gap was in the light field of the IAB-458 device. There is the interferometric suplement at the exit of the shadow device creating two pictures with the 32 mm distance between them. The lower part of the frame is the shadow image and the upper part is the interferent image. The light beam disturbed by the discharge interferes with the undisturbed beam which is remote from the discharge. The light filter with gating maximum cut own luminescence of discharge off.

The cineinterferogramms obtained allowed one to analyze the forming and evolution of flow picture in the spark gaps of various shapes and to determine a characteristic parameters.

Cinegramm of discharge creeping on semiconductor surface

Some flow interferograms with optimal initial tuning obtained in the experiments are shown on the Fig. 3. They allow one to observe the evolution of the discharge in the field of view of the optical system and to measure the gasodynamical parameters such as velocity and shape of the leader, the shock waves and so on. There are two vertically shifted images on each shot. The upper image is an interferogram and the lower one is a shadowgram.

The dynamics of the creeping discharge evolution is well viewed on the interferograms and shadowgrams. The first picture of Fig. 3 shows the moment of the leader origin in the very beginning of discharge. There are a part of the rod surface and two electrodes 50 mm apart from each other on the picture. In the moment of the 2.0 kV voltage feeding electric discharge emerges in between the rod and the electrode and the thin plasma zone – leader – forms sliding along the rod surface towards the second electrode. The leader greatly emits light and propagates along the rod in form of creeping plasma contact with the turbulent area consisting of plasma and heated air trailing in the behind.

The shot 1 Fig.3 shows the 10 mm long leader propagating on the semiconductor surface of the carbonized ceramics rod of TVO-10 resistor from the anode towards the cathode. The forward part of the leader has conical shape while the backward expand slightly around the anode. The shot 2 Fig.3 shows 36mm-long leader with the 3-4 mm high central part. The coupled shock wave propagates from the head of the leader at the angle of 30 degrees. The average leader velocity in around 1000 m/s. The maximal density gradient is
located in the upper half of the leader while the lower part of the leader shows realignment of the vertical interferometric strips.

After the leader arrival on the opposite electrode the discharge of the interelectrode interval occurs producing the 200 J of energy during 50 mks and the electric arc creates generating strong shock wave in the surrounding space.

The shot 3 Fig. 3 corresponds to the moment immediately after the capacitor discharge. The front of the cylindrical wave propagates with average expansion velocity of 610 m/s. The middle part of the disturbed zone located 15-20 mm from the spark-gap has the most gradient of optical density corresponding to the plasma zone of the arc discharge. The zone of minimal density is 5-7 mm high. This zone on the shot 4 Fig. 3 is expanded to 20 mm after 26 mks from the shot 3. The shock wave velocity exceeds 500 m/s.

The velocity of the cylindrical shock wave propagating from the arc discharge exceeded 800 m/s for experiments with ceramic rod TVO-10 with interelectrode distance 50 mm and voltage $U_0$ around 2.5 kV.

**Investigation of the leader velocity**

Two ways of the leader velocity measurements were used in the experiments. The first methods is based on per-frame recording analysis. In this method the distance traversed by the leader and time interval between the frames are measured. This data were used to calculate the average leader velocity.

The second method use oscilloscope recording of voltage and current that register the time of arrival of the leader to the grounded probe. The average leader velocity was measured from the time of traversal of the gap between the initiating electrode and the probe by the leader.

The discharge of the spark gap of the electrode emerges on the discharger initiation, plasma front propagates towards the grounded electrode. The arc discharge appears upon the leader arrival to the probe, discharging the capacitor. The use of the intercepting electrode enables one to measure the average leader velocity in the arbitrary interelectrode interval including the initial portion of its propagation with relatively small changes of the field intensity caused by the capacitor discharge and the decrease of the semiconductor rod surface non-shortened by the leader. The working length of rod was varied in range $L_0 = 30 – 203$ mm.

The conditions of the experiment ensured the $U_m$ in the creeping discharge phase not lower than the 85% of the $U_0$. The average error of measurements was ± 5%. Experiments were carried out in the air under room conditions.
Experimental results

The dynamics of shock waves generation in the creeping discharge evolution is well seen on the interferograms and shadowgrams. At the moment of voltage feeding the electric discharge forms in the span between the rod surface and the electron and the plasma contact emerges which moves from that site towards the opposite electrode.

The leader velocity can be both lower than the sound velocity in air and exceed the sound velocity. During the supersonic propagation of the leader the coupled shock wave develop on the leader front. The conical turbulent zone of plasma and heated air form behind the leader front.

The coupled shock wave created by the leader propagation in the air has approximately constant intensity determined by the leader velocity. The shock wave intensity grows as the leader velocity increase.

The investigations shown what the underpowered leader created in the first stage of discharge could not reach out the second electrode due to the capacitor drain. In this case there isn’t the electric discharge stage.

The cinegramm of the creeping electric discharge evolution is complemented by the typical current oscilogramm on Fig. 2. The recording of current also shows two stage of the sliding discharge evolution. In the first stage the initial current steadily increases as the discharge front slides along the rod reaching to the value approximately \((1.5-2)I_0\). The amount of the initial current is determined by the rod conductivity and the given initial voltage \(U_0\).

![Fig.4](image)

**Fig.4.** The creeping discharge velocity for various rod materials versus electric field intensity.

The dendencies of the creeping discharge velocity for various rod materials as function of field intensity are given at Fig. 4 in logarithmic scale. The data for experiments with silica carbide, eel carbon and carbonized ceramics rods of various specific area with specific resistance ranging from 0.08 Ohm/cm to 1.6 Ohm/cm are represented. The average velocity of discharge propagation varied between some tenths of meters per second to 3000 m/s for voltages ranging form 1.4 to 3.5 kV.

Discussion

The experimental data on leader velocity are shown on Fig. 4. The dashed line corresponding to sound velocity divide the data on subsonic and supersonic parts. In the lower part of Fig. 4 the points corresponding to subsonic leader velocity are situated. There is a considerable data jitter witnessing the poor experiment reproductibility and possible unstability of the leader propagation at low velocities.

The above part of Fig. 4 contains points for supersonic leader velocities. There is much less data jitter and better reproductivity showing stable leader movement. The points on Fig. 4 for various rod length and material and variable voltage are satisfactory approximated by the linear interpolation. The crook is visible in the part where the leader velocity exceed the sound.

The leader velocity increase with the voltage. In the error bounds of the experiment one may conclude the simple relation of the creeping discharge velocity on the electric field intensity for the given samples.

The supersonic leader velocities in the interelectrode span measured by the frame recording data turned out to be relatively constant and coincide with the values measured by the probe method. It’s accounted for the fact that the current what define the heat production in the leader head weakly varies along the spark gap length and hence the leader velocity is approximately constant along the rod.

Velocity of shock wave generated by the leader of creeping discharge moving in air also appear to remain constant for given electric field intensity. It allows one to estimate the excessive pressure in the shockwave front using the dependence of leader velocity as function of electric field intensity.

The excessive pressure in shockwave front versus electric field intensity is shown at Fig. 5. The dependence of excessive pressure was obtained using simulation of excessive pressure in an ideal one-dimensional shock wave with the Mach number from the experimental data on leader velocity shown on Fig. 4. It was assumed what the leader velocity corresponds to the stream velocity behind the ideal one-dimensional shock wave in
air. One may suppose the pressures in question exist in the coupled shockwave.

The main part of spark energy (not less than 70%) is released in the arc discharge stage during capacitor discharge. The released energy forms intense cylindrical compression wave in air.

The main feature of creeping discharge is a gap which is wider in 1-2 orders of magnitude than the electric strength of air. It results in greater quotient of energy transition of electric energy into shock wave due to the involvement of greater mass of air into plasma discharge cord forming compared to an ordinary spark discharge.

Thus creeping electric discharge turned out to be an effective generator of shock waves in air both in early stage during the leader movement on semiconductor surface and at the ending stage of electric discharge. The span and shape of shock waves are determined by the distance between electrodes and the shape of plasma canal of the leader and therefore by the rod shape. The intensity of shock waves may be adjusted by varying the discharge energy determined by the electrode voltage and electric field intensity and it also can be varied with selection of semiconducting rod surface material and the length of interelectord gap.

Apparently creeping discharge in pulse frequentonal mode can be used for effective adjustment of supersonic air flow past surface and hence to steer a supersonic aircraft.

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References