The thermographic study of the surface discharge electrode systems with a fixed and moving dielectric barriers

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Abstract. The paper presents the thermographic investigation results of temperature fields on electrode systems of surface discharges excited on a fixed and moving dielectric layers. It is shown that temperature in the electrode systems with stationary dielectric barrier is of 28-135°C while temperature of electrode systems with a movable dielectric layer doesn’t exceed 50°C. The effect of near-wall gas flows on the surface temperature distribution of electrode systems is discussed.

1. Introduction

It is well known [1-3] that barrier-type discharges are widely used in different fields of science, engineering, and technology. Currently, they are applied in chemistry [4], plasma medicine [5], plasma processing of materials [6], and etc. It is possible due to the use of dielectric barriers in electrode systems which prevent a spark breakdown at higher intensity of electric field. It provides possibility for embodiment of new electro-physical processes [1, 7].

Among barrier-type discharges, there are surface discharges which can form at the boundary between gaseous and solid dielectrics [8-9]. According to [10], the surface discharges are excited under non-uniform electric field action. It facilitates the conditions for the plasma formation in a thin gas layer near the surface of the dielectric barrier and the discharge propagation along the dielectric surface [9]. It allows us to use the surface discharges as a sources of ionization or as plasma electrodes which are applied to develop effective gas-discharge devices [8].

However, the devices integration into more complex systems isn't able without reliability growth of their operation. It requires further research and development in the surface discharge physics. In particular, it can be realized through the development of diagnostic methods for surface discharge investigation [3, 8].

Obviously, to monitor the energetic features of the surface discharge, the infrared (IR) thermography may be used [11-13]. According [11], IR-thermographic method is contactless and provides the temperature fields recording for electrode systems immediately. Also the method may be used to estimate the power distribution released in the discharge process [13]. For surface discharges, the adequate estimation of the power distribution is facilitated by the contact of the discharge combustion zone to the surface of the dielectric barrier [8-9] as well as the small optical depth of the plasma layer [14].

The paper presents the thermographic recording results of the electrode systems for low-current surface discharges excitation on fixed and moving dielectric barriers in the air at atmospheric pressure [15-16].
2. Experimental setup

Thermographic research was carried out by using electrode systems shown in Figs. 1 and Figs. 2. During the experiments, temperature fields were recorded, the discharge power consumption was estimated, as well as gas transfer processes near the surface of electrode systems were studied.

For thermographic measurements, IR scanner (IRTIS2000 with resolution 256*240 pix and wavelength $\lambda$=3-5 $\mu$m) and IR camera (Testo 881 with resolution 640*480 pix and wavelength $\lambda$=8-12 $\mu$m) were used. Also, the temperature was recorded by thermocouples (NiCr-Ni, $T$=−40-1200°C) mounted on the surface of interest. The uncertainty these instruments didn’t exceed 5%. The sharing of IR- equipment and thermocouples permitted to compare data obtained both methods [11].

To determine the discharge power consumption in the electrode system with the fixed dielectric barrier (see Fig.1), the double-channel oscilloscope (PSCU1000) that measured discharge current $I(t)$ and voltage $U(t)$ using the high-voltage divider (5000:1) and the shunt (R=26.5 Ohm) [14,17] was included in the experimental setup. For the electrode system with the movable dielectric layer (see Fig.2), the discharge power consumption was determined by kilo-voltmeter (C-197) and digital voltmeter (B7-35) used like ammeter [16]. According to [16, 17], these systems make possible to obtain current-voltage characteristic for each type of discharge (see Fig.3 and Fig.4) and to study the discharge process with time resolution.

The heat-mass transfer processes at electrode system were investigated by a particle image velocimetry (PIV) [18]. The method provided the vector velocity maps recording in the area illuminated by laser sheet. For this aim, the PIV-installation based on the pulsed laser (Solo-120XT, $\lambda$=532 nm) was used. The application of PIV and oscillographic equipment allowed us to reveal interconnection between energetics processes in plasma layer and gas convection near the dielectric barrier.

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**Figure. 1.** Electrode system for excitation of the non-arcing surface discharge on the stationary dielectric substrate: 1- high voltage power supply; 2-discharge electrode; 3-dielectric barrier; 4 – the grounded electrode

**Figure. 2.** Electrode system for excitation of uniform surface discharge on the moving dielectric layer: 1-cathode; 2 – kilo-voltmeter (C-197); 3 – rotor-electrode; 4- dielectric barrier; 5 – anode; 6- ammeter (B7-35). $V$=1-10 m/s, $d$$\cong$1mm, $h$$<0.5$ mm

**Figure. 3.** The current-voltage characteristic of the non-arcing surface discharge: a –point of discharge intensification. Discharge electrode perimeter length is 140 mm. Electrode system capacity is 68 pF.

**Figure. 4.** The current-voltage characteristics of the uniform surface discharge at different velocities of the dielectric barrier movement: 1-$V$=8.8 m/s; 2-$V$=16.6 m/s; a,b –points of discharge intensification. The electrode system parameters: $L=20$ mm, $d$$\cong$1mm, $h$$<0.65$ mm. Cathode length is 45 mm.
3. Results and discussion

The research results of electrode systems with fixed and moving dielectric barriers are illustrated in Fig.3-Fig.11. Here, the non-arcing surface discharge (NSD) on the stationary dielectric layer (see Fig.1) is formed by the alternating voltage with amplitude $U_a < 7$ kV and frequency $f = 8$ kHz [14]. In these conditions, the discharge propagates along dielectric surface from discharge electrode (see Fig.3) as multi-channel plasma structure. The discharge power consumption depends on the dielectric layer capacitance and achieves 63 Watt. The dielectric temperature changes from 28°C to 135°C. At the same time, uniform surface discharge (USD) is formed on the rotary electrode (see Fig.2) under direct current action [16]. With a voltage growth, the discharge propagates from anode to cathode like a uniform plasma layer (see Fig.4 and Fig.9). At $U = -18$ kV, USD overlaps the electrode gap $L$ without sparking. In this condition, its power consumption doesn’t exceed 25 Watt. The discharge differs from other the barrier-type discharges. The first, the current-voltage characteristic of USD depends on the movement speed of the dielectric layer (see Fig.4). The second, the USD-current increases with dielectric layer thickness ($d$) growth, although the capacitance of the dielectric barrier decreases in this case [19].

At the first stage of the study, the data obtained by the thermal imaging method were verified. For this purpose, the electrode system with the fixed dielectric layer and the grounded discharge electrode was used (Fig.5). The application of an electrode system with the grounded discharge electrode enabled to mount the thermocouple in the vicinity of NSD-generation zone. Such thermocouple position also provided a

![Figure 5](https://example.com/figure5.png)

**Figure 5.** The scheme for joint registration of temperatures by thermoelectric recording and IR imaging methods: 1 – the electrode system for excitation of the non-arcing surface discharge; 2 – surface discharge; 3 – thermocouple; 4 – IR radiation.

![Figure 6](https://example.com/figure6.png)

**Figure 6.** The comparison of temperatures obtained by thermoelectric recording and IR imaging methods: 1,4 – brightness temperatures ($T_b$) of the discharge electrode (site near the thermocouple) and of dielectric in the discharge zone respectively; 2, 5 – the corrected temperatures for the sites near the thermocouple and the discharge zone respectively; 3 – thermocouple data.

![Figure 7](https://example.com/figure7.png)

**Figure 7.** Registration of the temperature gradient on the surface of the discharge electrode at NSD-generation: 1 – temperature level in the discharge zone (IR data); 2, 3 – data obtained from the protected thermocouples mounted at the distances from discharge $l_1=1$ mm and $l_2=10$ mm respectively; 4, 5 – data recorded by the exposed thermocouples placed at the distances from discharge $l_2=10$ mm and $l_1=1$ mm respectively.

![Figure 8](https://example.com/figure8.png)

**Figure 8.** Instantaneous view of the air flow near electrode system of the non-arcing surface discharge at $U = 5$ kV: 1 – discharge electrode; 2 – suction flows at the edges of discharge electrode; 3 – outer tangential flows.
comparison of the temperatures recorded by thermoelectric method and IR imaging method. For comparison of data obtained by IR scanner and thermocouple, brightness temperatures recorded by IRTIS2000 were corrected according to the gray body model [11-12]. During correction, the reflectivity of the surface in the scanning zone was taken into account.

In experiment, surface discharge was excited by the alternating voltage with amplitude $U_a = 3$ kV. Power consumption of discharge was around 7.5 Watt. To correct brightness temperatures, the reflectance factors for a copper discharge electrode ($\lambda=3-5$ $\mu$m $R_{Cu}=0.95-0.98$) and fiberglass-plastic of barrier ($\lambda=3-5$ $\mu$m $R_{FP}=0.88-0.93$) were selected from reference data [11, 20]. It allowed us to compare temperatures obtained by IR scanner and thermocouple (see Fig.6). According to Fig.6, the discharge heated the dielectric surface up to 60°C (IR data), while discharge electrode had temperature around 52°C (thermocouple readings). Data comparison between thermoelectric method and IR imaging method in the site of thermocouple position showed that maximum temperature deviation was $\Delta T=1.5^\circ$C (curves 2, 3 in Fig.6). Such result allows us to recommend IR-thermography as reliable method for investigation of the low-current surface discharges and their energetics.

To estimate the heat flux from the discharge zone, two the exposed thermocouples were mounted on the surface of the grounded discharge electrode at the different distances from an electrode edge (Fig.7). The first thermocouple was placed near electrode edge at the distance $l_1=1$ mm, while the second thermocouple was placed in central part of discharge electrode ($l_2=10$ mm). Both of thermocouples have freely contacted with air.

During the experiment it turned out that the temperature near the electrode edge was higher than one in central part of electrode (see curves 4, 5 in Fig.7). It is contrary to infrared image in Fig.6. In order to explain this discrepancy, PIV registration of air movement near the electrode system was performed. PIV-recording was executed at frame rate $f_{FR}=8$ fps and laser impulses energy $W=30$ mJ. Data processing was carried out when the sampling window sizes were $32\times32$ pix and sampling window overlap was 50%.

As a result, a gas flow induced by the surface discharge was detected near the electrode system.
Figure 11. The thermal image of the electrical breakdown forerunner (a) and spark breakdown (b) in the electrode gap (L) of the uniform surface discharge: 1-cathode; 2-anode. Discharge mode: U=−16 kV, V=8.8 m/s, L=20 mm.

According to Fig.8, the surface discharge created the tangential air flows which propagated along dielectric barrier. It led to suction air flows formation in vicinity of discharge electrode. Suction flows were localized at the edges of the discharge electrode. These flows cooled the thermocouples that were present in the boundary layer. The phenomenon was confirmed by additional experiment when thermocouples were protected from air flow (see curves 2, 3 in Fig.7). In this case, the thermocouple readings at the electrode edge were higher than the thermocouple data in the central electrode part. Qualitatively, such result corresponded to the data of the thermal imaging method.

Thus, the near-wall flows may influence the temperature fields of electrode systems. It complicates the direct restoration of information about the zone of energy generation in a surface discharge and requires the application of inverse problems methods for solution [21].

The next stage of research was associated with observation of the interaction between the USD-plasma and the movable dielectric barrier in the rotor-type electrode system. In experiments, discharge was excited by voltage U=8−18 kV at the rotor-electrode velocity V=8.8 m/s. The discharge power consumption varied from 0.6 Watt to 12.6 Watt.

The thermographic measurements have been carried out by IR-camera (Testo 881). These results are presented in Fig.9-Fig.11. According to Fig.10 and Fig.11, dielectric layer is uniformly heated by USD during charging and discharging process near cathode and anode respectively. The data confirm the observed uniformity of the discharge plasma in visible range. With the discharge power consumption growth, the thermal mode of the dielectric barrier does not change significantly (compare Fig.9a with Fig.11a) due to the forced convection caused by the rotation of the rotor-electrode [22]. It permits us to explain the significant resistance of dielectric barriers during operation for such-type electrode systems.

Also, in the generation of a surface discharge, signs of a gradual destruction of the dielectric barrier were revealed (see Fig.11a). The further operation of the system led to the spark breakdown (Fig.11b). Obviously, the tracking of such signs will provide the reliability growth for electrode systems of surface discharges due to the system maintain on condition.

4. Conclusions
1. It has been experimentally shown that the thermal mode for electrode systems of an non-arcing surface discharge is of 28−1350 C while for electrode systems with a movable dielectric barrier, the thermal mode is much less intense (at a comparable power consumption) due to forced convection. It allows us to use the film dielectric barriers made from less heat-resistant materials in the design of the rotary-type, gas-discharge devices.
2. It has been revealed that near-wall flows induced by the discharge affect the distribution of the recorded temperature fields, preventing the direct restoration of information about the spatial zone of energy generation in the surface discharge.
3. It has been confirmed that IR thermography is an informative method for studying gas-discharge processes and systems by providing not only quality checking of their manufacture, but also revealing of gradual wear and destruction processes.
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